Dynamic Cyberspace Modeling from Network Automata

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Summary

Cyberspace, which is a complex system, constitutes dynamic networks of various interacting entities such as cyber-physical systems and world-wide-web of information. The quest for principles underlying the structural organization and dynamics of cyberspace often uses a Top-down approach, and no general framework for describing, categorizing, and analyzing its inherent properties has been established. This paper proposes a network cellular automata framework, characterizing and modeling cyberspace derived from the intrinsic constructs of cyberspace—entities, space, and time. Employing network (graph) theories for spatial topology and generalized cellular automata depicting the dynamic process, we provide a novel foundation for formal cyberspace modeling. Subsequently, A network automata, a generalization of standard Cellular automata, is defined with a cyberspatial map, which is a mathematical generalization of cyberspatial object characterizing the dynamic and structure of cyber-physical systems. Consequently, the cyberspatial map is found to be homomorphic to the network automata.

Key words:

Cyberspace, Network automata, cyberspatial map, relational topology, cyberspatial model.

1. Introduction

Cyberspace exhibits dynamic behaviors and has mathematically different components and entities connected most often nonlinearly and/or via a network with complicated feedback mechanisms. As dynamic behaviors ofc complex systems evolve along qualitatively different pathways and display great sensitivity to small perturbations. Cyberspace is characterized by many properties of a complex system [1][2].

- An Ensemble of varieties of entities: Cyberspace has many similar but different subsystems. Physical elements of cyberspace are comparable in size (for instance, how big–how much information how many links?) and may subject to some laws of physics. Non-physical components are similar in behaviors (obey the same rules) for instance, protocols that govern network functionality. The hierarchical (tiers) nature of network organization reflects similarity. For example; the set of backbone links carrying traffics and the technical and organizational model are based on functions and domains. The hierarchy of the network entities was found to be the consequence of scale-free and clustering properties [3].

- Interaction: Connected complex systems interact to realize the full functionality of the whole system. Messages are the means for cyber-physical systems to interact and exert force on one another [4]. Message in the form of a sequence of control packages (bytes, signals impulse) triggers changes in pattern and behaviors of entities in cyberspace. These interactions are far from equilibrium [2], thus gives rise to a non-equilibrium order.

- Adaptive behavior: This is a special case of a complex system whereby the structure and the behavior of the system change as a result of adaptive processes. Cyberspace is said to be an ultimate adaptive system [2][5]. Innovation, agility, robustness, and resilience are used to explore available benefits in the systems environment and to device appropriate response to threats while core functionalities are maintained. This adaptation usually manifests itself in cognitive and social domains. For instance, the convergence of technology leading to adaptation among devices, systems, and the environment.

- Robust orders: The order in complex systems is robust; being distributed and not centrally managed while stable under perturbations. In cyberspace, for example, the response a router made by updating routing tables for failure points (a dynamical process) is one of the essences in robustness.

- Heterogeneity/ decentralized control: Complex systems have a large number of components with a variety of scales and structures, which are self-organized without any central control. Similarly, cyberspace entities have technical and administrative diversities and no central control.

- Non-linear complex interaction/tipping-point: That is a sudden behavior change (e.g. from stability to instability). A spontaneous order is caused by the interactions of individuals following

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relatively simple rules. This property adds to limited predictability as a minor change of initial condition, which might seem negligible, resulting in a major dynamic over time. Cyberspace entities are non-linearly interacting entities.

- Simplicity and co-evolutions: Complex systems entities continuously co-evolve. Cyberspace aslo evolves in space and time and behaviors emerge out of an interaction between basic elements.

Various views of cyberspace and its related concepts lead to a semantic problem of definitions— what Lance Strate called cyberspace(s) [6]. Cyberspace has been discussed relative to physical space, for instance, considered as a "'Parallel' universe to our own" [7]. In other words, "physical space and cyberspace interpenetrate" [8]. From a geographical, Graham M. [9] argued that Cyberspace is an inherently geographic metaphor' in that it is spatially and materially based on physical infrastructure [10], interacting with the physical environment. It also exhibits representations of real space through maps and graphs, important for the study of real space and navigation [10] [11]. Bryant posits that the physical space and cyberspace are analytically equivalent [12], but even though cyberspace exhibits some characteristics of space theories (absolute, relational, Einsteinian, and Kantian), it can't be subsumed under one particular theory. This suggests that cyberspace is neither absolute nor relative rather both and more. It is simultaneously physical— tangible, real, and present in geo-space (G); informational— logical, virtual and present in info-space (I), and social— organizational, political, and present in socio-space (S) [4].

Cyberspace is a completely unprecedented space analog to physical, social, and thinking space in that it is not only confined to the digital world but also include physical, social, and mental space [13] [14] [14]. For example, the first Internet topology generator, used for protocol testing, posits that routers have a geographical position in space [16]. The subsequent model, the GeoBA model, is established based on the observation that the probability of finding a connection between two nodes generally decreases with the geographical distance between them [17]. Furthermore, Considering the possibility of an inhomogeneous spatial distribution of vertices, Yook et al. [17] proposed a topology generator in which the vertices are distributed in space, forming a scale-invariant fractal set, with a fractal dimension compatible with the value found in real router-level maps.

However, cyberspace has is no metric meaning of distance and orientation like in physical space [4] [18]. Current cyberspace characterizations mainly use topological structure to express information content and simplifying the distance between node connections and the orientational relationship of node switching [19].

With no unified theoretical framework, which has the potential to simulate different complex and complicated phenomena, for practical modeling of cyberspace and its dynamic analysis, cyberspace definition, delimitation, and theoretic problems are better addressed through formalized cyberspace [20]. We argue that cyberspace is better understood by considering the basis of our conception of existing theories. The advancement of technology and cyberspace concepts lead to an endless proliferation and creating a need for formalization and categorization, in addition to the absence of a rigorous framework that could be used to analyze the dynamics of cyberspace and its properties. The study of these properties is crucial, for example, non-linear interaction of combat forces and local actions induce long-range order such as cascading failure as a result of localized attacks [1].

