Complex Adaptive Blockchain Governance

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Abstract. The blockchain revolution upholds the decentralizing ideal of "control nothing." It is natural that such a pursuit would face issues of governance that demand reasonable control; control that is both operational as well as adaptive in nature. Eliminating middlemen and handing over controls to a trusted system of trustless agents does not thereby bestow trust across time. This is especially true when relentless change is the order of the day. Issues of governance rise up when the blockchain systems (especially those that have embedded smart contracts) are forced to operate increasingly away from its original intent. Smart contracts need governance when beset with the problem of the unknown-unknowns. Guided by the axiomatic approach, this paper looks at the paradoxical issue of blockchain governance from a Complex Adaptive Systems (CAS) perspective that helps frame the fundamental problem of decentralization. The objective is to solve the Blockchain Governance Kernel Design. Real-life examples are used to illustrate the findings.

Keywords: Blockchain; Stigmergy; Governance; Complex Adaptive System; Heterarchical Hierarchy; Unknown-Unknowns; Smart Contract

1 Introduction

Consider C.P. Snow's proposition of the growing chasm between "The Two Cultures" [1]; i.e., between the sciences (which includes the social sciences) and the humanities, but now from a design perspective. Design as a discipline that deals with human artifacts (be they social, technical or socio-technical), has to bridge Snow's chasm in every single instance of design. This is because meaning and purpose, i.e., the root FR's that mandate any given design, ultimately reside in the human-centric humanities which includes disciplines such as languages, history, philosophy, arts and the law [2-4]. Thus, for example, the design of an equitable governance system is ultimately rooted in the realm of law and justice. The research reported herein integrates across both the above cultures in order to make explicit the kernel governance design in the context of the ongoing blockchain revolution.

There is a fundamental difference in the requisite bridging-over that is necessary when considering technical versus social systems. Technical system designers have well-developed disciplines such as cognitive engineering, business-analysis, ergonomics, and others to help establish the preamble and move the design activity into the technical realm. In contrast, social system design is barely a discipline. There is no similar preamble body of knowledge that helps translate the social system FR's into the language of the social sciences. There are no rich traditions, no well-accepted bodies-of-knowledge as to how design operates in the social realm. For example, it is only recently that the nascent concept of stigmergy is helping disambiguate Adam Smith's economy-wide, organizing principle of the "*invisible hand*" [5]. A disciplined approach to design, therefore, is more evident in the technical as compared to the social/organizational realms. The design of technological artifacts is more amenable to principled structuring as compared to the design of social artifacts. As Prof. Suh has noted, the ad-hoc approach is the accepted norm in the case of social artifacts [2]:

> *In many organizations well-defined FRs are often lacking or not completely understood by everyone in the organization, and the organizational structure does not have specific DPs to satisfy FRs. The job of the management is to define FRs and establish DPs, but this has been done ad hoc, very much as in other fields of design.*

While technical system designs have come a long way since the 1990s when the above critique was first made, social system designs remain as is. Heretofore, the social and the technical have existed side-by-side, content to drift apart in their separately evolving cultures. However, now we are entering the realm of massively fine-grained socio-technical systems such as the world of IoT (Internet of Things). The above divide across these two cultures is therefore not sustainable. The odd marriage between the two cultures does not scale; instead, it has the potential to result in large-scale, out-of-balance socio-technical system failures. Every system has a certain capacity for change beyond which it starts to show pathologies. Current social systems are ill-prepared to receive dramatic influxes of technology such as the promise of IoT [6].

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Design of the governance kernel of socio-technical systems is a challenge of the first order. This challenge is two-fold. Governance has to operate both at the agent as well as at the institutional level. Firstly, the design of social systems is more nuanced than the design of a purely technical system. This is because natural laws are easier to discern compared to the social. For example, the ideal of justice enshrined in the rule of law that governs a given social order is not as apparent as, the force of gravity enshrined in the Newtons law of gravity. Natural laws govern the physical sciences; there is, therefore, no other governance needed. In contrast, design (be it technical, social, or socio-technical) requires governance--since it needs to account for the human element. The bounded rationality problem conditions human decision-making. While natural laws are universal in scope, human decision making is constrained to operate within the limited knowledge scope of individuals and groups. Humans have different knowledge bases and perceptions. These differences inevitably lead to misunderstandings and conflicts that then needs governance at the agent level.

A second issue that social system designers face is that of institutionalized injustice. Human agents are endowed with free-will. As we just discussed, when bounded rationality meets free-will, human agents may commit erroneous decisions. However, free-will is also a significant reservoir for corrective governance forces that unleash when agents face institutional-level injustices. Indeed, the exercise of free will (both individually as well as collectively) has the power to change the course of nations and organizations. In other words, organizational units do not have the power to dictate commands that violate the moral code unilaterally. Given the painful history of how humans have socially engineered their way into political/criminal dominance over others, and then institutionalized this dominance, it is crucial to safeguard against such abuses via proper governance. Moreover, with the advent of massive socio-technical systems, the prospective danger of such institutionalized dominance via the exploit of cognitive biases is abundantly clear and present. Cultures may exhibit differences regarding their respective tolerance for injustice; but eventually, social elements rebel and overthrow nodes of injustice. This, of course, is a costly process of redress that a proper governance model can help address upfront. Thus, if properly designed, elements of governance can help safeguard against acts of injustice at the institutional level.

Governance operates at two levels: the agent and the institutional. Governance at the agent level primarily needs to safeguard against bounded rationality; governance at the institutional level needs to safeguard against institutionalized injustice. As discussed in Section 7 on CAS, these two levels of governance bifurcate into the α and β levels of governance respectively. Given the apparent differences in size and operational scale, making course-corrections at the institutional level is far more demanding than the same at the agent level. It is akin to maneuvering and changing course of a massive oil tanker versus an agile sports-car. Even so, and as we shall see, the kernel design for both of these governance systems may be obtained via a surprisingly similar lower-triangle arrangement of heterarchical hierarchies. This is because in both cases, governance ultimately does reduce to the problem of *unknown-unknowns* in the context of knowledge architectures that operate either at the agent or the institutional level. In either case, the addition of heterarchic controls may, therefore, help solve the governance issue.

In essence, this is the promise of the blockchain revolution (i.e., the addition of decentralized heterarchic controls). The blockchain technology initially was created as a support system for bitcoin transactions. However, it is now turning out to have far-reaching economy-wide implications for conducting peer-to-peer transactions absent any gatekeeper middlemen. Governance in a knowledge-economy implies the establishment of appropriate regulatory nodes that help keep open the flow of information and knowledge with proper regard for privacy and property-right concerns.

Note however that the design of a CAS system (that is emergent, self-organizing and adaptive) is a step removed from the traditional design of systems that are predominantly non-self-organizing. Here the design is left incomplete at a meta-level; the final stages are orchestrated in a self-actualizing boot-strap from its inchoate embryonic state to its fully actualized adult form. The closest exemplars of self-organization may be found in the realm of biological entities that have brought forth their ever adaptive, ever-evolving designs via genetic trial and errors spanning immense temporal expanses. Trapped within the sparse coils of the DNA (which consists of about 1.5 GB of DVD-sized data), one may witness the essence of the Information Axiom operating in a self-organizing context. Herein, the genetic code orchestrates the embryonic self-articulation and development of a complex living entity (consisting of about 150 zettabytes of data and requiring about 30 Manhattan-size datacenters to merely store) that can struggle, adapt and thrive in heretofore novel and unknown environments with ever-changing risks and opportunities. Biological as well as blockchain-based socio-technical systems may be studied under the rubric of CAS (Section 7) to help elicit issues of decentralization, self-organization, emergence, etc.

Section 2 surveys the relevant literature on governance as it relates to the blockchain technology. Section 3 highlights the issue of trust amongst trustless agents--which fundamentally undergirds the blockchain way. Section 4 studies the rise of complexity as a driving force for creating new organizational structures. Section 5 summarizes research on organizational design. Section 6 presents the phenomenon of stigmergy and stigmergic gearings that help structure a CAS. Section 7 describes the CAS system; i.e., the basic as well as iterative. Section 8 establishes the concept of decentralization (that underpins much of the blockchain technology) in terms of CAS. Section 9 defines the role of governance. Section 10 looks at the phenomenon of Emergence and Self-Organization in the context of governance. Section 11 explores heterarchies and hierarchies in the context of governance.

Section 12 helps reduce the problem of governance (both agent level as well as institutional) to the heterarchical-hierarchy of knowledge architectures. Section 13 examines governance regarding the unknown-unknowns. Section 14 frames the Axiomatic Design framework for CAS. Section 15 structures the basic blockchain design from an axiomatic perspective. Section 16 extends this design to include smart contracts. Section 17 discusses the kernel blockchain governance design. Section 18 concludes and wraps up the current work.

2 Literature Review

Governance of digital assets takes on a whole new meaning when almost anything and everything can be tokenized and traded by quasi-anonymous agents which include machines and IoT's.

In [7], Campbell-Verduyn provides a broad-brush introduction to the issue of global governance in the context of the blockchain. Blockchain-based trading platforms started showing the cracks in the operative governance framework (or the lack of it) when enterprises such as Mt. Gox and SilkRoad started surfacing the underlying "*deep and dark-web*" side of the new technology. The key issue raised is whether the blockchain technology "*gives rise to new governance problems and pathologies? [7]*" Every shift in the technological front leaves many who are vulnerable to new information asymmetries. If so, what is the role of governance in mitigating these asymmetries while allowing innovation to proceed forward? But hastily drawn governance rules could very well kill the golden goose that may just turn out to be immensely transformative and liberating. Also, as the governance researchers clearly understand, blindly subscribing to the Lawrence Lessig formulation of "*Code is the Law [8]*" is an invitation to enter a Hobbesian Leviathan monolith. It is therefore critical to understand the foundational basis of human trust; and how much of it could be replicated via a trusted system of trustless agents?

The problem of interdisciplinary complexity inherent in blockchain is also echoed in [9] wherein Lopp asserts that: *"One challenge to understanding bitcoin is that it is a multifaceted cross-disciplinary system that is constantly evolving."*

In [10], Ehrsam (co-founder of Coinbase) asserts the strategic significance of blockchain governance in that it could be "*the largest determinant of our future trajectory as a species*" when it potentially gets used to bootstrap powerful AI across the distributed landscape. Crossing over to the humanities end, Ehrsam highlights that it is governance that "*keeps communities together and, in turn, gives a token value*." He further argues for on-chain governance (i.e., code is law) in terms of its consistency, fairness and speed of decision making. He does, however, caution that the Leviathan metasystem could easily get exploited if flaws were to be discovered; also, that it becomes "*harder to change once instituted.*"

As a direct rebuttal to Ehrsam's stand on the costs and benefits of on-chain governance, Zamfir (lead developer at Ethereum's Casper protocol) asserts in [11] that blockchain governance (as well as governance in general) cannot "*be understood as a design problem.*" The reason suggested as to why governance falls outside the purview of design is because governance is a process, and processes presumably fall outside the scope of design on account of the dynamics involved. This, of course, is an untenable position in favor of adhocracy; processes can and should be subject to design. Nevertheless, Zamfir's highlighting of the need for adaptiveness when designing governance structures is on target. Furthermore, it dovetails well with the adaptiveness embedded in a CAS architecture. Zamfir also takes issue with Ehrsam's stand on on-chain governance as being "*incredibly risky*" in inviting automatic upgrades of the governance processes without adequate human due-process and oversight. Again, a proper design of the governance kernel ought to make clear the appropriate contexts where one may resort to on-chain versus off-chain governance.

In [12], DuPont forensically analyses the governance failure in the Ethereum based DAO (Decentralized Autonomous Organization). The DAO promised transparency, efficiency, fairness and a democratic decision-making process. In just a month, it managed to raise USD 250 Million; yet within days of its launch, it suffered a massive "attack" (draining it off USD 35 million) from which it never recovered. The study exposed the "*inherent complexity of bringing to life an algorithmic and experimental organizational model*." After the attack there were three post-attack options presented:

- Code is Law (on-chain): Let the attack stand. Attacker gains USD 35 million
- Soft Fork (off-chain): Let USD 35 million vanish.
- Hard Fork (off-chain): Return the funds to the "investors" who willingly participated in the trading platform but felt taken advantage of. The attacker lost USD 35 million.

