TU Wien

Emergence in Cyber-Physical System of Systems (CPSoS)

H.Kopetz

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together with A. Bondavalli, F. Brancati,B. Frömel, O.Höftberger, S. Jacob

Outline

- Introduction
- Multi-Level Hierarchy
- Definition of Emergence
- Classification of Emergence
- Emergence in Safety-Critical Systems
- Conclusion

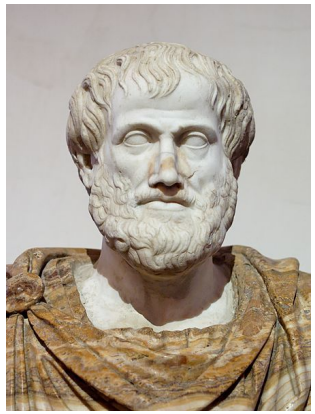
The *Essence* of *Emergence*

*The Whole is Greater than the Sum of its Parts**

The Level of the Whole: The *CPSoS*

The Level of The Parts: The Cyber-Physical Systems (CPSs)

Emergent (Novel) Phenomena come about by the ***interactions*** *of the parts*.



***Aristotle**

Born: in Stageira, Greece February 20, 0384

Died: June 04, 0322

Emergent Structures vs. *Behavior*

The novel phenomena can be *structures*, *behavior* or *properties*.

In *System of Systems* we are primarily interested in *emergent behavior.*

Emergent behavior is ***diachronic*** and is associated predominantly with *control hierarchies*.

Emergent Behavior	Beneficial	Detrimental
Expected	Normal Case	Avoided by Design
Unexpected	Pleasant Surprise	Problematic

Emergence: *Understand* Multi-Level Hierarchies

The phenomenon of *emergence* is always associated with levels of a *multi-level hierarchy.*

- The understanding and analysis of the immense variety of things and their behavior in the non-living and living world around us requires appropriate *modeling structures*.
- Such a *modeling structure* must limit the overall complexity of a *single model* and support the step-wise integration of a multitude of *different models*.
- One such widely identified modeling structure is that of a *multi-level hierarchy.*
- Each level of a hierarchy possesses its unique set of laws.

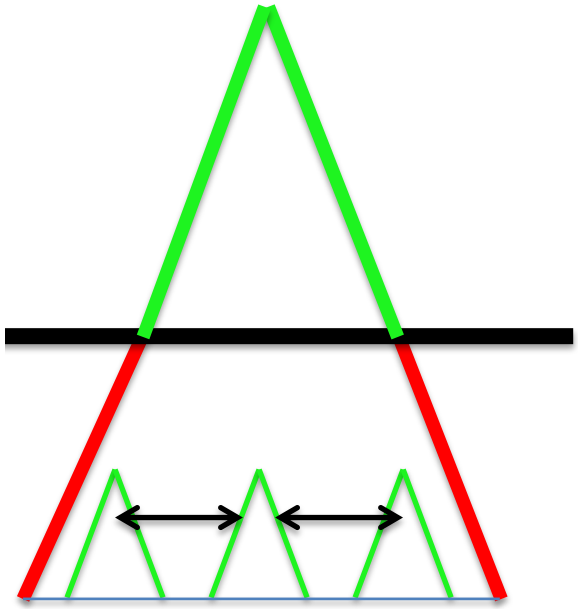
If there are important systems in the world that are complex without being hierarchic, they may to a considerable degree escape our observation or understanding (Simon, 1969, p.219]

Recursion in a Multi-Level Hierarchy

- A *multi-level hierarchy* is a recursive structure where a system, the *whole* at the level of interest (the *macro-level*), can be *taken apart* into a set of sub-systems, the *parts (holons)*, that *interact* statically or dynamically at the level below (the *micro-level*).
- Each one of these sub-systems can be viewed as a *system of its own* when the *focus of observation* is shifted from the level above to the level below.
- This *recursive decomposition* ends when the internal structure of a sub-system is of no further interest.
- We call such a sub-system at the lowest level of interest an *elementary part* or a *component*.