Summarized by Fig. 1 and detailed in section II, three perspectives of depicting cyberspace (as dimensional manifold space, as network space, and as information space [18] [21]) are integrated from existing theories. In physical space, for instance, the energy or force, which is the result of dynamic relationships, may have a similar notion in cyberspace as cyberspace is never an empty container (fundamentally formed by the movement of electrons, and forces exerted by information in the form of messages flowing among cyberspatial objects). Cyberspace is a manifold populated by cyberspatial objects and their spatial relationships, the totality of events involving these relationships as Cyberspacetime. Emphasizing the relational aspect of cyberspace, an aspect of a cyber field can be established through a simple dyad. An essential concept in absolute space is the physical object (geo-referenced item) while spatial relation is vital in relative space-— both related by special model of space called the proximal model of space [22]. In proximal space, the neighborhood refers to a localized node and embodies the notion of nearness (including functional influence) or spatial proximity. This enables an extension of classic cellular automata neighborhood to non-contiguous neighborhoods base on relations of influence between the objects.

A classic cellular automaton (CA) is a decentralized discrete dynamic framework, with an inherently spatial form, having an underlying network of cells that can change state at each time step. Each cell is considered as a finite state automaton and that the next state of the cells depends on the neighboring cells and update rules. The whole structure can be regarded as a parallel processing device. Despite the simplicity of this classical automaton, it evolves a complex pattern after considerable time steps. CA are integrated with networks to analyze the topological properties of complex systems. For example, studies show CA density Classification capability in small-world topologies [23] [24]. The dynamics of evolving networks are also examined through the use of Cas [25] [26]. As entropy measures can be obtained from the Spatio-temporal patterns and the degree distribution of a network, CA is a potential candidate for much more dynamic models of complex systems.

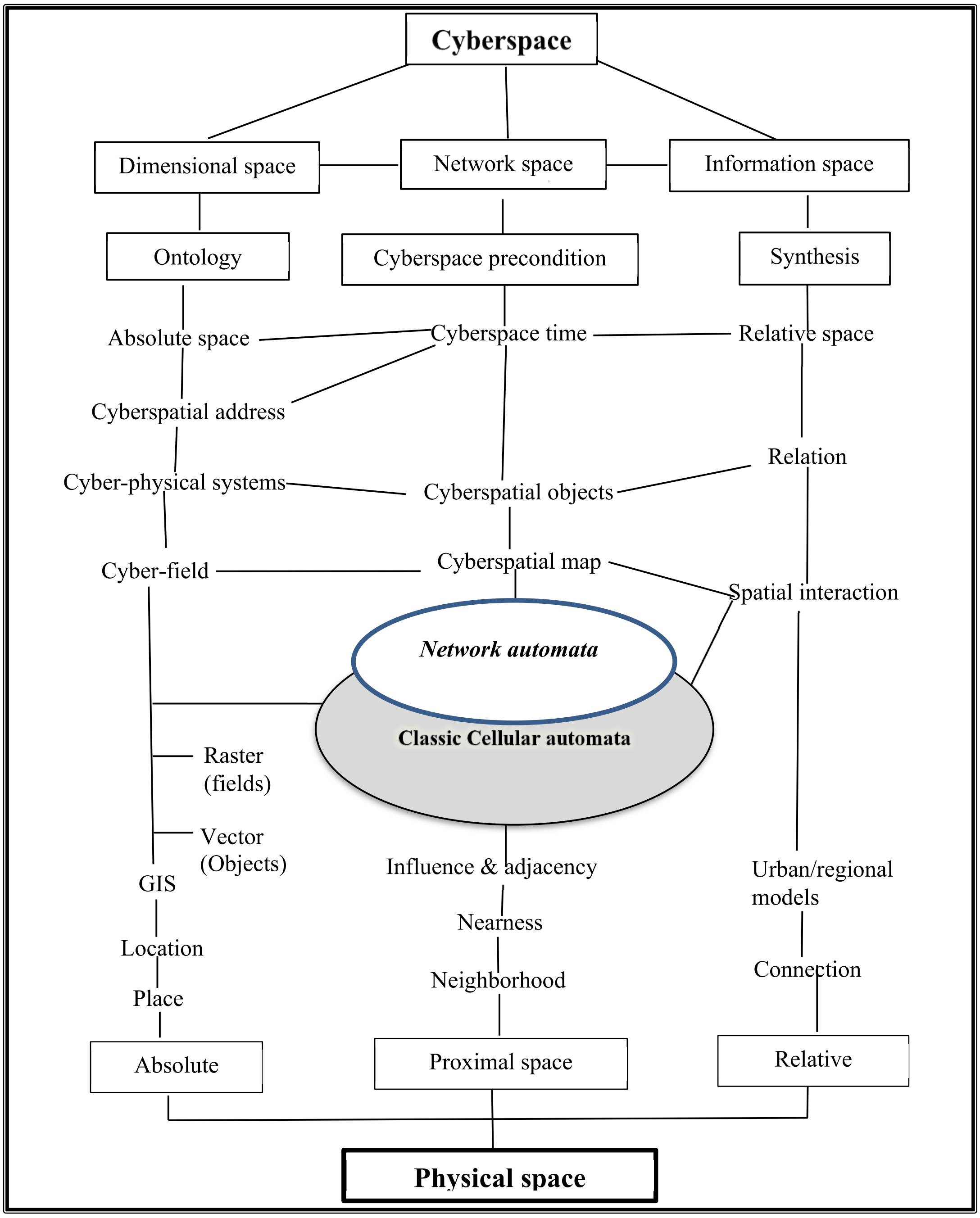


Fig. 1 Integrating cyberspace with existing theories

2. Background to a unified perspective of Cyberspace

The formal conception of cyberspace is at the intersection of cyber science, cyber information technology science, and cyber philosophy bridged by Cyber logic [27]. More specifically, the existence of space and spatial entities governed by a topological rule and instructional information that the entities used to changes their states and the state of other connected entities. We summarize these three different fields in Fig. 2, as detailed in [20].