Ultimately the DAO that was supposed to be hands-off and accepting of the "Code is Law" dictum, violated its own governance and did a hard-fork by reverting to human governance.

Based on the DAO failure, Voshmgir highlights the problem of the Unknown-Unknowns in [13]: *While machine consensus can radically reduce bureaucracy, the question of how to deal with unknown unknowns that manifest over time has not yet been resolved.*

3. Trust: Sed Quis Custodiet Ipsos Custodes?

At its root, all socio-technical systems either rely on trust or make costly allowances for a potential breach of trust. With social trust in place, one can tentatively foresee, plan and design our socio-technical engagements. Trust is the underlying basis for designing socio-technical artifacts. Society pays an enormous overhead for securing trust. Traditionally, trust-systems (both internally as well as externally) are hierarchically orchestrated. Internal hierarchies preside over breaches of trust within an organization. External hierarchies preside over breaches that cross organizational boundaries. Hierarchic governance structures are inherently flawed in the sense that the top nodes can be compromised over time. Hence Lord Acton's dictum in [14] that "*power tends to corrupt, and absolute power corrupts absolutely*." This same sentiment was expressed two millenniums ago by the Roman poet Juvenal when he coined the phrase [15]: *Sed quis custodiet ipsos custodes?* (i.e., but who will guard the guardians?). Going further back into antiquity, similar suggestions may be discerned in Plato's *The Republic*. Having established an authoritarian top-down hierarchical social order, Socrates is here first shown to raise the problem of corruption at the top nodes; he then appeals to self-governance in order to help resolve this conflict; i.e., the self-indulgent notion that the "*best man has within himself the divine governing principle*" [16]. However, within *The Republic* itself, there are passages [17] that indicate that Plato looked down upon such a self-deceptive, self-referential design construct as a contemptable "*noble lie,*" (γενναῖον ψεῦδος: i.e., a lie or wrong opinion about the true origins).

Fundamentally, there is no escaping the fact that all hierarchical systems lack sufficient design parameters to help resolve the problem of the top-nodes going rogue. It was founding father, James Madison who first recognized in [18] the fatal flaw in a purely hierarchical design (symbolized as |H henceforth and as in [19]). Instead he proposed the now institutionalized heterarchic governance (symbolized as |h henceforth and as in [19]) within the US federal government; i.e., a model of *checks and balances* along with a clear *separation of powers* across three co-equal hierarchies in order to help make sure that the top nodes always have external oversight. It, therefore, may be argued that the ongoing US experiment in self-governance is indeed a lower-triangle decoupled design as the coupling via self-referentiality so evident in the Platonic logic has now been eliminated.

The blockchain model is likewise potentially revolutionary in scope in that it has within it, the ability to democratize and make ubiquitously available such heterarchic controls across all levels of any given socio-technical systems; not just at the highest echelons of the US Federal government.

4. Rising Socio-Technical Complexity

In [20], Prof. Bar-Yam suggests that society at large is shifting away from deeply hierarchic models, and in favor of more and more decentralized, heterarchic or mixed-mode |h-|H control. This is because distributed governance/control has a larger capacity for dealing with increasing socio-technical complexity. One may witness this in the academic realm, where interdisciplinarity is on the rise; and (traditionally) hierarchical disciplinary group boundaries are becoming porous.

Heterarchic linkages add extra burden in the realm of governance for the simple reason that heterarchies do not play nice; they instead jostle for dominance. Here, governance involves sense-making across domains and disciplines. And in order to be coherent and make sense, one of the erstwhile co-equals eventually starts to dominate the heterarchic complex. For example, in the case of the US Federal government, historically we do have three co-equal branches. However, over time, the judiciary (given its ability to explicate the governance narrative and create consistency across the total political span) has carved out a dominant long-term role; the executive (given its protagonist role in the near term) similarly dominates the contemporary stage; and much of the legislative branch stands reduced in stature The executive and judiciary have usurped much of the law-making ability of the legislative at both the consequential coarse as well as the fine-grain. The judiciary is not per se at fault; instead the default is in the purview of the other two as they lack explicit grasp of a missing FR, namely the need for historical consistency similar to judicial review. This is indeed a flaw in the founding design; for there is a hidden sense-making functional requirement that has been left unaddressed. Each of the co-equal branches ought to have had an ongoing sense-making role. Contrary to Emerson [21], consistency is not "*the hobgoblin of little minds*"; it in fact is what provides the directive thrust. Court precedents are not easily overturned; established case law sets the stage for what follows. Such binding sense-making is missing in the other two co-equal branches.

Sense-making is intimately related to the nature and shape of human knowledge. As discussed in Section 12, human knowledge is heterarchically hierarchical. Human knowledge dynamics, therefore, have a key role in the evolution of governance. Governance ultimately refers to the over-arching body of knowledge that provides guidance wherever conflicts arise. While heterarchical contributions enrich the growing corpus, it is the hierarchical aspect of human knowledge that is responsible for sense-making. Sense-making is fundamentally hierarchical in nature. Absent the distilling of such knowledge hierarchies, information fails to make sense. Larger the number of agents engaged in abstract, high-order sense-making, greater the chance that the engagement will devolve into heterarchic nonsense. Such is the fundamental weakness that the legislative faces. While it is heterarchically able to bring multiple points of views to the governance table, it is unable to integrate this into coherent hierarchically-sound agreements. Here, for example, is a report [22] on the attempt to merely determine the number of federal criminal laws at hand:

> *In 1982, while at the Justice Department, Mr. Gainer oversaw what still stands as the most comprehensive attempt to tote up a number. The effort came as part of a long and ultimately failed campaign to persuade Congress to revise the criminal code, which by the 1980s was scattered among 50 titles and 23,000 pages of federal law.*

Justice Department lawyers undertook "the laborious counting" of the scattered statutes "for the express purpose of exposing the idiocy" of the system, said Mr. Gainer.

Consequences of such accountability failures in the governance corpus are dire. For example, the above report summarizes the legislative failure on sense-making with the following comment [22] by law professor Prof. John Baker: "*There is no one in the United States over the age of 18 who cannot be indicted for some federal crime. That is not an exaggeration*."

Sense-making is especially relevant in the modern context of vastly expanded and heterarchically-rich, socio-technical systems such as the coming world of IoT's where machines directly transact with other machines at an unprecedented scale. The speed and scale of modern socio-technical operations make it abundantly clear that humans are increasingly left out of the decision loop as it is beyond our human comprehension. Fundamentally, humans are conceptual entities. The new era of human/machine symbiotics [23] we are now entering, ultimately has to make sense. Governance is fundamentally rooted in sense-making. It is this that is at stake when dealing with technologies of trust across the human/machine divide. And unless we are careful, just as the case was with the judiciary dominating the sense-making role and by default, taking up the "*first amongst equals*" position, machines may likewise be deliberately or accidentally programmed to serenade us with convincing but deceptive "*noble lies*" that exploit our individual and collective cognitive biases & weaknesses. When cast in this sense, the design of an equitable governance structure for the coming blockchain way of organizing our socio-technical systems may prove to be of existential import.

It is worth noting here that Cynefin [24-25] is also about sense-making in an interdisciplinary setting. Indeed, as the Welsh word Cynefin suggests, the emphasis is on multiple-belongings, i.e., multiple domains that mash-up to create the unwieldiness of modern complexity.

5. Complex Socio-Technical Organizational Design

Prof. Banathy was a pioneer in advocating for a disciplined design of social systems. He was of the opinion that we are now squarely in the "*postindustrial information/knowledge era [3]*." Consequently, organizational designs that arose in the industrial machine age does not scale given the exponential rise in the "*speed, intensity, and complexity of change*." Compared to design initiatives in other disciplines, he was painfully aware of the lack of attention regarding social-systems design. Prof. Banathy held that when considering social systems design, there is a tangible "*shift from product thinking to process thinking* [3]." In direct contrast to this view was Ethereum's lead developer, Mr. Zamfir who dismissed processes as being outside the purview of design.

Social-systems have an overarching "*concern for justice* [3]." Ethics, therefore, plays a pre-eminent role when designing social systems. The system ought to be equitable and just to all parties concerned, be they central or peripheral in the activities subsumed. In other words, governance plays a central role in all social system designs. The proper design of the governance unit for a blockchain-based social system ought to help establish clear boundaries that when breached may trigger appropriate smart contracts and/or legal recourse. Blockchain governance is therefore not independent and free-floating outside the appropriate societal moral code. What is, however, a departure from the norm is the fact that the blockchain based governance structures can adjudicate many of the conflict scenarios with machine-like precision and efficiency. It is as if vast parts of the social order may now be governed by benevolent arbitration judges that resides in the form of smart contracts coded up within the machine.

Social system designers are often faced with problems that are "*anything but well defined* [3]." Such problems may have inconsistent FR's, inconsistent constraint-sets, upstream designs that are coupled, problem-space that is dynamic across time, etc. This is to be expected since we are dealing with inconsistent ontologies across far-flung inter-disciplinary fronts. While keeping ye holistic view, design may, therefore, have to proceed in small iterative steps across the FR-DP divide. When inconsistencies are detected, this may lead to repeat back-tracks up the design hierarchy.

Social systems are primarily designed towards the benevolent nurture, growth, and development of the human potential. A properly designed governance unit helps adjudicate equity throughout the system--both in its homeostatic phase as well when the system adapts and evolves beyond its stable stage; i.e., "*self-organization incorporates self-transcendence, the creative reaching out of a system beyond its boundaries* [3]." CAS is capable of modeling such shape-shifting behaviors. Díaz and Olaya highlight the role of emergence in [4]:

"Human beings co-design the social systems that they form, this is why those designs might be intentional up to some point but they are also emergent, dynamic, incomplete, unpredictable, self-organizing, evolutionary and always 'in the making'"

In 2014, Prof. Norman and others put forth the DesignX framework [26] for tackling the design of complex socio-technical systems. It had nine problem categories within its scope. These categories include some of the problem areas mentioned above such as cognitive-biases, bounded-rationality, interdisciplinarity, requirements & constraints that do not always cohere (but can periodically or chaotically change), precedent designs that are inherently coupled, non-linearity in the element-to-element interactions, causality that operates across multiple scales and long/unpredictable latencies. Armed with these complexities, Prof. Norman critiqued the Axiomatic Framework along the following lines [26]:

"With sociotechnical systems, it is seldom possible to follow the Independence Axiom: two-way or even n-way interdependencies are common. Moreover, these interdependencies are often unknown, discovered only after the fact."

In other words, the design-matrix (that tracks FR-DP couplings two-by-two), is inadequate when dealing with FR-DP clusters that may not compose between them into a static, well-integrated, 2-dimensional matrix. The example referred to in [26] that illustrates this phenomenon pertains to the design of the treatment schedule in an elderly healthcare service where patients often present multiple ailment complexes and severe side-effects from earlier treatments. What usually starts out as a single-organ failure quickly devolves into a chaotic complex of treatment and care that spans multiple specialties [26]:

"When patients have multiple chronic conditions, a common occurrence in the elderly, there are numerous different professionals involved in the treatment, with complex interconnections among them (including, in some cases, a lack of communication). These problems defy easy analysis."

The above set of nine problem categories are some of the fundamental design challenges of the modern world--and there are no easy answers. However, easy answers include the "*muddling through*" approach advocated in the DesignX framework. This approach advocates small, incremental steps that in principle, refuses to consider the problem as a whole [26]:

"This approach requires a different design philosophy than might be used when considering the project as a whole. Now, the design must be modular, with multiple small, relatively independent parts, incremental changes that can be implemented, and linkages that are designed for flexibility."

Indeed, if such a "*muddling through*" approach were to be institutionalized in medical-care, it would be cause for alarm. Furthermore, such an approach fails to take advantage of some of the modern tools at our disposal, such as stigmergy (Section 6), Axiomatic Design [27], Cynefin [24,28], Agent Base Modeling (ABM) [29], Data-Sciences [30] and others. Each of these approaches attempts to learn workable heuristics that are holistic in scope while also attempting to meet the current expediency. These are a more responsible approach than merely "*muddling through*." Indeed, the muddling-through approach may be considered as being unnecessarily defeatist in embracing of the adhocracy philosophy of yesteryears--even as complexities abound.