The *Holon: An Entity of a Two-Level Hierarchy*

Whole
(Macro-Level)



Parts
(Micro-Level)

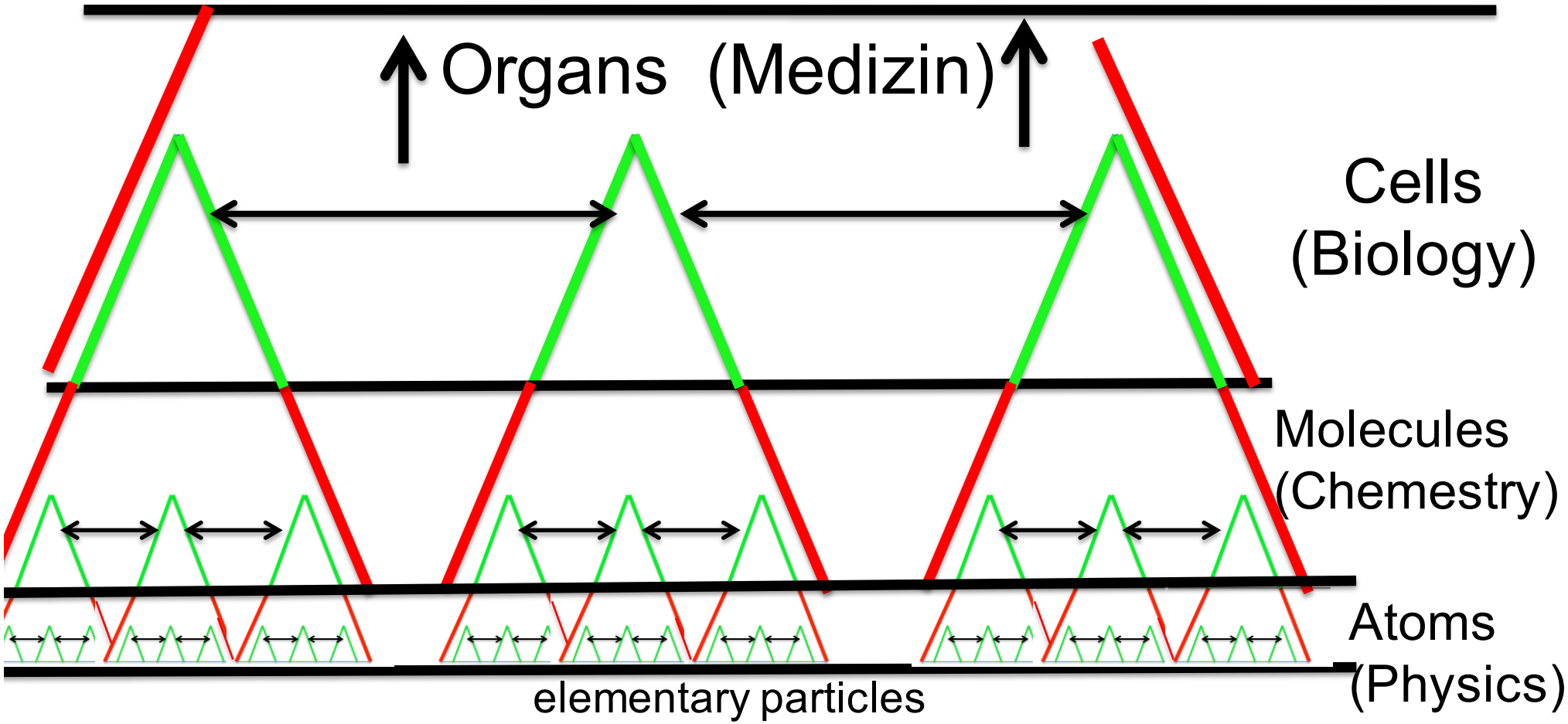
Holon

Koestler has introduced the term *holon* to refer to the *two-faced character* of an entity that is considered a whole at the *macro level* and an ensemble of parts at the *micro level*.

The word *holon* is a combination of the Greek "*holos*", meaning *all*, and the suffix "*on*" which means *part*.