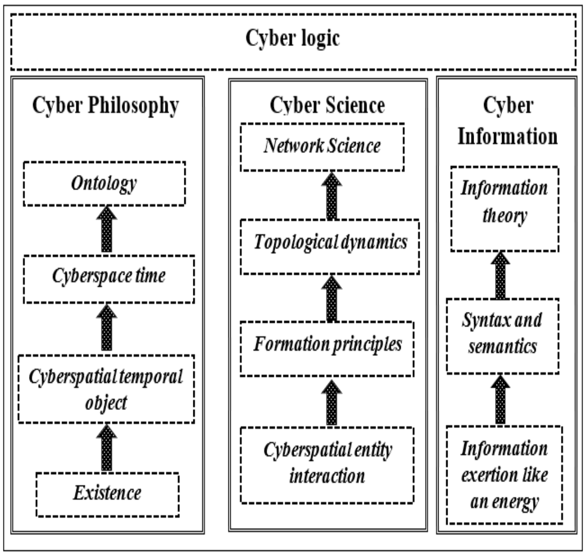


Fig. 2: Cyberspace disciplines

Unfortunately, most discussions of cyberspace assume the common-sense conception of space even though cyberspace is not void, it comes into existence through the movement of electrons (from a physical level) for instance. Whether expressed in physical form as a cyber-referenced cyber-physical object or conceptual form as a virtual object, the essence of space in cyberspace is the cyberspatial address defined as a frame of reference for locating cyberspatial objects (objects, processes, and events) [4], which implies cyberspace as a container of objects (cyberspatial objects /cyberspatial temporal object). As much as information technology is an embodiment of absolute space, it is born out of a relative-space-oriented approach, which is constituted through the spatial relations among cyberspatial objects. Organized as a network of networks [28], cyberspace also has a cyberspatial object as a node in the network (which is the precondition of cyberspace), Fig. 1.

The networks of cyberspatial entities in cyberspace manifold form the basis for information space, which is a synthesis based on information content. Cyberspace is an information space [29] in which the World-Wide-Web created an amazing universe of information by linking information resources. The Information has its location (e.g. Domain Name System), category (business, education, science, etc.), and forms (for instance, text, graphics, image). When viewed as a map, its distribution is potentially subject to analysis. Not only the information, but various aspects can be also be mapped [30]. A spatial framework defining and mapping numerous aspects of cyberspace, such as physical locations of entities, traffic situations, and so on is termed "Cybermap" [31] [32]. It was described in [31] that this kind of mapping in four-fold; physical space referent, the infrastructures of cyberspace; material and immaterial spatial forms; and map/spatialization form (static, animated, interactive, dynamic).

We formally extend the cybermap notion by including the concept of space and time to explain the dynamic of cyberspace, a term we call Cyberspatial map. It allows non-contiguous neighborhoods, an extended CA, based on relations of influence between cyberspatial agents, integrating functional and spatial relations. The theoretical basis for using cellular automata in cyberspace modeling is their embodiment of space and time. Its formalism describes an abstract structure suitable for representing domains with spatial features, as the foundation of every spatial representation is an implicit space model. A highly abstracted model of spatial relationship, graph (Network), provides a way to represent connectivity and relationship between the objects. Thus, a spatial type of CA model called Network cellular automata (graph-CA or GCA) is proposed. The three existing theory fields considered are:

2.1 Cyberspace as dimensional manifold:

Addressing the problem of cyberspace ontology, a formal foundation is built. Heim [33] superficially stated this problem as the need to explain how entities exist within cyberspace and the ontological status itself. However, various questions remained unanswered: “Is cyberspace a kind of space?” [34], "What is cyberspace? Is it or does it have a dimension? Are there things in cyberspace? Are things in cyberspace properly called objects? Are such objects or is cyberspace itself substance(s) or process(es)? Is cyberspace or the objects in it real or ideal? What is the categorical scheme of cyberspace? How should cyberspace fit into a broader categorical scheme?” [35]. These meta-theoretic notions questioned the material reality of cyberspace, the structure, and the dynamic of entities in cyberspace in space and time.

Taken cyberspace as Euclidian and compact with perpendicular axes, implies that the orthogonal Euclidean 3-space vectors produce zero dot products, and that system behaviors could be isolated to realize compact functional designs–an important system design principle. Building on the work in [4], we characterized the dimensional aspect of cyberspace geometrically by a tuple $\mathbb{C} = (\mathrm{C}, \mathrm{L}, \Omega, \mathrm{V})$, Where:

- C is assumed Euclidian and compact of primarily 3 dimensional (Physical (P_i^P), logical (P_i^L), and information (P_i^I)) plus time.
- L is a connection on C. Its torsion which is the rate of change of the direction of the unit vector, is assumed zero. The **Torsion** is the value τ(L) = 0
- Ω as a differentiable 1-form field on C, as a point set with neighborhoods homeomorphic with the Euclidean space, Such that Ω≠0.
- V is a vector field on C. Such that each point of the manifold $\mathbb{C}$ is an entity or an "event" which is characterized by their instant and point in time and place of occurrence. Two events/processes $p, q \in \mathbb{C}$ occurs at the same place in the space if and only if they belong to the same address.

Each point of the manifold $\mathbb{C}$ is a potential entity/object of the cyberspacetime. This geometrical structure allows one to "stratify" the manifold $\mathbb{C}$ into a succession of three-dimensional spaces so that each object is characterized by its instant and the hierarchy (place) of its occurrence.

2.2 Network as a precondition of cyberspace:

Network science is an essential field that explains complex systems and is a modeling approach whereby objects (nodes) and their relationship as a graph [36] [37] [38]. Graph theory provides a natural framework for precise mathematical modeling of complex networks [39] [40] [41] [42] [43]. From biological to technological, most of the networks in complex systems are multi-layered [44] [45]. Cyberspace, classified as a complex system, is also described in multiple layers [46] [47] [48] and formed a networked system [49] [50]. At least five layers of entities are considered, with the majority of research using three layers. Three-layered network of network (NoN) model for an enterprise cyber system was proposed in [28]; the physical (Hardware) layer, the Logical layer (Software; Functions), and the Social layer (User; Computer). Having several technologies and protocols along with multiple layers (multi-level and multi-technology networks) is refers to as multi-layer networks [51] [52].