Even so, Prof. Norman's critique about the inadequacy of the design-matrix in tracking complex coupling clusters is well taken and needs to be addressed. Indeed, biological systems are highly coupled. In fact, an uncoupled biological system may legitimately be considered to be dead. Thus, while the design axioms continue to inspire (i.e., the FR-DP mapping could be considered as "*form follows function*" in the biological realm), the tools used to implement the axiomatic design framework may need to be extended.

For example, the AD/CT extension [31] recognizes the time-dependence of a given design. In other words, the design matrix (along with its couplings) are not static and unchanging across all the operational phases that a given design is faced with. It is in fact, time-dependent. In this expanded sense, the overall design is an ensemble of appropriately governed designs that are either pre-set or just-in-time improvisations composed of known elements. The underlying time-dependence may be periodic or aperiodic. AD/CT can help streamline and resolve many of the objections raised by Prof. Norman.

6. Governance

Governance has taken center-stage on account of at least two major global trends, and often working at cross purposes [32]:

1. Globalization
2. Democratization

Globalization as the top-down legacy framework is being challenged by the bottom-up democratic fervor that has swept across the world stage ever since ubiquitous smart-phones and blogs brought about an overthrow of the highly scripted and staged "*noble lie.*" Now added into the mix is the promise of the blockchain technology that threatens to flatten and shorten the existing value-chains, end-to-end. Consequently, a traditional firm now faces competitive and regulatory challenges from multiple dimensions. A governance misstep in any of the exposed fronts may have serious consequences.

Governance is about collective decision-making, and may be defined as in [32] as follows:

Governance is about the rules of collective decision-making in settings where there are a plurality of actors or organisations and where no formal control system can dictate the terms of the relationship between these actors and organisations.

Note the emphasis on:

1. Rules
2. The collective scope
3. The decision-making process, and the
4. Lack of formal control systems

While formal rules may easily get coded in smart contracts, informal, on-the-fly, negotiated rules are much harder to codify. Also, the collective scope squarely places modern-day governance in the unwieldy heterarchic side of the ledger as opposed to the well-behaved hierarchic side that may be safely encoded in smart contracts. Also, the decision-making process itself has to have its own slowly-changing meta-rules as to "*who can decide what, and how decision-makers are to be made accountable [32]*." But the most challenging aspect of modern-day governance is the realization that really "*no one is in charge*"; i.e., "*no formal control system can dictate the relationships and outcomes*". And as we shall see (in sections 7-8), this aspect of "*no formal control*" is what makes modern governance a CAS problem. The provenance of decentralized control may be traced at least as far back as the writing of the Old Testament [33]:

> *Go to the ant, you sluggard; consider its ways and be wise! It has no commander, no overseer or ruler, yet it stores its provisions in summer and gathers its food at harvest.*

The lack of formal control mechanisms is a distinct departure from traditional models of top-down governance.

7. Stigmergy

So how is it that non-conceptual entities like ants, that even though lacking a central controlling agent, are still able to coordinate and collaborate in vast numbers (i.e., in billions [34])? The answer to this is *stigmergy*. Etymologically it is of Greek origin (*stigm-oi* meaning pricking, signing, marking; and *erg-on* meaning work), while entomologically it is from a study in 1959 by P.P Grasse on termites [35]:

> *The stimulation of the workers by the very performances they have achieved is a significant one inducing accurate and adaptable response, and has been named stigmergy.*

Stigmergy denotes call to work based on local signs or markings left by self or other agents at some time in the past and during the course of their work (either as a side-effect of the said work or as something in addition to the work). These markings aggregate to provide organizational directives available at various levels, both within the environment as well as within and between agents, thus leading to the visual of stigmergic gearings (Fig. 1). Thus, even though there is no one controlling, there is nevertheless system-wide control. These gear-trains may or may not all engage simultaneously; instead, they may be asynchronously meshed in different groupings as per some meta-level (α_i-β_j) logic.

Examples of stigmergy abound in nature. For example, the pheromone markings that an agent ant (α_i) leaves behind as it navigates an unknown terrain helps it to navigate back home instead of being lost. Moreover, if perchance, it does chance upon a choice food item, these same trails then help recruit other ant compatriots in jointly squirreling away the find back to the nest (Fig. 2).

The pheromone trails that aggregate across the environment is the emergent pattern (β_j). Gearing upwards, the pattern-making potential (i.e., the chance ability to create, sense and communicate asynchronously via pheromones), must have had to be evolutionarily written into the genetic constitution of the ant or its predecessors (at some remote point in the past).

Stigmergy is thus a two-way street; it is not just that the agent is leaving tell-tale markings in the environment; the environment is also signing back but at a much more glacial gearing pace. This captures the A and the Ω, but there could be many more engagements across the span that could veer off laterally.

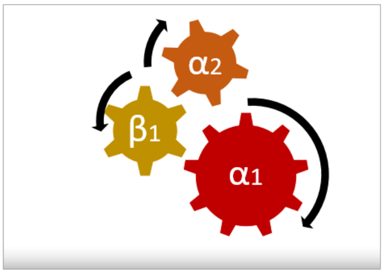


Fig. 1. Stigmergic gearings

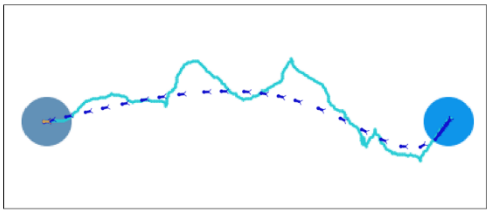


Fig. 2. Stigmergic trails (using NetLogo [36])

Thus, these gear-trains are not just linearly laid-out; instead, they constitute fractal-networks, and networks-of-networks that branch off and engage other such gearings. Governance is the sum-total effect of the multi-faceted β-level gear-train network on the evolving α-level agent body.

Stigmergic gear trains may work to enhance or inhibit a given agent/group-level activity, thus leading to non-linear effects [37]:

> *In more complex self-organising systems, there will be several interlocking positive and negative feedback loops, so that changes in some directions are amplified while changes in other directions are suppressed.*

Also, these stigmergic gear-trains are a direct analog to the modern blockchain; except that nature displays abundant varieties of these offerings, each of which has painstakingly been forged in its exacting survival-of-the-fittest workshop. One such example is the immune system which we discuss in Section 15. Blockchain designers would be wise to study similar nature-inspired chains.

The two-way nature of stigmergy (as mentioned above) does not thereby imply any additional agency embedded in the environment; but that the environment is also signing back (in an "*action/reaction*" Newtonian sense) and thus shaping the evolution of the protagonist agent. Longer the stigmergic chain, greater the need to unitize and embed the ricochet as second nature within the agent. Emergence is the global precipitation of these stigmergic patterns into the environment; while submergence is the local embedding of the unitized write-back (i.e., the ricochet) into the constitution of the agent for facilitating future emergence.

As illustrated above, stigmergy helps in the social organization of lower level life forms such as ants and termites. However, stigmergic ordering is not just limited to the lower forms; indeed, much of human organization (or the lack of it) may be attributed to stigmergic successes and failures. For example, the organizing market power captured in Adam Smith's "invisible hand" metaphor may be attributed to stigmergy [5]:

> *"Adam Smith's ''invisible hand'' metaphor used to denote the unintended emergent consequences of a multiplicity of individuals' actions, is stigmergic in all but name…"*

Indeed, the price of goods are the pheromone markings that helps organize the vast reaches of our global economy without explicit direction (i.e., the invisible in the "invisible hand" metaphor). Stigmergy operates as a problem-solving coordination mechanism wherever living entities are faced with problems that are beyond their limited individual ken. Billions of ant's and other insects wouldn't be able to coordinate and thrive but for their stigmergic know-how. It is therefore not surprising that we humans have also been engaging in stigmergic rituals without explicitly knowing it. Parunak analyses a whole slew of such human-level stigmergic processes in [38], including forest trail-formation, highway traffic-flows, democratic elections, document editing, social-media groupings, viral-marketing, Google page-ranks, peer-to-peer computing, Amazon-style recommender-systems, etc. The blockchain is yet another stigmergic innovation to help coordinate human (as well as human-machine) activities. In each of these systems, the patterns that emerge have significant potential to help organize and scale the human potential.

The study of emergence spans many domains including economics [39], biology [40], sociology [41], mechatronics [42], nanotechnology [43], spatial computing [44], philosophy [45] etc.

From a designer's viewpoint, stigmergy is critical in learning to read nature without stumbling on "*intelligent design [46]*." It is crucial for understanding and deciphering designs in nature towards creating and validating an integrated perspective that spans across the natural as well as the artificial. It is the causal thread that connects function and form; i.e., the Functional Requirement (FR) to its Design Parameter (DP) in the natural world. Given the scale, scope, immense time frames as well as the vast combinatorial sweep across which nature operates, it behooves us as keen students of design, to perk up and listen. Deciphering the submerged building blocks would render much of the biological order transparent and seamless across the artificial/natural divide. This is of significance given that while throughout 20th century, physics was the dominant science, the 21st century is the century of biology. And stigmergy can help bridge the conceptual bridge across these vastly different sciences. But that requires carefully mapping the underlying gear-train. Or in the words of Francis Bacon: "*nature, to be commanded, must be obeyed [47]*." In this context, the axiomatic framework could be fruitfully employed in tracking the myriad gear-trains that nature employs to keep its machinery fine-tuned and humming. For example, from a design-matrix perspective, the aforementioned +/- feedback effects across the gear-train complex could be qualitatively captured in a matrix as shown in Fig. 3 below. Here the design matrix captures the delivery of the FR along the diagonal (denoted X), as well as its off diagonal +/- control-set gearings to help keep the main FR-DP (along the diagonal) on its track. And moving across the A-Ω gear-train spectrum, the aforementioned unitization would result in the familiar design hierarchy that helps drill down from the macro-view and into the micro.

X	0	0
+	X	0
—	+	X

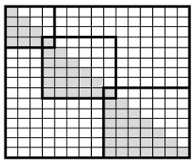


Fig. 3. Design Matrix of Stigmergic Gearings/Hierarchy

Unlike direct and imperial command and control in the human realm, stigmergic command is far subtler, indirect, distributed and democratic. This is because there is no master gear; no single point of control; instead there are very many stigmergic gears distributed across the unwieldly control landscape. Indirection implies asynchrony as well as a lack of specificity as to who the recipient of the message is. Needless to say, stigmergy is thus intimately connected with governance as it is via stigmergic gearing that the individuals in a group as well as the group as a whole is able to orchestrate a global order despite having "*no commander, no overseer or ruler [33]*."

Note that the stigmergic signal is not a clear explicit imperative command for the next agent to do something or the other. Instead it is like a mark left on a shared common blackboard for the next agent that comes by, to use it as it pleases. For example, the openly displayed stigmergic signal may very well be read by an adversary and then put to nefarious uses against the original agent and/or its group. Stigmergic signals are therefore not an imperative command of what should be done next; instead it is a recording of what has transpired up to the point when the mark was made. The imperative element instead resides in the collective emergences as well as in the agent that picks up the baton. Thus, from an agent modeling perspective, the "*what next*" is probabilistic.

In an abstract sense, markets are primarily an expression of the human quest for freedom (via division of labor); i.e., freedom to make better use of our scant resources, especially time. The blockchain technology helps escalate this timeless quest as it unblocks and frees up the agents towards engaging in many more degrees of freedom and ad-hoc mashups than previously imaginable. If prior to the advent of the blockchain, the markets were operating along highly choreographed pathways; after the advent of the blockchain, the markets have now entered a world of jazz-like improvisations that have the potential to topple many of the strait-jacketed middle-men controlled pathways. With the elimination of superfluous middlemen, not just organizations; whole industries may be flattened.

Note that lock-in is a problem that stigmergic systems (such as cryptocurrencies) face. As suggested in [48]:

> *...path-based idiosyncrasies may become locked in as material artifacts, institutions, notations, measuring tools, and cultural practices.*

Under lock-in, stigmergic systems are unable to fork away from the dominant strand on account of lack of followership. The first movers therefore have a strategic advantage which is not easily overcome. In the natural world diseases, viruses and bacteria are the heterarchical pathways that nature exploits in order to constantly stress-test the resilience/viability of the total evolving biomass away from stagnant lock-in. Likewise, in the blockchain context one may expect similar heterarchic thrusts and parries across the unguarded/evolving attack surfaces.