From this perspective, we define cyberspace as the multilayer network of entities as a pair $\mathrm{T} = (\mathrm{L}, \mathcal{C})$ where: $\mathrm{L} = \{\mathrm{G}_\alpha;\ \alpha \in \{1,\dots,\mathrm{M}\}\}$ is a family of graphs $\mathrm{G}_\alpha = (\mathrm{E}_\alpha, \mathrm{C}_\alpha)$ as layers or subnetworks of T

$\mathcal{C} = \{\mathrm{E}_{\alpha\,\beta} \subseteq \mathrm{E}_\alpha \times \mathrm{E}_\beta; \alpha, \beta \in \{1,\dots,\mathrm{M}\}, \alpha \neq \beta\}$ is the set of interconnections between entities of distinct layers G_α and G_β with $\alpha \neq \beta$.

The elements of $\mathcal{C}$ are crossed layer connections, the elements of each C_α are intralayer connections of the topology T and the elements of each $\mathrm{E}_{\alpha\,\beta}$ $(\alpha \neq \beta)$ are interlayer connections.

The set of entities at the layer G_α will be given by $\mathrm{E}_\beta = \{E_1^\alpha, \dots, E_{N_\alpha}^\alpha\}$ and the influence is given by the adjacency matrix of each layer G_α is given by: $A^{[\alpha]} = \left(a_{ij}^\alpha\right) \in \mathbb{R}^{N_\alpha \times N_\alpha}$ where:

$$a_{ij}^\alpha = \begin{cases} 1 & if\ (E_i^\alpha, E_j^\alpha) \in \mathrm{C}_\alpha \\ 0 & otherwise \end{cases}$$

For $1 \leq i, j \leq N_\alpha$ and $1 \leq \alpha \leq M$.

The interlayer adjacency matrix $\mathrm{C}_{\alpha\,\beta}$ is the matrix given by: $A^{[\alpha,\beta]} = a_{ij}^{\alpha\beta} \in \mathbb{R}^{N_\alpha \times N_\beta}$

$$a_{ij}^{\alpha\beta} = \begin{cases} 1 & if\ (E_i^\alpha, E_j^\beta) \in \mathrm{C}_{\alpha\beta} \\ 0 & otherwise \end{cases}$$

The map of the network of T is then a graph *map* $T = \mathrm{E}_\tau, \mathrm{C}_\tau$ where

$$\mathrm{E}_\tau = \bigcup_{\alpha=1}^{M} E_\alpha,$$

$$\mathrm{C}_\tau = \left(\bigcup_{\alpha=1}^{M} C_\alpha\right) \cup \left(\bigcup_{\substack{\alpha=1 \\ \alpha\neq\beta}}^{M} C_{\alpha\beta}\right)$$

These definitions allow the model to take into consideration the connectivity in distinct networks; the features of the connections and the relationships between entities that belong to various layers, and the entities belonging to each layer.

2.3 Cyberspace as Information:

Cyberspace consists of entities such as network devices, software systems, and information [53]. The information stored or transmitted can be raw data (basically denoting a simple or complex variable such as a sensed parameter of an entity, set of parameters, or a message). It forms a spatial relationship as a result of communication with and through the devices. However, aggregation and integration of multiple information are bound by rules governing its organization. The theory of conceptual spaces as a knowledge representation framework explores how different information can be formalized, both from a psychological point of view and for developing an artificial system [54].

Conceptual information space is considered as 4-tuple (Q, Δ, C, Γ), where Q is a set of quality dimensions which is the framework used to assign properties to objects and to specify relations among them, Δ is a set of domains, C is a set of concepts in the space I, and Γ is a set of instances representing the concepts [55] [56] [57]. This presents a framework, consisting of cognitively meaningful attributes in various domains within the geometrical structure, to model, categorize, and represent the concepts in a multi-dimensional space.

A cyber informational object exists as an entity, which is quantified using a fundamental unit, Shannon entropy which is a measure of the information in a message. The Shannon entropy of a variable X is defined as:

$$H(x) = -\sum_{x=1}^{N} P(x)\, log_{2^P}(x)$$

Where $p(x)$ is the probability that X is in the state x, and $p\ log_2\, p$ is considered 0 if $p = 0$. [58]

Information in form of a message is defined as $m_{i,j} = \{e_i, e_j, n, l, t_k\}$. Sent from entity e_i to e_j; for a payload l with a particular action/service selector, $n \geq 1$ and "message sent" time t_k [4].

Consider M as the set of all messages $\{m^1, \ldots, m^w\}$ possible for X, and $p(x)$ as the probability of some $x \in M$, then the entropy of X would be defined as $H(X) = E_x(I(x))$ where $I(x)$is the entropy contribution of an individual message. This situational information not naturally describable in absolute space are interaction protocols that determine the most complex, unpredictable forms of cyberspace evolution.

3. Cyberspatial map: Cyberspace spatial modeling

Aim to advance rigorous formalism for cyberspace analysis and spatial modeling, cyberspatial map, C, is a set of cyber-units (an essential unit of cyberspace representing cyberspatial object's information), each of which comprises of a pair of a cyberspatial object as a node/entity and associated state(value). Each cyberspatial object is identified by its relative position $P_i(t_k) = \{G_i, I_i, S_i\}(t_k)$ at a time $\mathbf{t_k}$, which is a cyberspatial address defined as a subset of n-dimensional space [4]. Adopting the proximal model of space map algebra, particularly the work in [59], we provide cyberspace spatial modeling as follows. Given P and S, a cyber-unit is denoted by $P_i \times S_i$ and therefore cyberspatial map is a function from a set of positions to a set of states $\boldsymbol{M}^{\mathbb{C}}: P \to S$ defined by :

$$\boldsymbol{M}^{\mathbb{C}} = \{((p_i), \boldsymbol{m}(p_i)): p_i \in P, m(p_i) \in S\}$$

Where $p_i \in P$ is the identifiable cyberspatial position of a cyberspatial object e_i and $m(p_i) \in S$ is the state (attribute/value) of the object at that position. The set of all S valued cyberspatial map on P is given by S^{P}. The various spatial structure is defined on the set P; Conceptually as a continuous field of a discrete domain, for example, two-dimensional space (a regular grid) having the limit determined by × ($P = R \times R$ for the set of reals, R) or a restricted network domain. The set of states could be a set of integers, real numbers, binary numbers, characters, a set of characters, or a complex structure– giving the current states of nodes. The aggregate properties of these units then form the global state of cyberspace.