While stigmergic-coordination is remarkable in its scale and scope, it is not the same as cognitive thought and reasoning. Attempts to anthropomorphize stigmergy and posit the existence of an "*extended mind*" is in error. There is no "*extended mind*" agency, no stigmergic cognition, and therefore no basis for stigmergic epistemology as in [5]. Hypothetically speaking, if the extended mind exists in a distributed, asynchronous sense, it must incarnate whenever an agent partakes or contributes to the growing stigmergic corpus. It is then like the luminance of the lightning bug--it comes and goes out of existence. Even so, the fundamental problem is that of will. No executive center animates the extended mind figment. All will, action, and responsibility remains vested in the underlying agents. This restriction has jurisprudential implications for the blockchain enterprise. Legally speaking, one cannot litigate against the emergent β_j-pattern; one may only sue the α_i-agents either individually or collectively [49]. The extended-mind concept is a flawed concept; it serves no rational purpose. Thinking along this line could place the blockchain founders in legal jeopardy.

Similar restrictions also apply to humans operating stigmergically as a group. There is no organ that can be posited as a repository of group cognition. Stigmergic epistemology [5] is, therefore, an oxymoron. Anthropomorphically positing otherwise is an error. Same is true for the rest of the philosophical train (i.e., there is no validity to stigmergic metaphysics, ethics, politics, aesthetics, etc.). However, what can be studied is the validation of stigmergically arrived conclusions via cognitive means resident in independent individual entities. Thus, the philosophic underpinnings of stigmergically arrived truths revert to normal philosophy. There can, therefore, be no stigmergic validation of design or governance. Thus, no matter how good a stigmergically arrived design may be, it still needs independent analysis and validation using the normal tools of human reasoning. Conceptual knowledge therefore has dominance.

8. Complex Adaptive Systems (CAS)

Professor John H. Holland (1929-2015) is rightly considered the father of genetic algorithms. He also laid the foundational work in the study of CAS. As he has described it [50], CAS's "*are systems that have a large number of components, often called agents that interact and adapt or learn.*" Holland proposed a two-tiered system as shown in Fig. 4a below. The lower α-tier follows a fast-dynamic and is engaged in the flow of resources between diverse agents (α_i grouped in level *i*) that are also leaving behind stigmergic markings; while the upper β-tier follows a slower-dynamic that captures and aggregates the stigmergic markings into emergent patterns (β_j grouped in level *j*), which is then emitted system-wide as stigmergic signals that help the governed agents to self-organize and scale.

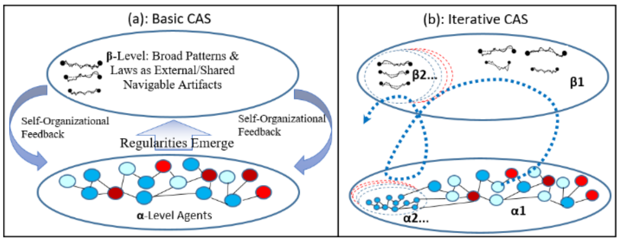


Fig. 4. Complex Adaptive System: Basic vs. Iterative

Note that for the sake of simplicity, all the agents in Fig. 4(a) have been placed homogeneously in the lower tier, while all the emergent artifacts have been placed homogenously in the upper tier. Such a simplification does not quite capture the aforementioned gear-train logic. Instead, what may be happening is that each follow-on feedback-loop/iteration is bifurcating the target population into higher levels of organizational complexity. In each subsequent iteration, the population is now composed of bifurcated ensembles of agent-nodes and artifacts (as indicated by the dotted-ovals in Fig. 4(b)). Gearing, therefore, iteratively creates self-organization and structure in both of these interacting entity spaces. In each follow-on iteration, the respective number of nodes in each of these dotted-ovals is asymptotically decreasing (with allowance for population dynamics) while the dotted-ovals proliferate. Agents may, of course, migrate across these boundaries.

While it is true that the β-tier is entrusted with the governance mandate (i.e., the role of control and governance) of a vast network of unwieldy, decentralized agents that populate the α-tier, it is likewise, not immune from further restructuring (i.e., higher order gearings).

In his post "*Notes on Blockchain Governance* [51]," Buterin (who founded Ethereum) gives partial evidence of the α-β CAS structuring in the blockchain architecture when he writes:

> *Generally speaking, there are two informal models of governance, that I will call the "decision function" view of governance and the "coordination" view of governance.*

The coordination view is the β-tier view, while the decision-function view pertains to the α-tier agents that act on the coordination signals. Also, as mentioned earlier in Section 7, it is the decision-function view that has legal liability.

Buterin also gives evidence about the layering (at least in the β-tier) when he writes that "*the coordination model of governance…exists in layers* [51]."

9. Centralization/Decentralization & CAS

Here we explore centralization vs. decentralization in the context of CAS. In [52], Paul Baran was the first to outline the distinction (see Fig. 5) between the two:

> *Although one can draw a wide variety of networks, they all factor into two components: centralized (or star) and distributed (or grid or mesh). The centralized network is obviously vulnerable as destruction of a single central node destroys communication between the end stations. In practice, a mixture of star and mesh components is used to form communication networks.*

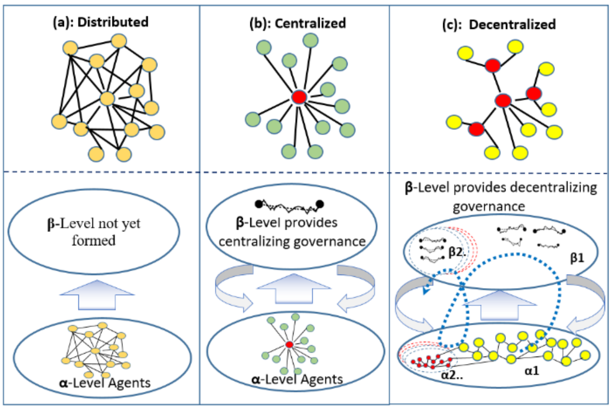


Fig. 5. Distributed vs. Decentralized from a CAS Perspective

When cast in the CAS-framework, it is clear that centralized vs. decentralized is relative. Absent the β-tier, α-tier agents are distributed (Fig. 5a). It is only in the governance context of the β-tier that the α-agents may be considered as centralized (Fig. 5b) or decentralized (Fig. 5c). Also, there is a natural progression across these three self-organizing architectures. Extending this natural progression, one could easily see that there are far more architectures beyond the above mentioned three. Indeed, the full rigor of network sciences may be put to use in extending the categories. For example, the mammalian nervous system is a hybrid architecture that incorporates both centralized as well as distributed control. The vocabulary, therefore, needs to be enriched with mathematical rigor. Also, note the loss-factor approach being used in defining these critical concepts; i.e., the "*centralized network is obviously vulnerable as destruction of a single central node destroys communication between the end stations*." While such vulnerability duly needs to be noted, it, unfortunately, fails to capture the positive functions that the β-tier provides. It is akin to saying that the stoppage of the heart muscle will result in death which doesn't quite describe the positive function the heart muscle performs. This same loss-function approach may be witnessed in the works of other researchers who followed Baran's approach. Nevertheless, the above four preliminary concepts may be summarized as follows:

- **Distributed/Non-Distributed**: Pertains to the agent-spread in the α-tier, and across its various bifurcations/groupings.
- **Centralized/De-Centralized**: Pertains to the governance/control-logic in the β-tier (as arranged across its various bifurcations/groupings).

With the β-tier providing the controlling logic, all of the α-agents would appear as centralized to the β-tier if indeed there was agency embedded in β. But there is no agency in the β-tier; hence usage of "*control*" as it pertains to the β-tier is purely anthropomorphic.

Buterin categorizes centralization vs. decentralization along the following three axes [53]:

- **Architectural (de)centralization**: how many agents is a system made up of? How many of these agents may be lost, without loss of function?
- **Political (de)centralization**: how many agents ultimately control all other agents/infrastructure the system is made up of?
- **Logical (de)centralization**: how monolithic or dispersed are the underlying data structures/interfaces? How much of this infrastructure may be lost, without loss of function?

There is ambiguity in the above classification that may be clarified using the CAS-framework:

- **Architectural (de)centralization**:
  - *How many agents is a system made up of?* Agent population size pertains to the α-tier; this does not directly pertain to the issue of centralization vs. decentralization.
  - *How many of these agents may be lost, without loss of function?* This refers to system resiliency and therefore does pertain to the governing β-tier. However, Buterin does not explicate how merely the counting of α-level agent's, as well as the fraction that may be lost, is thereby sufficient in helping establish the system as being centralized vs. decentralized. Indeed, until we look at the controlling patterns that have been established in the β-tier, it is impractical to say whether a given system is architecturally centralized or decentralized. The example that Buterin provides is equally ambiguous: *traditional corporations are architecturally centralized as it has just one head office.* While this may sound plausible, note that this has nothing to do with the number of agents as well as the loss function. It is, therefore, a non-sequitur.
- **Political (de)centralization**:
  - *How many agents ultimately control all other agents/infrastructure the system is made up of?* While the element of control is salient in the context of centralization/decentralization, it is

an error to think that the controlling logic of a system (that often outlives the agent life-expectancy) is to be found in such short-lived agent entities. Consider the suggested example: *traditional corporations are politically centralized (one CEO)*. This again is erroneous; the political power is indeed being exercised by the transient CEO agent; but the pattern of power assimilates in the office of the CEO, which is a β-tier artifact that outlives any given CEO. So, the question is not regarding how many agents control the rest of the organization; instead, it is whether the rules and protocols vested in the office of the CEO help establish a centralized or a decentralized organization (which in the case of the traditional corporation, is indeed centralized—but it doesn't have to be).

- **Logical (de)centralization**:
    - *How monolithic or dispersed are the underlying data structures/interfaces? How much of this infrastructure may be lost without loss of function?* Now, this is indeed part of the β-tier, as it pertains to information flows and the patterns around it. However, consider the example suggested: *traditional corporations are logically centralized (can't really split them in half)*. A centralized corporate database, in and of itself does not guarantee centralized control; indeed, a decentralized organization could very well harness a centralized corporate database. Instead, the focus ought to be on the β-tier rules and protocols that help establish centralized vs. decentralized control.

Using the above ambiguous framework, Buterin classifies the blockchain technology along the three axes [53]:

> *Blockchains are politically decentralized (no one controls them) and architecturally decentralized (no infrastructural central point of failure) but they are logically centralized (there is one commonly agreed state and the system behaves like a single computer).*

The problem with Buterin's classification scheme is that it doesn't address the heart of the decentralization issue. Also, the three suggested axes are ad-hoc and could be easily augmented; for example, they could very well include economic (e.g., microfinance), aesthetic (e.g., decentralized control among jazz musicians), scientific (e.g., the citizen science movement), etc.

Consider the legal implications of the above misclassifications. If (as Buterin asserts) no one controls the blockchain, then no one may be litigated against. However, that is not what is happening in the real world. For example, SilkRoad had six of its decentralized servers tracked down, and its founder Ross Ulbricht, arrested for money-laundering [54]. Ripple is currently facing multiple class-action lawsuits (with CEO Bradley Garlinghouse named as a defendant) claiming securities law violation [55]. Similarly, Tezos and its founders face multiple class-action lawsuits [56] for securities law violation. The case against Tezos is significant as it was designed as a meta-level operator that would smoothen all future governance issues. However, because of poor corporate governance structuring and the resultant fallout between the founders, their ICO (Initial Coin Offering) got stalled, resulting in the lawsuits [56]:

> *"One thing is clear though: there is a certain irony in how Tezos, the cryptocurrency aiming to solve governance issues on the blockchain, crashed due to governance issues."*

From a legal as well as business point of view, it is critical to understand the relative nature of centralization versus decentralization. What appears decentralized for agents at the α_i-level (and below) is indeed centralized for agents operating at the level of α_{i+1} (and above) and under the direction of β_i. That being the case, agents at the α_{i+1} (and above) are legally liable. Buterin is therefore in error when he claims that "*blockchains are politically decentralized (no one controls them) [53]*." In fact, wherever two or more human agents engage, legal disputes are certainly possible. Furthermore, litigation is more than likely when necessary boundaries are left unstated. In the blockchain context, disputes can occur between agents at the same level, or across levels. It serves no one any favors when the leadership tries to hide the agency issue behind the decentralization veil whenever disputes cross levels. True blockchain leadership would be in setting up timely and appropriate responsibilities, limitations and boundaries as the system scales. Or as Robert Frost would wisely but reluctantly suggest, "*good fences make good neighbors* [57]."

Srinivasan and Lee [58] have proposed a Lorenz Curve/Gini Coefficient based framework to help quantify the degree of decentralization in a given system. The Gini coefficient spans the range of 0.0-1.0. The closer the coefficient is to 1.0, more centralized the system. A related concept, the Nakamoto Coefficient is also reported in [58] that tracks the agent level thresholds that tip the cumulative area under the Lorentz curve into 51% control. From the CAS-perspective, the key insight is in the fact that this framework suggests studying the blockchain system as being composed of 6 essential subsystems, namely:

1. Mining: by reward
2. Client: by codebase
3. Developers: by commits
4. Exchanges: by volume
5. Nodes: by country
6. Ownership: by addresses

This approach comes closer to the CAS-ideal as it acknowledges the existence of a variety of controlling gear-trains that need to be independently & jointly tracked. Also, note that the metrics are focused on stigmergic outputs (such as measuring the developer-focused commit distribution). But lacking an integrated framework, this approach is unable to combine the Gini/Nakamoto subsystem measurements into a coherent system-level measure; it is therefore forced to treat the subsystems as stand-alone. Furthermore, the concept of decentralization is far more generic than just the blockchain context; for example, the above six subsystems play no role when considering the degree of decentralization in a corporate organization. Here, the underlying bipartite α-β CAS machinery is what is missing. By highlighting and referring to the generic CAS machinery, we may be able to liberate the decentralization concept to its rightful stature. Also, from a principled design perspective, it is important to articulate the driving functional requirements in the above endeavor; i.e., the "why" we are looking for decentralization here vs. centralization there. For example, taking a page from the biological realm, there is a reason why parts of our nervous system are under central control; while other parts are under decentralized control. Blindly optimizing along the decentralization ideal would miss out on these hybrid architectures.

10. Emergence, Self-Organization and Governance

In [37], Wolf and Holvoet differentiate between emergence and self-organization. Referring to Fig. 4, emergence is the upward moving arrow from α to β; while self-organization is the downward pointing feedback loop from β to α. These two flows can and often do occur asynchronously. Long-winded asynchronous loops easily confound the tracing of the causal structures. Governance is predominantly associated with the downward β→α command orchestrations, but it is equally important to underscore the formative α→β pattern-captures. In this sense, emergence ought to precede self-organization. However, it is possible to graft foreign patterns and artifacts onto an immature blockchain offering, resulting in lack of coherence. All the key elements (including the governance units) selected from the overall blockchain ecosystem [59] needs to cohere within the evolving context of a given blockchain community setting to make a unique blockchain offering. Once the base structures have materialized, every new emergence and its corresponding self-organizational restructurings ought to be appropriately governed. Given the speed, anonymity, and heterarchically-hierarchical reach of the blockchain based markets, traditional governance structures do not seamlessly carry over. Governance artifacts ought to have the same level of speed, anonymity-piercing and heterarchically-hierarchical reach (on an as-needed basis) that closely parallels any of the breaches across these dimensions. Or to quote Callimachus of Cyrene, we have got to "*set a thief to catch a thief [60],*" but now in real-time.

11. Hierarchy, Heterarchy & Governance

Closely related to the conceptual pair of centralization-decentralization is the conceptual pair of hierarchy-heterarchy. We briefly considered this earlier when discussing the issue of trust (Section 3) as well as the rise of complexity (Section 4). For example, in Section 3 we asserted that "*it, therefore, may be argued that the ongoing US experiment in self-governance is indeed a lower-triangle decoupled design*." Such a design may be depicted as shown in Fig. 6 below:

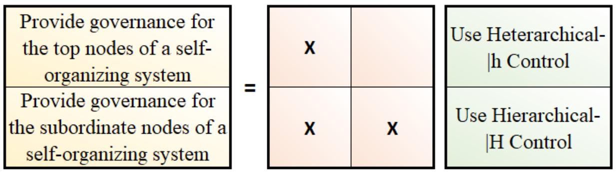


Fig. 6. Heterarchically Hierarchical (|h-|H) Governance

Heterarchic control of hierarchical systems (i.e., |h-|H as depicted above) is an expensive proposition as it demands a delicate balancing act of power-sharing between competing hierarchies. It is therefore rarely used, except in providing governance of the very top-most nodes; and in the cases of national import. However, the problem of "*who will guard the guards themselves [15]*" occurs throughout the system; not just at the top nodes. Indeed, Lord Acton's insight that "*power tends to corrupt, and absolute power corrupts absolutely [14],*" is applicable across all nodes, (except maybe the lower-most) in every socio-technical hierarchy. This is because as a hierarchical system scales, it provides sufficient latency for information flow, sufficient nooks and crannies to bury the proverbial skeletons of misconduct. It is similar to the distinction between local vs. global maximum in the field of mathematical programming (Fig. 7). Thus, while there may be just one global optimum, there may indeed be many local optima based on the local settings. Likewise, in hierarchic (as well as in heterarchic) organizations, there may be local as well as global top nodes that may be compromised. Indeed, it may even be asserted that it is the local top nodes that jostle to take on the mantle of the global top node (Shakespeare's Othello vs. Iago being a case in point [61]). Hence it may be crucial to nip the bud of corrosive power at the early local stages before it scales and migrates over to the global slot.

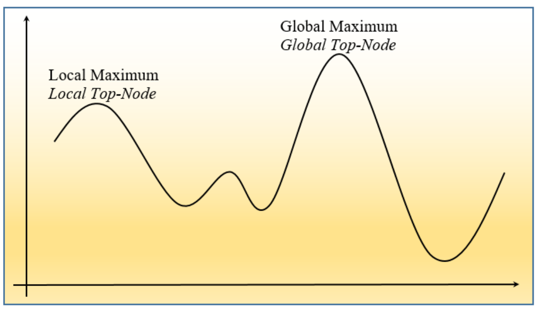


Fig. 7. Problem of the Local vs. Global Top-Node

If properly designed, the blockchain approach could effectively democratize and make available the above |h-|H governance architecture across the board. This is why establishing a proper governance model for the blockchain approach has significant beneficial implications society-wide. As discussed in Section 2, the fundamental problem in democratizing and scaling up the governance kernel is in clearly understanding when to use the machine vs. when to apply human intervention; in other words, when is it appropriate to use on-chain vs. off-chain governance vs. a mixed setup?

How should one go about adding heterarchic controls (via the blockchain technology) into traditional hierarchic governance models, and across the board? Here, an analogy may help in grasping the auxiliary evidence scheme that the blockchain technology offers. Consider the task that a particular lawyer is faced with, i.e., of ascertaining the veracity of a given client or witness. The task is to check if the client is telling the truth. One way is to painstakingly check each statement, to check for internal consistency and to independently validate it against other bodies of evidence. However, there is yet another way to check if the client is lying; and that is to bring in a micro-expressions expert. Micro-expressions [62] are fleeting (i.e., lasting less than half a second) betrayals of inner conflict that the subject is incapable of hiding or suppressing. The act of concealment is being orchestrated by the pre-frontal cortex, which the amygdala effectively short-circuits by leaking the subterfuge in an involuntary micro-expression. In this sense, micro-expressions are auxiliary evidence streams that may help catch a lie. Using the blockchain technology is akin to using micro-expressions to help adjudicate a conflicted situation; it provides easily verifiable auxiliary streams of evidence that may be available to anyone in public. However, note that on its own merit, micro-expressions do not reveal the factual basis of the conflicted case; only that whatever the client is asserting has an element of concealment in it. In this sense, it is preserving the client-attorney privilege as far as the micro-expressions expert is concerned. Likewise, the blockchain technology cryptologically conceals the factual basis of a given transaction; but it has the potential to reveal if that transaction is conflicted with something prior that happened and as recorded within the ledger the blockchain controls. Such self-on-self is what makes current blockchain governance hierarchical in nature; it, however, does not solve the original problem of top-node governance; i.e., that of "*who will guard the guards themselves* [15]?"

This was painfully evident on June 17th, 2016, when the Ethereum based DAO (Decentralized Autonomous Organization) suffered the infamous DAO attack that legally exploited weaknesses in its code-base [3]. Section 6 briefly described Ethereum. It is a programmable, Turing-complete blockchain infrastructure that can authenticate and run code (in the form of smart contracts), not just keep track of the underlying transactions. The DAO was built on top of Ethereum as a decentralized, cryptocurrency-based, crowd-funded platform where investors could directly fund and manage new enterprises that would, in turn, run on Ethereum. In a period of just one month, the DAO was able to raise the equivalent of 250 million USD, the largest crowdfunding success as of May 2016.

However, the DAO attack fundamentally crippled the visionary zeal. Faced with dire losses (in the order of 35 million USD), the principals banded together in an ad-hoc manner to perform a hard-fork; i.e., to violate their own pre-established rules of conduct, to revert back to the genesis state while simultaneously changing the rules of operation to make it favorable to the majority. This is indeed the ancient problem of governance at the top nodes of an organizational hierarchy, be it human or technology-based at the top-nodes. Merely handing the administration of agreements between willing agents over to smart contracts (i.e., a rule-based digital logic used to verify and enforce an agreed upon contract between two or more agents) does not obviate the top-node problem. Hierarchically governed socio-technical designs are fundamentally coupled on account of too few DP's. To understand how one may go about introducing elements of heterarchic gear-train governors into a predominantly (smart contract based) hierarchic mix, one has to delve into the architecture of human knowledge alongside the issue of the unknown-unknowns.

12. Heterarchically-Hierarchical Knowledge and Governance

Earlier, in Section 4 we had asserted that governance is intimately related to sense-making, which in turn is related to the nature, shape, and dynamics of human knowledge. It is by understanding the epistemological roots of human knowledge that one may formulate the proper division of labor between the human and the machine (i.e., between off-chain and on-chain governance). In other words, what is it that the human is good at; likewise, what is it that the machine is good at? Smart contracts are smart only to the extent that the human ingenuity has embedded the smarts within them, including the necessary smarts for knowledge dynamics originating both within as well as outside one's ken.

Given the abstract nature and spread of human knowledge, it may be observed that knowledge has a dynamical and heterarchically-hierarchical (|h-|H) structure as shown in Figs 8.a-f below. This figure is adapted from [19]. Concretes are far more numerous than abstractions; this implies that domain-specific human knowledge (Fig. 8b) has a conical/hierarchical shape.

Induction flows along an upward arch, while deduction flows along a downward arch. Abductive cascades utilize both inductive as well as deductive streams in problem-solving (including designerly) situations [63]. These distinctions ought to inform the on-going debate as to the proper division-of-labour between humans and machines: induction (that favours human faculties) versus deduction (that favours the machine) ought to be the proper role demarcation between the two sets of entities in any socio-technical system. Call this demarcation the *Inducto-Deductive Front (IDF)* shown as the dotted line in Fig. 8.a-d. For abductive cascades (with the IDF at cascade apex), both agents human and machine agents would need to work in close symbiotic coordination [23,64].