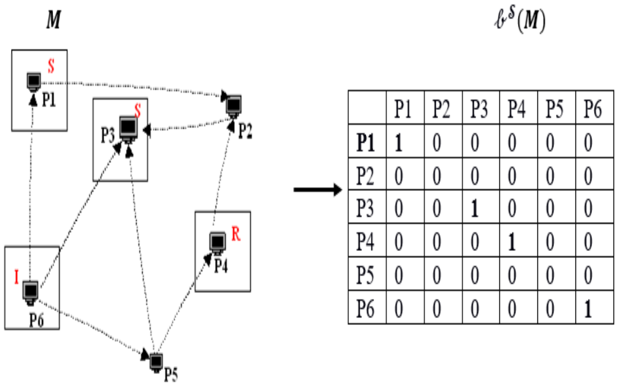
While each object has a particular value at a time, a generalized case is where the object takes more than one state simultaneously— multi-variate situation. In this case, the set of states is the set product of these values, and therefore;

$$S(t) = \prod_{i=1}^{n} S_i(t)$$

Basic operation defined at each position p_i is influenced by the global state of cyberspace, $\boldsymbol{M}^{\mathbb{C}}$. This local operation is formalized from a local function f' on the state of cyberspace at each position in P:

$$f(\boldsymbol{M}^{\mathbb{C}}) = \{[p_i, f'[m(p_i)]]\}$$

Characteristic function $\mathscr{b}: \mathrm{A}^{\mathrm{P}} \to \{0,1\}^{\mathrm{P}}$ representing a binary cyberspatial map for an attribute value $\mathscr{b}: A \to \{0,1\}$, for example, calculates whether the attributes at each position are included in a given set. Consider a basic model of virus propagation—the susceptible-infected -recovery (SIR) model. Similar to a biological system, a scale-free network can model such a virus spread— cyberspatial entities (AS, router, or PC) defined as a node in a network, linked together by edges, in a given topology. Let $\boldsymbol{\mathcal{S}}$ have values of SIR (Susceptible, Infected, Recovery) epidemic model $\boldsymbol{\mathcal{S}} = \{\boldsymbol{S}, \boldsymbol{I}, \boldsymbol{R}\}$**.** Then a cyberspatial map $\boldsymbol{M}^{\mathbb{C}}$, in Fig. 3, is transFig.d into $\mathscr{b}^{\mathcal{S}}(\boldsymbol{M}^{\mathbb{C}})$ by a characteristic function $\mathscr{b}^{\mathcal{S}}$. Accordingly [60], any local operation between cyberspatial maps is induced by an operation on an attribute set S.



	P1	P2	P3	P4	P5	P6
P1	**1**	0	0	0	0	0
P2	0	0	0	0	0	0
P3	0	0	**1**	0	0	0
P4	0	0	0	**1**	0	0
P5	0	0	0	0	0	0
P6	0	0	0	0	0	**1**

Fig. 3 Cyberspatial map characteristic function application.

Extending the local operations at each node e_i at position p_i to have a global influence (a function from a local rule on the value of mapping at each location in P) paves a way to generalized spatial relations between entities;

With this, the neighborhoods of classic cellular automata formalism is also generalized. Defining the influencing positions is achieved using a metarelational cyberspatial map (R), where each position is assigned a relational cyberspatial map (R_i). R_i is the set of all nodes in P influencing node p_i for each node $p_i \in P$. For example, to represent connectivity, a binary map on the set of nodes P such that R_i is populated with binary values— 1 as the presence of connection/influence and 0 otherwise, Shown in fig. 4. The situational information of each position is expressed with the relational map. The meta relational cyberspatial map is then given by:

$$R = \{(p_i, R_i)\}$$
$$R_i = \{(p_i, r_i(p_i)) : r_i(p_i) \in \{0,1\}, \forall p_i \in P\}$$

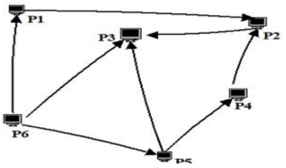
Therefore, a relational cyberspatial map represents the situational information for each entity. It expresses any arbitrary neighborhood/influence associated with a node. A metarelational cyberspatial map is in essence a way in which each node is related to each other node. To compute global configuration from the metarelational cyberspatial map, we need a medium level metarelational cyberspatial map, $M \otimes R$, in which each location p_i is associated with the set of values from influencing nodes. The global cyberspatial map function is then a function on $M \otimes R$, representing the attributes of influencing positions:

$$M \otimes R = \{(p_i, Y_i)\}$$
$$Y_i = \{(p_i, y(p_i)) : y_i(p_i) = m(p_i) r_i(p_i)\}$$

The cellular automata (CA) space corresponds to the metarelational cyberspatial map R_{CA}, where the node's relational map is defined by the CA's neighborhood operator. The function on the previously valued metarelational map is substituted as the transition rule, giving a new cyberspatial map at time $t+1$ from the previous map, at time t.

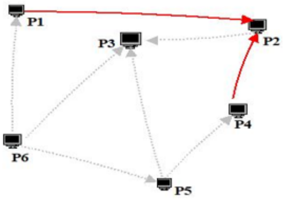
$$M_{t+i} = f(M \otimes R_{CA})$$

The cyberspatial object, the state values, the metarelational cybermap, and the network design principle (the rules set) constitute a dynamic cyberspatial map, capable of modeling additional generalization with edges non-uniformly distributed and extension of classic CA to an irregular neighborhood as network automata. The relational and metarelational cyber mapping express influential or situational information in the forms of cyberspatial maps, and the potentiality to define a set of operations within and between different set of entities so that the topological and situational based information be integrated and processed.