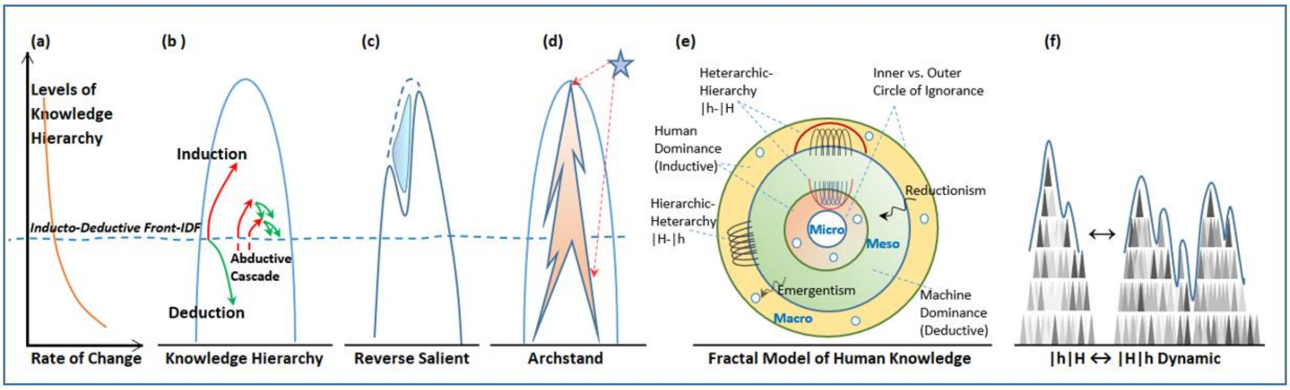


Fig. 8. Human knowledge as heterarchically hierarchical (|h-|H)

The rate of change in the knowledge corpus is more pronounced along the lower rungs as compared to the higher, abstract levels (Fig. 8a). Reverse-salients (Fig. 8c) are lagging knowledge fronts (the *known-unknowns*) that occur because of differentials in growth spurts across domains that are close enough to make sense if conceptual barriers didn't exist. When they do gap-close, it ripples across the knowledge fabric radially (i.e., hierarchically-|H) as well as tangentially (i.e., heterarchically-|h).

Another source of knowledge dynamic is the archstand [63]—an integrated external perspective such as the Non-Euclidean framework that led to the Theory of Relativity. When stand-alone domains are organized using domain kinship metrics, one may expect these conics to exhibit a self-similar fish-scale (hierarchically-heterarchic) fractal structure (Fig. 8e). Humans are at the mesoscale. Unknowns from the macro-world dominate the outer realms; unknowns from the micro dominate the inner regions. Knowledge is sandwiched between these two outer and inner circles-of-ignorance that are expanding and contracting respectively. Regions beyond are the ultimate terra incognita; the vast unknown-unknowns.

Between hierarchies and heterarchies, hierarchies exhibit relatively stable vertical linkages; whereas heterarchies exhibit dynamic ties that are conceptual mashups in the making. At finer grains, hierarchies may contain heterarchies and vice-versa, and switch dominance across time (Fig. 8f). Knowledge flux involves the constant jostling between heterarchies and hierarchies. Without hierarchies, higher-level heterarchies do not form nor engage; without heterarchies, hierarchies tend to become stale, iconoclastic and insular. The emergence/flourishing of a discipline arises from heterarchic assaults and hierarchic defenses; both forces are necessary. Heterarchies encourage falsifiability while hierarchies encourage verifiability; both are essential. Therefore, in the context of governance, both of these forces ought to be judiciously engaged. When heterarchical assaults reach above the IDF, inductive human ingenuity ought to be marshaled; in contrast, when heterarchic assaults land below the IDF, the machines may well be capable of handling the issue. Likewise, when issues of verifiability range above the IDF, it would again demand human ingenuity to overcome the default. But if it occurs below the IDF line, the smart contract infrastructure may be sufficient to handle it.

In Section 4 (on rising complexity) we had indicated that there is an on-going phase shift away from deep-hierarchies and into hybrid |h-|H systems with many ad-hoc laterals. Interdisciplinarity is on the rise; and traditional disciplines are heterarchically being cross-pollinated. This has been discussed at length in [19]. One of the progressive schemes (the Jantschian) is as shown in Fig. 9 below. In CAS-terms, such a progression is to be expected, given the upward gearing across α↔β.

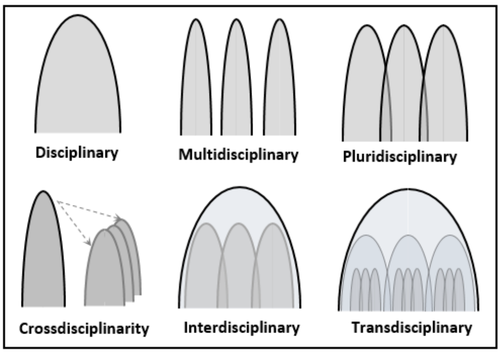


Fig. 9. Terms of Interdisciplinarity (Jantschian) [19]

While the overall envelope of the unknown-unknowns is as shown in the knowledge sandwich of Fig.8.e, there are many nuances (such as the case of reverse-salients, i.e., known-unknowns) that need to be addressed. We turn to the issue of unknown-unknowns next.

13. The Unknown-Unknowns and Governance

Defense Secretary, Donald Rumsfeld popularized the issue of the unknown unknowns [65]:

> *Subject. What you know. There are known knowns. There are known unknowns. There are unknown unknowns. But there are also unknown knowns. That is to say, things that you think you know that turns out you did not.*

The problem is how to parse this with logical consistency in mind.

You/Team→			c	c	c	c	s	s	s	s
			h	h	l	l	h	h	l	l
Society/Adversary↓			t	f	t	f	t	f	t	f
C	H	T	CHTcht (KK)	CHTchf (KU)	CHTclt (KK)	CHTclf (KU)	CHTsht (Kk)	CHTshf (Ku)	CHTslt (Kk)	CHTslf (Ku)
C	H	F	CHFcht (UK)	CHFchf (UU)	CHFclt (UK)	CHFclf (UU)	CHFsht (Uk)	CHFshf (Uu)	CHFslt (Uk)	CHFslf (Uu)
C	L	T	CLTcht (KK)	CLTchf (KU)	CLTclt (KK)	CLTclf (KU)	CLTsht (Kk)	CLTshf (Ku)	CLTslt (Kk)	CLTslf (Ku)
C	L	F	CLFcht (UK)	CLFchf (UU)	CLFclt (UK)	CLFclf (UU)	CLFsht (Uk)	CLFshf (Uu)	CLFslt (Uk)	CLFslf (Uu)
S	H	T	SHTcht (kK)	SHTchf (kU)	SHTclt (kK)	SHTclf (kU)	SHTsht (kk)	SHTshf (ku)	SHTslt (kk)	SHTslf (ku)
S	H	F	SHFcht (uK)	SHFchf (uU)	SHFclt (uK)	SHFclf (uU)	SHFsht (uk)	SHFshf (uu)	SHFslt (uk)	SHFslf (uu)
S	L	T	SLTcht (kK)	SLTchf (kU)	SLTclt (kK)	SLTclf (kU)	SLTsht (kk)	SLTshf (ku)	SLTslt (kk)	SLTslf (ku)
S	L	F	SLFcht (uK)	SLFchf (uU)	SLFclt (uK)	SLFclf (uU)	SLFsht (uk)	SLFshf (uu)	SLFslt (uk)	SLFslf (uu)

Legend:
Process by which knowledge gained: C/S (Conceptual/Stigmergic) for {Society,Adversary} vs c/s (conceptual/stigmergic) for {you, team}
Confidence in knowledge possessed: H/L (High/Low) for {Society,Adversary} vs h/l (high/low) for {you, team}
True status of knowledge possessed: T/F (True/False) for {Society,Adversary} vs t/f (true, false) for {you,team}

Fig. 10. The Unknown-Unknown Knowledge Asymmetry Exploit

For the sake of brevity, let us notate these options as KK (Known-Known), KU (Known-Unknown), UU (Unknown-Unknown) and UK (Unknown-Known). Elsewhere [66] Rumsfeld also opined that:

> *There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns. These are things we don't know we don't know.*

This quote considers just three of the options: KK, KU, and UU, with UK missing. The way Rumsfeld has parsed the second option KU (i.e., things that we know we don't know) suggests that the first lettering is about our state of confidence in our state of knowledge; and the second lettering is about the base state of our knowledge. Thus, the missing variant UK in the above formulation indicates poor confidence in a given assertion that we accept.

Once we parse this base structure, it then becomes clear that there are many more shades of the Unknown-Unknowns that lurk in the shadows, especially when we start considering issues of stigmergic knowledge as well as what our adversaries likewise know. Understanding the problem of the Unknown-Unknowns is central to understanding how blockchain governance is likely to evolve. For example, in analyzing the DAO debacle, Voshmgir highlights the problem of the unknown-unknowns faced by on-chain "*codified governance rulesets*" (CGR's) [13]:

> *In reality, formalised and codified governance rulesets can only depict known knowns and known unknowns, but have very limited capabilities to properly deal with unknown unknowns.*

The earliest formulation of one of the combinations may have been by the poet John Keats in Endymion wherein love-struck demi-god Endymion ponders the mysteries that wrap the object of his affections, the moon*:* "*O known Unknown! from whom my being sips [67].*" The realm of the unknown-unknowns can inspire as well as frustrate inquiry. Here Keats puts forth the idea that things of beauty have both familiar as well as unknown facets; and that we come to grasp the unknown by systematically working our way to the edge of the known realms.

Indeed, there are many pathways into the realm of the unknowns, not just the four that Rumsfeld put forth. One's true state of knowledge about some pertinent issue may be cross-mapped against what the society-at-large (or your adversary in a game-theoretic sense) is aware of. Also relevant to the problem is how the knowledge being claimed was arrived at; i.e., whether conceptually or stigmergically? In the human context, stigmergic knowledge gets coded in mores, heuristics and, habits of individual thought and action (both at the individual as well as at the societal level).

If it was conceptually arrived at, then it has a greater chance of error; but if true, it has far-reaching potential to scale. In contrast, if it was stigmergically arrived at, then its basis may be stronger (provided it avoids the problem of the aforementioned stigmergic lock-in); but being pre-conceptual, it does not scale easily. It is therefore of strategic value to convert stigmergic knowledge into the conceptual realm.

So, what are the combinatorial possibilities that populate the realm of the unknown-unknowns? Denote you (or your teams) state of knowledge in small-caps. Denote the state of knowledge of society-at-large (or perhaps your adversary) in large-caps. The resultant combinatorics may then be bifurcated along the following dimensions:

- Process by which knowledge is gained: C/S (Conceptual/Stigmergic) for {Society, Adversary} vs. c/s (conceptual/stigmergic) for {you, team}
- Confidence in knowledge possessed: H/L (High/Low) for {Society, Adversary} vs. h/l (high/low) for {you, team}
- True status of knowledge possessed: T/F (True/False) for {Society, Adversary} vs. t/f (true, false) for {you, team}

Mapping the resultant combinations into the known/unknown characterization is fairly straightforward with stigmergically derived true and false states in small-caps {k, u}; and conceptually derived true and false states in large-caps {K, U}. Thus CHTcht(KK) would denote both you as well as your adversary possessing conceptually-derived knowledge that is of high-confidence and happens to be true, leading to a situation of conceptually derived known-knowns. When the adversary's knowledge is mapped against one's own, there are 64 combinations as shown in Fig. 10 above. Note that the matrix assumes a two-player game structure, though one or both players could represent coordinated groups. Also note that the UK style coding (in parenthesis) is different from the Rumsfeldian coding as it denotes two opposing agents. Each new such player expands the combinations by a multiple of 8. These combinations create knowledge asymmetries (with comparative advantage to the {K, k} team, if paired against a {U, u} adversary) that are ripe for exploitation, thus triggering governance. These asymmetries are, therefore, at the foundation of the governance conundrum, that in its essence, checks to see if agreed-upon knowledge flows have been thwarted to result in the given asymmetry. Consider for example the cell *CHTshf (Ku)* highlighted in green in the top-right quadrant of Fig.10. Here the adversary's knowledge about some matter (say the true worth of a smart contract) is conceptual, of high confidence and true; in contrast, your knowledge about that same matter is mere stigmergic hearsay, but of high confidence and happens to be wrong. Diagonally across from *CHTshf (Ku)* is the diametrically opposite case of *SHFcht (uK)* (highlighted in red) where the asymmetry now favors the individual actor as opposed to society at large. Here the socially networked group is operating stigmergically, has fatally high confidence in its findings which in fact is wrong; in contrast, the lone operator is operating conceptually, has high confidence in its findings and is in fact right. In the world of finance, hedge-funds try to exploit *SHFcht (uK)* types of knowledge asymmetries. And when a smart contract is executed based upon such asymmetries, there are bound to be outcries of failures in governance. This indeed is what transpired in the case of the DAO-attack.

Playing the role of the adversary, if indeed one wishes to widen the {K, k}- {U, u} gap even further strategically, it may be worth introducing Axiomatic Design/Complexity Theory based complexing red-herrings as suggested in [68]. This may be even more potent when dealing with a {k}-{u} type knowledge gaps (which happenstance is much of the operative human knowledge); the reason being that it is challenging to debug stigmergic linkages that have been deliberately sabotaged for the explicit design purpose of throwing off one's adversaries.

14. Axiomatic Design for Complex Adaptive Systems

The creative mashup between two diametrically opposed design methodologies (i.e., the top-down Axiomatic approach vs. the bottom-up Design Patterns approach) was discussed in [69-70]. Thus, the top-down V-approach was juxtaposed with the bottom-up Λ-approach to create the N-model. As it turns out, the N-model comports well with the Complex Adaptive Systems framework. The design-patterns approach that leads with the upward-stroke of Λ is akin to the $\alpha \rightarrow \beta$ emergent stroke in a CAS system; likewise, the axiomatic approach that leads with the downward stroke of V is akin to the $\beta \rightarrow \alpha$ self-organization stroke in a CAS-system. Together they compose to make the N-model which indeed is the overall gearing dynamic behind the $\alpha \leftrightarrow \beta$ CAS system. However, as mentioned earlier (in Section 1), the design of a CAS System is a step removed from the traditional design of systems that are predominantly non-emergent/non-self-organizing. There is an inherent embryology of the CAS system that the designer has to yield to; i.e., the CAS designer needs to think more like a farmer rather than an engineer and adjust to the vagaries of emergence, such as that between pests and pollinators [71].

To come up with a design that is holistic and emergent requires the designer to be steeped in the practice of design; i.e., it is combinatorically challenging. Also, emergence requires beneficial interaction between the design elements, thus favoring lower-diagonal decoupled vs. uncoupled designs, which is not the usual norm. In the case of the diagonal design, the whole is equal to the sum of the parts. Emergence, however, requires beneficial interaction, which is feasible only if non-diagonal elements are present. Thus, in most cases, the uncoupled has dominance over the decoupled given the lower informational complexity. Emergence is the rare occurrence that could be flipping this dominance to combinatorically win the race with lower information content. This, however, is merely a hypothesis that needs to be validated. Many of the biological systems (given the enormous temporal-combinatorial space that they have been stigmergically operating over and finessing the information axiom) have strong elements of emergent qualities (such as life, consciousness, everything that pertains to the emotional faculties, etc.). Biological designs present rich opportunities to test this hypothesis.

By adopting the axiomatic approach, the $\beta \rightarrow \alpha$ design is decomposed both

- laterally and non-hierarchically across the various realms such as customer, functional, physical, process (CR, FR, DP, PV, etc.) as shown in Fig. 11 below, and
- vertically and hierarchically within each of the above realms.

In a rapidly evolving design context, it is impractical to approach design in staged, linear waterfall fashion as in CR↔FR↔DP↔PV. Instead, it is better modeled (as shown in Fig. 11 below) as a fully linked network of information nodes. The linear structuring still dominates, but it is now augmented with auxiliary flows. Each of these realms has their own $\alpha \leftrightarrow \beta$ CAS structures that form over time. Furthermore, since human knowledge is hierarchical, the design trace that leverages this knowledge is likewise hierarchical.

By visualizing the design in the context of knowledge hierarchies, one may begin to appreciate the historical import of Prof. Suh's work [2]. In fact, something similar (see Fig. 12) happened in Renaissance Italy around 1420, with the invention of linear perspective [72] by the Italian architect/artist Filippo Brunelleschi. Ancient Rome indeed did have something close to linear perspective; however, the ancients used multiple vanishing points in its paintings, thus leaving a sense of lack of coherence in the presentation. Brunelleschi did study the ancients. He then came back to Florence to revolutionize the world of representational art as we now know it. With a single vanishing point, all the objects in the field of vision compose in a realistic, coherent, eye-pleasing fashion. Indeed, juxtaposing any of the art-works prior to Brunelleschi's approach, one immediately senses the flatness and lack of proportions in the former vs. the three-dimensionality and compositionality in the later.

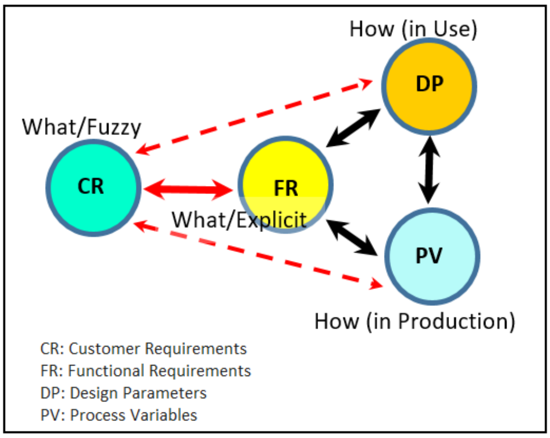


Fig. 11. Design Information Flow Network

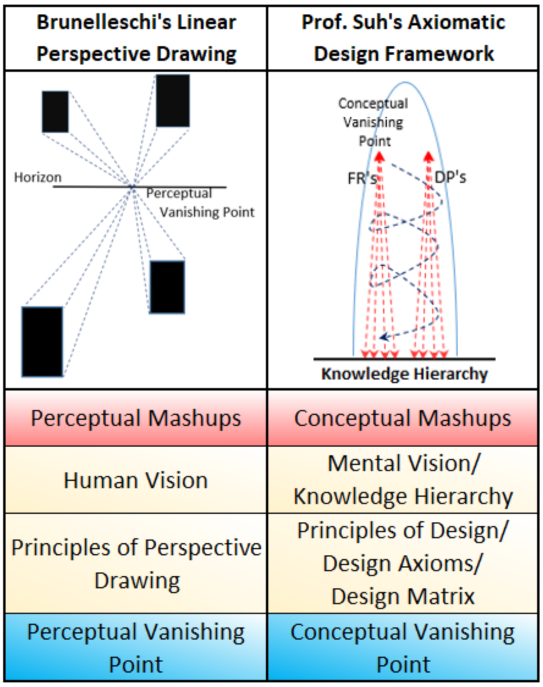


Fig. 12. Perceptual vs. Conceptual Mashups

Likewise, Prof. Suh's work on axiomatic design is at least of equal stature (if not more); for what Brunelleschi stipulated in the realm of perceptuals, Prof. Suh has stipulated in the realm of conceptuals. The ability to bring unity and coherence in the realm of the conceptual artifact space is monumental in scope, especially in the field of education in general; and not just design education. Here, the teaching of anatomy and physiology from a "*Form follows Function*" perspective [73] is worth noting as it offers significant insights into the potential scope. As was the case for paintings prior to Brunelleschi's perspective drawing, much of education today is a sprawl that lacks conceptual unity and coherence. This same sprawl is evident in the blockchain realm [9]. Again, there is untapped potential in modeling instructional sciences along the biological template.

15. Basic Blockchain Design

The web has evolved from a sprawling network of hyperlinks in the 1990s (Web1), to being programmable (Web2) in the 2000's--thus enabling social media, e-commerce, and other similar restructurings. These restructurings allowed a few to scale upwards and enjoy global reach.

So now we are on to the third phase; i.e., Web3. The problem with Web2 was that (as was the case with the Napster-model with its centralized set of index files), at the center of many of the Web2 business models, there exists a centralized database that amasses immense power to structure and shepherd the flow of thought and commerce. These models implicitly took advantage of power-laws that favor the highly connected central nodes. It is true that on the one hand, these Leviathans have enabled tremendous productivity gains compared to what existed prior; but on the other hand, they have de facto established governance-in-stealth for all the peripheral nodes. It is not to say that there is any malevolent element in these designs; it is merely that anything so centralized (as per Lord Acton's dictum) will perforce be restrictive towards the free-flow of thought and association.

Allow discreet agent stigmergy	X							Cryptographic Tokens
Verifiability of Transactions	X	X						Cryptographic Hash
Lightweight transaction-set	X	X	X					Merkle Tree, Patricia Tree, etc
Trustless Trust	X	X	X	X			=	Consensus Model (POW, POS, etc)
Immutable Transactions	X	X	X	X	X			Blockchain Ledger
Distributed Resilience	X	X	X	X	X	X		Distributed P2P Ledger

Fig. 13. Basic Blockchain Design

To put things in perspective, every google page-rank discriminates against those who create and search for the road-less-traveled; for the average person rarely goes beyond the first five search results [74]. In contrast, Web3 portends to be genuinely democratic by eliminating all central nodes and associated intermediaries who currently enjoy a high degree of betweenness-centrality [75] by inserting themselves in between nodes that otherwise would be P2P. Human/machine agents now genuinely can engage P2P without the need for gatekeepers and connectors. To put this in context, the ongoing revolution portends the ability "*to build ridesharing without Uber, apartment sharing without Airbnb, and social media without Facebook and Twitter* [76]."

The top-level CR for the blockchain may be stated as follows:

> *Need* ***consensually-trusted****,* ***immutable****,* ***distributed and decentrally-managed****,* ***verifiable****,* ***publicly and efficiently searchable*** *record of all transactions (since genesis) that are* ***private and discreet, but stigmergically-marked*** *for public-viewing, that pertains to a given economic activity and that may be made by adversarial/trust-less agents.*

When restated in the FR-DP framing, the above CR translates into the basic blockchain design is as shown in Fig. 13 above. The design-matrix indicates a decoupled, lower-triangle design. The couplings systematically build-up across the FR list, top to bottom. For example, the FR: Trustless-Trust (highlighted in red) is being delivered using all the previous DP's, along with the Consensus Model DP.

In the BitCoin case, just as soon as consensus is achieved, new tokens are released as a reward for the successful miner who expended computational resources to help bring about consensus. Thus, in this phase of token creation, a small part of the overall design has one of the design matrices in a different form which leads off with the consensus model. This agrees with the extended AD/CT (i.e., TDPC: Time-Dependent Periodic Complexity). In the discussion below, we have chosen to focus on just the broad design (as shown in Fig. 13 above) and ignore all such finer variations.

The blockchain is a CAS system that fundamentally operates on stigmergy. Discreet stigmergy requires agents be allowed to mark their environment (here, the blockchain ledger) discretely (i.e., without having to reveal their respective true identities). This is similar to ants leaving pheromone droppings—except that in the blockchain context, the agents enjoy a certain degree of anonymity. Cryptographic tokens (bitcoin, ether, gas, etc.) are the cash-like pheromones that various stakeholders use to engage in economic activities. They are cash-like in the sense that they shield the privacy of the agents; but they are stigmergic in the sense that the transaction now has a permanent, publicly-viewable/traceable record. Thus, when spent, the tokens leave their stigmergic markings that if properly aggregated, could help evolve the system forward. Cryptographic stigmergy [77] looks at the stigmergic design of the overall system to help precipitate direction-providing emergences and the corresponding self-organization around it.

Transaction security is obtained via standard, cryptologic hash functions such as SHA-256.

The Merkle tree data-structure that encodes all the transactions in a given block is designed to help verify the existence and validity of the growing chain of transactions in a computationally efficient fashion (costing less than O(Log2(N)) in space and time).

The paradoxical property of trustless trust is obtained via various consensus models (such as PoW: Proof-Of-Work; PoS: Proof-Of-Stake, etc.). Cryptoeconomics [78] studies the creation of economic incentives (such as tokens allocated to miners for performing computationally intensive work such as PoW) to bring about consensuses in a distributed and potentially adversarial setup. For example, the PoW model embedded in the BitCoin system allows decision-making via consensus (via the Byzantine Fault Tolerant algorithm [79]) despite approximately $1/3^{rd}$ of all agents going rogue. Blockchain offerings may be differentiated using the consensus model differentiator that power their respective answers to the problem of securing Trustless Trust.