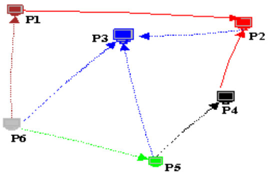
	P1	P2	P3	P4	P5	P6
P1	0	1	0	0	0	0
P2	0	0	1	0	0	0
P3	0	0	0	0	0	0
P4	0	1	0	0	0	0
P5	0	0	1	1	0	0
P6	1	0	1	1	0	0

1) Cybermap interaction and Connectivity



	P1	P2	P3	P4	P5	P6
P1	0	**1**	0	0	0	0
P2	0	0	0	0	0	0
P3	0	0	0	0	0	0
P4	0	**1**	0	0	0	0
P5	0	0	0	0	0	0
P6	0	0	0	0	0	0

2) Influence on position **P2**



	P1	P2	P3	P4	P5	P6
P1	0	1	0	0	0	0
P2	0	0	1	0	0	0
P3	0	0	0	0	0	0
P4	0	1	0	0	0	0
P5	0	0	1	1	0	0
P6	1	0	1	0	1	0

3) Metarelational cybermap for Cybermap interaction

Fig. 4 Cyberspatial map, relational map, and metarelational cybermap

Another important factor in cyberspatial mapping is time. In this context, we provide the Newtonian absolute time within Minkowskian coordinates to comprehensively describe the dynamics of cyberspatial mapping. A Cyberspatial map consists of position P and an associated set of states S, at a time T. The cyberspace unit is then denoted by $P \times \mathrm{T} \times S$ and thus cyberspatial map as a function from a set of entities in a position at a certain time $P \times \mathrm{T}$ to a set of states S, $\boldsymbol{M}^{\mathbb{C}}: P \times \mathrm{T} \to S$ defined by:

$$\boldsymbol{M}^{\mathbb{C}} = \{((p_i, t), m(p_i, t)) : (p_i, t) \in P \times S, m(p_i, t) \in S\}$$

For the cyberspatial position $(p_i, t) \in P \times S$ in time $t \in \mathrm{T}$, and state $m(p_i, t) \in S$ of the object at that position.

With time explicitly defined, the cyberspatial map is a series of time shot of slices. A time shot of a cyberspatial map $\boldsymbol{M}^{\mathbb{C}}$ at a time $t_i \in T$ is now $\boldsymbol{M}^{\mathbb{C}}: P \times \mathrm{T} \to S$ to $P \times \{t_i\}$, Precisely $m_{t_i}: P \times \{t_i\} \to A$ such that $m_{t_i}(p_i, t) = \mathrm{m}(p_i, t)$: for $(p_i, t) \in P \times \{t_i\}$

The notion of cyberspatial map time shot allows the description of cyberspatial map dynamics: $(\{T, A^P, (A^P)^P, (\{0,1\}^P)^P\}, \{\otimes, g\})$ where g is the dynamic universal influence function given by $m_{t+p_i} = g(m_t \otimes R)$

The cyberspatial map slice at a time t_0+k is recursively determined from the initial cyberspatial map at the time t_0 by : $m_{t_0+k} = g(\ldots(g(g(m_{t_0} \otimes R) \otimes R)\ldots) \otimes R)$ this formed as series of cyberspatial map time shots $m_{t_0} m_{t_0+1} m_{t_0+2} \ldots m_{t_0+k}$ which we called ***cyberspatial map dynamics.***

The space in classical formalism is generally taken to be a single plane corresponding to a particular attribute under which to be modeled, which does not consider the interactions among multiple numbers of attributes. To deal with dynamic interactions among multiple map layers corresponding to multiple variables and attributes, the

framework of a cyberspatial map dynamics is extended into a multi-layer (or multi-variate) map dynamics.
Given the set of attributes or the entities:

$$A = \prod_{i=1}^{z} A_i$$

The multilayered cyberspatial map is given by:

$$m: P \rightarrow \prod_{i=1}^{z} A_i$$

and the multilayered cyberspatial map at a time is given by:

$$m: P \times T \rightarrow \prod_{i=1}^{z} A_i$$

Where $m = (m_{t_0}, m_{t_0+1}, m_{t_0+2} \dots m_{t_0+m-1})$ and $m_{t_j} = m|p \times \{t_j\}$

4. Network Automata

As "The spatial structure underlying such CA models is most conveniently described and understood as a graph" [61], relaxing the neighborhood restriction of classical cellular automata, such that cells can have a different neighborhood, enables the establishment of various relations between the entities.

From the Cyberspace multilayer network of entities a pair $\mathrm{T} = (\mathrm{L}, \mathcal{C})$ we consider a single layer of cyber-physical entities as a homogenous set of cyber entities, such that the network G_α is given by $G = (E, \mathrm{C})$ where $E = \{\mathrm{e}_1, \mathrm{e}_2 \dots, \mathrm{e}_n\}$ is an ordered non-empty finite set of the entities, and $\mathrm{C} = (\mathrm{e}_i, \mathrm{e}_j)$ is the connectivity or the set of edges as finite pair of elements in E; two entities are said to be adjacent (or neighbors) and hence influence each other if the edge between them exists. The adjacency matrix of the entities network is $A = \left(a_{ij}\right) \in \mathbb{R}^{N \times N}$ where

$$a_{ij} = \begin{cases} 1 \; if \; (\mathrm{e}_i, \mathrm{e}_j) \in \mathrm{C} \\ 0 \quad otherwise \end{cases}$$

For $1 \leq i, j \leq N$ and $1 = \alpha = M$.

The neighborhood of an entity $\mathrm{e}_i \in E$, $\mathrm{N}_{\mathrm{e}_1}$, is the set of all entities of G which are adjacent to e_i, that is, $\mathrm{N}_{\mathrm{e}_1} = \{\mathrm{e}_j \in E$ such that $(\mathrm{e}_i, \mathrm{e}_j) \in C\}$. The degree of a node e_i, de_i, is the number of its neighbors.

Therefore, the network automata defined on a network G is a 4-tuple $CA = (E, S, N, f)$ where:

- The set $E \subseteq \mathbb{Z}^d$ is a d-dimensional space which defines the cellular space of the CA such that each cell is of the form $\mathrm{e} = (e^1, e^2, \dots, e^d)$ where each coordinate $e^i (i = 1, 2, \dots, d)$ is the reference frame and for simplicity represented as an integer
- S is a non-empty finite set of states that can be assumed by the entities at each time t. The state of an entity e_i is denoted by $s_i^t \in S$ generated according to transition function f.
- N is a neighborhood function which assigns to each entity its neighborhood $N: E \rightarrow 2^E$

  $\mathrm{e}_i \rightarrow N(\mathrm{e}_i) = \mathrm{N}_{\mathrm{e}_i} = \{e_{i1}, e_{i2}, \dots, e_{i\mathrm{d}_{ei}}\}$

  where each coordinate e is a vector of d integers.
- f is a transition rule/function $f: S^k \rightarrow S$ which is defined as:

  $s_e^{t+1} = f(s_{e_{i1}}^t, s_{e_{i2}}^t \dots, s_{e_{i\mathrm{d}_{ei}}}^t) \in S$, where $s_{e_{i\mathrm{d}_{ei}}}^t$ is the state of the entity $e_{i\mathrm{d}_{ei}}$ at time t.

A configuration of the automaton is a function $c = E \rightarrow S$ given by $c = \{(\mathrm{e}_i, c(\mathrm{e}_i)) | \mathrm{e}_i \in E\}$ where $\mathrm{c}(\mathrm{e}_i) \in S$ therefore $\mathrm{c}(\mathrm{e}_i) = \mathrm{s}_{\mathrm{e}_i}$. The configuration expresses the assignment of an automaton state to every node of the CA space and represents a global state obtained by the simultaneous sum of the local transition function to each node.

Given a set of all configurations, S^e for Given cellular space, E, position, P, and $e \subseteq \mathbb{Z}^d$, a universal transition function F is a rule $F: S^e \rightarrow S^e$ defined as:

$$F(c)(e) = f(c(e + e_{i1}), \dots, (c(e + e_{i\mathrm{d}_{ei}}))$$

This implies that the concurrent application of local transitions rules f to all nodes of the space results in a universal function.

4.1 Result and discussion

Our formalism, inherent from network theories, allows model structures to be described, explored, and represented in many ways. The graph-theoretic framework enables us to specify model structures precisely.
Consistent with the graph CA, various models structured can be defined or analyzed with our formalism, including multilayered network CA. One of the potential structures is the hierarchical structure, as cyberspace consists of a large number of interconnected Cyberphysical systems and autonomous systems.
A multilayer network automaton is a graph-CA divided into a set of subgraphs $\{\mathrm{G}_\alpha; \alpha \in \{1, \dots, \mathrm{M}\}\}$ each $\mathrm{G}_\alpha = (\mathrm{E}_\alpha, \mathrm{C}_\alpha)$ forming a layer or subnetwork. Usually, the distinct subgraphs are nonoverlapping such that $\mathrm{E}_\alpha \cap \mathrm{E}_\beta \; \forall \alpha, \beta$.

Considering an ordered partitioning of the subgraph G_α such that $\mathrm{E}_{\alpha\,\beta} = \emptyset \Leftrightarrow |\alpha - \beta|$, then the multigraph CA is layered. For example, the hierarchical model of cyberspatial entities as an autonomous system such as

Transit-stub and Tiers structural topology generator of the internet model can be depicted (Fig. 5). A Transit domain could be a Wide Area Network (WAN) or Metropolitan Area Network (MAN), basically a regional or a national Internet Service Provider (ISP) while a Stub consists of other interconnected Local Area Networks (LAN).

The three layers of entities (shown in Fig. 5(a) as a physical (geo-spatial) layer, logical layer, and information layer) can be depicted, consistent with the previous formal description. An entity in a given layer will be affected by the behavior of other entities in the same layer as they interact and will send/receive feedback to/from a relative entity from an immediate or subsequent layer.

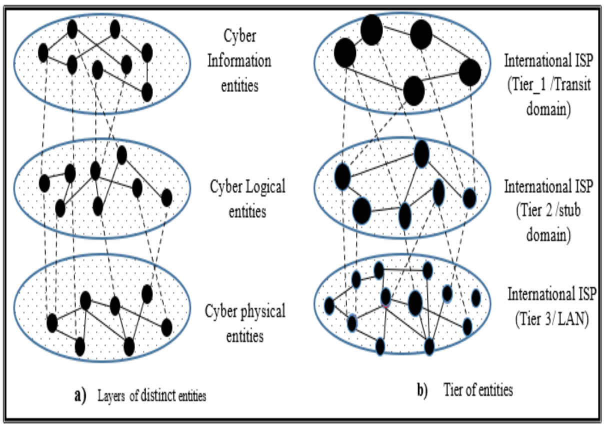


Fig. 5 Interpretation from a network perspective.

Also, structural measures for the topology description are enabled. With the automaton running on a graph (network), the variety of ways to describe, measure, and explore the structural properties of the model from graph-theoretic perspectives are possible. There are many statistical features of graph structures available such as the size of the largest connected component, link density, node degree relationships, the graph diameter, the characteristic path length, the clustering coefficient, and the betweenness centrality. The most widely considered property is the node degree distribution, which is validated by finding a particular pattern, for example, power law. The ubiquitous recognition of power laws in engineering, geophysics, biology, astrophysics, technology, etc. is seen as proof of self-organized criticality and the edge of chaos concepts [62] [63] [64]. Power laws are intrinsic in the interconnected system; these two features are not the only origin of a power law.

Axiom: Cyberspatial map is homomorphic to the Cellular automata.

Consider any $CA = (E, S, N, f)$ and a cyberspatial map $\boldsymbol{M}^{\mathbb{C}} = \{(p_i, m(p_i)) \colon p_i \in P, m(p_i) \in A\}$ and let functions h_1 and h_2 be $h_1 \colon E \rightarrow P$ and $h_2 \colon S \rightarrow A$. That is, the set of positions and the attributes set are defined such that these two functions are injective. For every coordinate of e of the cellular space and every location $p_i \in P$ of the cyberspatial map, $h_1(\mathrm{e}) = h_1(p_i) \rightarrow \mathrm{e} = p_i$. Then a mapping between the automaton configuration and the cyberspatial map can be induced $\text{ɧ} \colon \rightarrow S^E \rightarrow A^P$, defined by $\text{ɧ}(c) = \{(h_1(\mathrm{e}_i), h_2(c(\mathrm{e}_i))) | \mathrm{e}_i \in E\}$ Where A^P, is the set of all cyberspatial map. Thus, any configuration of the CA, c is equivalent to the cyber map, m as the functional relation is maintained.