As a biological analog, the immune system [80] is a perfect example of the blockchain along with its own Proof-of-Work (called the fever) which is the computational struggle that various cells from the immune system go thru in order to recognize invading antigens as a friend or a foe. Once identified, the body never forgets. It keeps the evidence of all its successful struggles in its growing ledger, i.e., its collection of antibodies.

The blockchain ledger is a growing linked list of transaction records that have been bundled into timed blocks. The chained ledger has been accumulating these blocks ever since the genesis of the blockchain under study. Each such timed block of transactions is bundled in an efficient, easily verifiable data-structure such as the Merkle tree. Each new addition contains in its header the hash of the previous block. This makes both the nodes as well as the overall chain highly resistant to modification. Longer the chain grows, harder it is to break.

Finally, Network Resilience is obtained via the P2P distributed protocols.

Satoshi Nakamoto designed the PoW based blockchain for the P2P bitcoin cryptocurrency [81]. The contractual logic that is embedded in the BitCoin blockchain may be abstracted out and generalized to help secure trusted transactions across the whole gamut of global economic activity. The Ethereum project was the first to recognize the value of such decoupling's. While the Blockchain provides the underlying infrastructure, it is what gets built on top of it that defines the business offering. Each such offering provides unique affordances targeting specific business eco-systems. The rules and boundaries of these eco-systems (along with their governance protocols) are established via the logic of the smart contracts.

16. Smart Contract and Governance

Smart contracts are contracts written in code that will execute when matching conditions that make up the agreement are met. In other words, it is "*cocked, locked and ready to fire*"; there are no off-ramps. Smart contracts have been envisioned across multiple domains, including crowdfunding, financials (buying and selling of tangibles/intangibles, insurance, derivatives), legal, etc. Smart contracts are point-to-point with all middlemen having been dis-intermediated. It, therefore, has substantial potential to inflict losses in the hands of the naïve, careless or uninitiated (i.e., the KU type asymmetry).

The blockchain-based smart contract technology has the potential to transform society as a whole for the better; better in the sense of faster, cheaper and fairer transactions. Thus, given the enormous potential to smoothen the flow of commerce while bringing down costs, it is incumbent on the designers of blockchain based smart contracts to get the governance aspect done right. If it is designed for scaling, it ought to cover for the variety of knowledge asymmetries that exist across the spectrum of participants as well as the dynamics along a fast-moving front. Voshmgir emphasizes the pace with which the context for a smart contract design could rapidly move away from its original intent [82]:

> *First use cases show that as circumstances change, protocols can become inappropriate for the new environment and require modification.*

In other words, it is not just that the design space is rapidly evolving; here the FR’s themselves are rapidly evolving; i.e., the half-life of any given FR is also rapidly being cut short. This in itself is highly unprecedented in the world of design. In other words, there is a high premium for designing systems based on first principles as compared to short-sighted pragmatics.

Since the smart contract offering sits on top of the blockchain infrastructure, the CR for the design may be stated as follows:

> *Need the ability to* ***structure*** *and* ***verify*** *auto-executing contracts that incorporate arbitrarily complex business rules and trade on a given blockchain offering.*

Structure Auto-exec Contracts	X								Smart Contract
Contract Verification	X	X							Oracle
Allow discreet agent stigmergy	X	X	X						Cryptographic Tokens
Verifiability of Transactions	X	X	X	X					Cryptographic Hash
Lightweight transaction-set	X	X	X	X	X				Merkle Tree, Patricia Tree, etc
Trustless Trust	X	X	X	X	X	X			Consensus Model (POW, POS, etc)
Immutable Transactions	X	X	X	X	X	X	X		Blockchain Ledger
Distributed Resilence	X	X	X	X	X	X	X	X	Distributed P2P Ledger

Fig. 14. Blockchain-Based Smart Contract Design

When restated in the FR-DP framing, the above CR translates into the blockchain-based, smart contracting infrastructure as shown in Fig. 14 above. The smart contract is the structured, auto-executing contract. It is neither a legal contract nor necessarily smart. Just as any other trading instrument, the legality of the contract needs to be ironed out in the appropriate legal setting. The smart in the smart contract depends on how well the coding reflects the underlying economic incentives. For example, the DAO as a smart contract [12] was anything but smart.

The blockchain infrastructure wouldn’t necessarily have the necessary data and logic to verify if and when all the preconditions specified in the smart contract have been sufficiently met. An oracle is a 3rd party service that exists outside the blockchain to help verify that the preconditions encoded within the smart contract. These artifacts provide ways and means to interface with the real world. Being outside the underlying blockchain setting, they may have unique governance issues that need to be addressed independently.

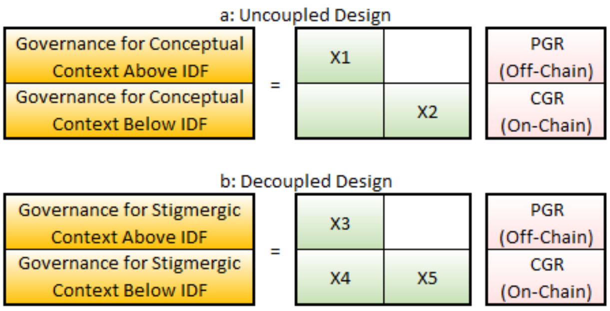
17. Blockchain Governance Kernel Design

As was discussed in Section 13, knowledge asymmetries create governance issues. However, knowledge asymmetries are the basis for initiating any successful trade; and is therefore not wrong per se. Indeed, wealth creation requires such knowledge asymmetries. Also, the half-life of knowledge is short and getting shorter. In other words, there are no guarantees that a given vantage point will remain forever. However, at any given time, if the asymmetries are severe or resulted from a prior information-agreement breach, it then opens up problems of poor governance. Good governance, therefore, involves creating adequate channels of information flow for timely decision-making for all parties to participate in sufficient amount of openness while also allowing specific strategic/proprietary information to remain hidden and off the grid (either permanently, or at least for a while). Insights from Cryptographic Stigmergy [77] as well as Cryptoeconomics [78] would be needed to design the appropriate information signaling mechanisms and economic incentives that help streamline the required information flows. Here we delimit the context to the kernel governance design to help decide between the off-chain/on-chain approaches.

When we place the matrix of the Unknown-Unknown asymmetries (Fig. 10) alongside the *Inducto-Deductive Front (IDF)*, it raises the issue of how the design-matrix gets transformed when one of the parties on either side is a machine working off a highly specified Codified Governance Ruleset (CGR) as opposed to a human working off a more abstract Principled Governance Ruleset (PGR)? While the CGR could be codified into the on-chain governance modules, the PGR would be administered in pre-agreed, human-centered, arbitration-like off-chain governance setups that cross organizational boundaries. Fig. 15 (below) shows the kernel governance design indicating when one or the other ought to be used.

When the knowledge context is conceptual and below the IDF, CGR-coded machines can adjudicate governance modules coded as on-chain, smart contracts (i.e., via X_2 CGR in Fig. 15a). In contrast, when the knowledge context is conceptual but above the IDF, governance remains off-chain and human adjudicated (i.e., via X_1 PGR in Fig. 15a).

When the knowledge context is stigmergic and above the IDF, governance remains firmly off-chain and human adjudicated (i.e., via X_3 PGR in Fig. 15b). The case where the knowledge context is stigmergic and below the IDF is a bit more nuanced. For even though the knowledge context is safely below the IDF (and therefore could use CGR), given the stigmergic uncertainties, it always needs human oversight. It is a case of the decoupled design (as shown in the lower half of Fig. 15b). It is, therefore, a mixed case that uses both off-chain as well as on-chain logic. This is the fundamental answer to the on-chain vs. off-chain governance debate between Ehrsam [10] and Zamfir [11] that we discussed in Section 2.



c: Governance Problem Context

Choices ↓	Conceptual		Stigmergic	
	Below IDF	Above IDF	Below IDF	Above IDF
PGR (Off-Chain)		X1	X4	X3
CGR (On-Chain)	X2		X5	

Fig. 15. Governance Kernel Design

From a CAS-perspective, the various configurations (in Fig.15 a-b) are in dynamic flux; protagonists are continually re-positioning for strategic advantage. However, each of these configurations has β-level patterns that frame the governance issue. Most dynamic (and therefore requiring the highest amount of governance effort) are those patterns that have intrinsic knowledge asymmetries (i.e., the UK type); and the ones that need the least amount of governance have fundamental knowledge symmetries (i.e., UU, KK type). However, here too, if the β-level patterns indicate that one or both parties suffer from high-confidence coupled with poor-grasp (or alternatively, good grasp, but low confidence), then problems of governance may surface. This adds greater onus to the "*Know Your Customer*" (KYC) type guidelines.

Fig. 16 shows the overall composition of the Blockchain design along with the governance sub-modules (as discussed above) factored in. DAO was missing these governance sub-modules. Dominance of the governance sub-modules is evident given its top-row position. Within the governance sub-modules (and in agreement with Section 7), the conceptual dominates the stigmergic on account of its logical consistency. However, the conceptual does need to factor in the broader inductive base that the stigmergic provides.

Gov-Conceptual above IDF		x												Conceptual PGR (Off Chain)
Gov-Conceptual below IDF			x											Conceptual CGR (On Chain)
Gov-Stigmergic above IDF		x	x	x										Stigmergic PGR (Off Chain)
Gov-Stigmergic below IDF		x	x	x	x									Stigmergic CGR (On Chain)
Structure Auto-exec Contracts		x	x	x	x	x								Smart Contract
Contract Verification	=	x	x	x	x	x	x							Oracle
Allow discreet agent stigmergy		x	x	x	x	x	x	x						Cryptographic Tokens
Verifiability of Transactions		x	x	x	x	x	x	x	x					Cryptographic Hash
Lightweight transaction-set		x	x	x	x	x	x	x	x	x				Merkle Tree, Patricia Tree, etc
Trustless Trust		x	x	x	x	x	x	x	x	x	x			Consensus Model (POW, POS, etc)
Immutable Transactions		x	x	x	x	x	x	x	x	x	x	x		Blockchain Ledger
Distributed Resilence		x	x	x	x	x	x	x	x	x	x	x	x	Distributed P2P Ledger

Fig. 16. Governance Kernel for the Blockchain Design

19. Conclusions

Given the leveling of the playing field, the dis-intermediation of the middle-men, and the transparency of blockchain-based transactions, it is highly likely that the information flows are on the verge of scaling exponentially. Stigmergy steps in when information flows scale beyond aided/unaided human cognitive limits. In other words, the α↔β gearing (as discussed in Section 7) will most likely ramp up as the technology gains mainstream support. This paper has provided CAS based governance guideposts as to what may be expected. Salient points include:

- Review of pertinent literature on blockchain governance to highlight novel pathologies and the problem of the unknown-unknowns
- The issue of trust as it relates to the top nodes in a hierarchical organization; and its solution via heterarchical control (courtesy James Madison) which in essence is a decoupled lower-diagonal design for a fundamental governance problem ever since Plato.
- How organizational structures as well as sense-making changes with rising complexity.
- The unique challenges faced in the context of large-scale socio-technological organizational designs.
- The challenge of governance where "formal controls" are missing.
- The role of stigmergic gearing in both biological as well as human decision-making context.
- The original formulation of an iterative CAS.
- The original formulation of how the iterative CAS framework may be utilized to help understand the crux of the centralization/decentralization issue.
- The framing of governance from a heterarchically-hierarchic human knowledge architecture perspective. Then using this approach to fundamentally frame the issue of human vs.

machine dominance in decision making (i.e., induction vs. deduction).

- The framing of the Unknown-Unknown nuances and the way these show up in the context of governance.
- The distinction between emergence vs. self-organization; and how the disruption of the natural flow between these two processes can lead to governance pathologies.
- Highlighting the historical significance of Axiomatic Design (in the context of knowledge architectures) as proving a unifying conceptual vanishing point (similar to the perceptual vanishing point in the case of perspective drawings); except being in the realm of conceptuals, it has far greater import, especially in education.
- The blockchain technology when viewed from an axiomatic perspective is seen to be a lower-triangle decoupled design.
- The promise as well as the governance problem of smart contracts.
- The design of the blockchain governance kernel as helping decide between on-chain vs. off-chain governance.

Informed by the above guide-posts, a follow-up study will go into the Agent-Based Modeling of archetypical blockchain offerings.

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