Given h_1 and h_2, any neighborhood $\mathrm{N}_{\mathrm{e}_i} = \{e_{i1}, e_{i2}, \dots, e_{i\mathrm{d}_{ei}}\}$ is also equivalent to the metarelational influence map $R = \{(p_i, R_i)\}$, $R \in (\{0,1\}^{\mathrm{P}})^{\mathrm{P}}$ defined by:

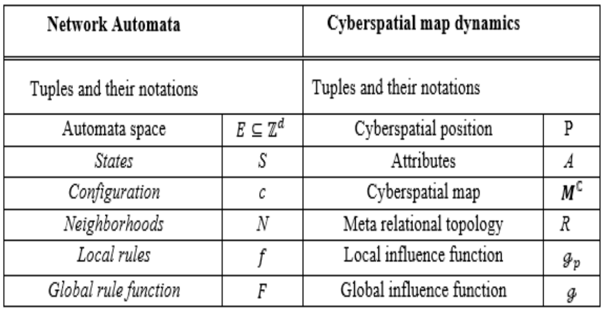
$$R_{p_i}(p_j) = \begin{cases} 1 & p_i = h_1(\mathrm{e}_i) \; and \; p_j \in \{h_1(e_{i1}), \dots . h_1(e_{i\mathrm{d}_{ei}})\} \; for \text{ some } \mathrm{e}_i \in E \\ 0 & otherwise \quad p_i, p_j \in P \end{cases}$$

Similarly, we establish a correspondent between transition rule f and local influence function, a function that transforms each cybermap value associated with each position in $R_p$into a new value at the position p_i: denoted by $\mathscr{g}_p$. Where $\mathscr{g}$ is the universal influence function computed from the parallel application of the local functions to all the positions of a relational cyberspatial map, which can be spatially homogeneous or heterogeneous. The values at each of the influencing locations area computed from a combined operation between the cyber map m and the meta relational map R, resulting in an integrated new R denoted $\mathscr{g}(M \otimes R)$. Therefore, an arbitrary transition rule f can be mapped to an influence function $\mathscr{g}_{p_i}$ as given by:

$$\mathscr{g}_{p_i}(M \otimes R_{p_i}) = \begin{cases} h_2\left(f\left(c(e + e_{i1}), \dots, c(e + e_{i\mathrm{d}_{ei}})\right)\right) & for \text{ some } e, p_i = h_1(e) \\ 0 & otherwise \;\; p_i \in P \end{cases}$$

Therefore, $\boldsymbol{\mathscr{g}(m \otimes R)} = \textbf{ɧ}\ \boldsymbol{(F(c))}$**,** and thus, the **universal influence function simulates** precisely the same behavior as that of the CA. As such, for any arbitrary cellular automaton $CA = (E, S, N, f)$, we can have a dynamics model $(\{T, A^P, (A^P)^P, (\{0,1\}^P)^P\}, \{\circledast, \mathscr{g}\})$ which is homomorphic M. Table 1 below shows the correspondence.

Table 1: Network automata and cyberspace dynamics.



Network Automata		**Cyberspatial map dynamics**	
Tuples and their notations		Tuples and their notations	
Automata space	$E \subseteq \mathbb{Z}^d$	Cyberspatial position	P
States	S	Attributes	A
Configuration	c	Cyberspatial map	$\boldsymbol{M}^{C}$
Neighborhoods	N	Meta relational topology	R
Local rules	f	Local influence function	g_p
Global rule function	F	Global influence function	g

We found a discrete mathematical model at the intersection of cyber disciplines—cyber information, cyber science, and cyber philosophy bridged by Cyberlogic [27]. This set a foundation for questions such as: To what extent is cyberspace augmented by the theory in physics, the network theory, and agent modeling paradigms? Does the concept of absolute and relative space help to explain and/or advance the theory of cyberspace? What concepts of network theory can be readily re-appropriated? And, can the network-based agent model help to describe the cyberspatial object dynamics? and what hint can be used to have an integral model? This paper proposes application of network cellular automata framework characterizing cyberspace, improving both theory and applications towards the answers to these questions. The generalized CA capable modeling cyberspace as linked to the relative and absolute notion of space, and consistently implementable through integration with matrix-algebra and network theory. The power of the CA as defined by important properties, such as its evolutionary structure, Self-organization, Self-repairing, and distributed computation, are potentially utilized.

5. Conclusions

Cyberspace has been approached from different disciplines and approaches and not much has been done in formulating characteristic dynamics, complexity, multidimensional, and multi-temporal features. A basic correlation between cyberspace and existing theories from three fields has been shown to enable defining the concepts of space and time in cyberspace and to explain the principles governing the evolution of cyberspace.

We have shown that cyberspace can be characterized by cyberspatial map dynamics. Network automata is a generalization of standard Cellular automata modeling, defined with the cyberspatial map which is a mathematical generalization of cyberspatial objects characterizing the dynamic and structure of cyber-physical systems. Through graph theory representing spatial structure and generalized cellular automata depicting the dynamic process, we provide a novel foundation and found that the cyberspatial map is homomorphic to the network automata. As networked of entities best topologically explained using the graph theory, cyberspace topological structure is coupled with the dynamical processes as known from some properties inherent in networks such as fault-tolerant properties and the spreading of epidemics.

With evolving concepts of cyberspace across multiple disciplines, we have outlined several key issues toward the general theory of cyberspace and its modeling, such as:

- Cyberspatial dynamics in time: An existence of spatial framework to characterize various types of cyberspatial entities and cyberspace manifold.

- Multidisciplinary cyberspace: Homogenous and heterogeneous entities and ubiquity of cyberspace conception across various fields entail pre-existing and new theories.

- Cyberspatial map: A meaningful basis to replace mental space conception of cyberspace.

We, therefore, provide a theoretical foundation that for a deeper research on those key issues to advance the cyber theory development.

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