Viewed from the outside, the *macro level*, a holon is a *stable whole* that can be accessed by an interface across its surface(green line). Viewed from below, the *micro-level*, a holon is characterized by a set of *confined interacting parts.*

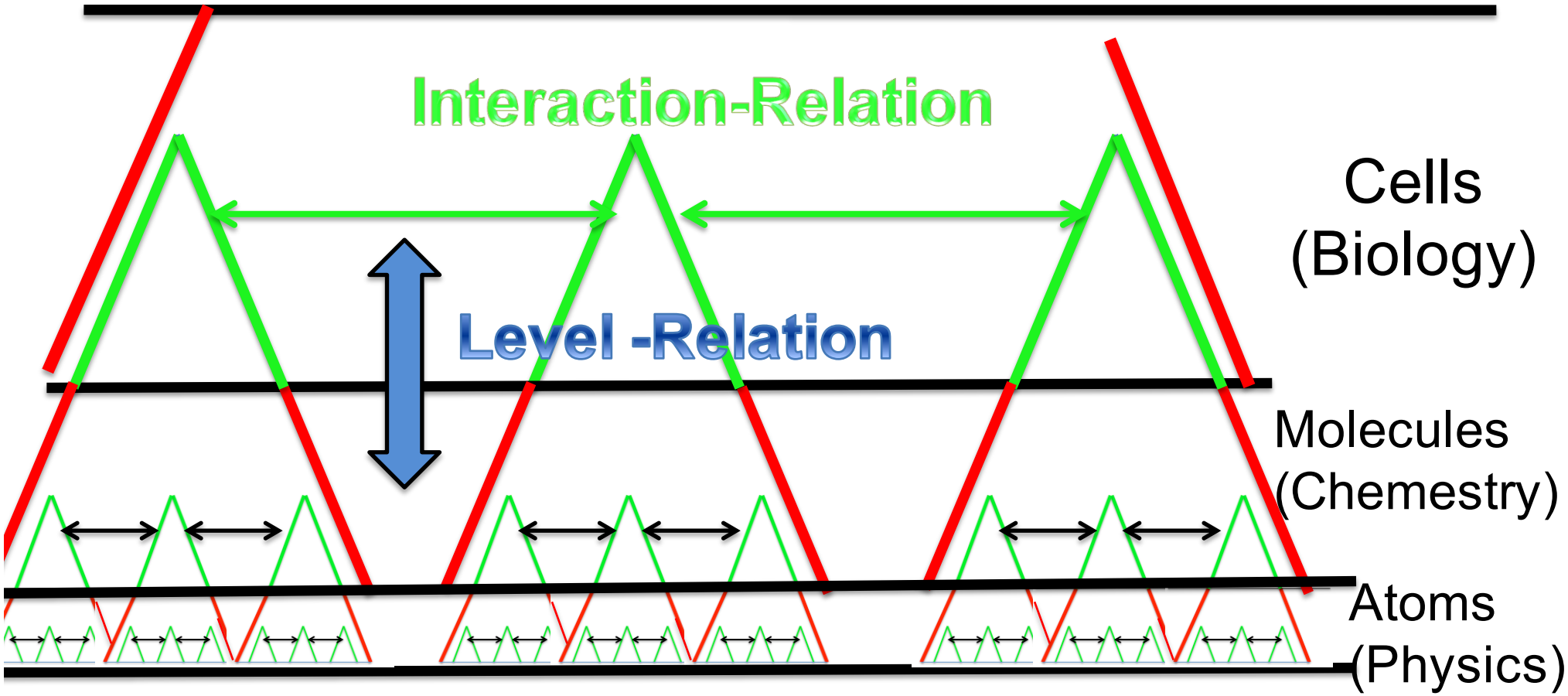
Multi-level Hierarchy (*Holarchy*)



Surface without Interactions

Surface supporting Interactions

Multi-level Hierarchy (*Holarchy*)



Surface without Interactions

Surface supporting Interactions

Level Relations

(i) Containment: The Whole *contains* or *consists of* the parts, forming a *nested* hierarchy.
Example: Hierarchy of *atoms*, *molecules*, *cells* . . .

(ii) Control: The Whole *constrains* the Behavior of the parts
Example: Blinking of Fireflies

(iii) Description: The Parts can be described at different levels of abstraction
Example: Conway's Game of Life.

It is important to note that the different *level relations are non exclusive*. From the point of view of behavior, the control hierarchy is most relevant.

Control Hierarchy

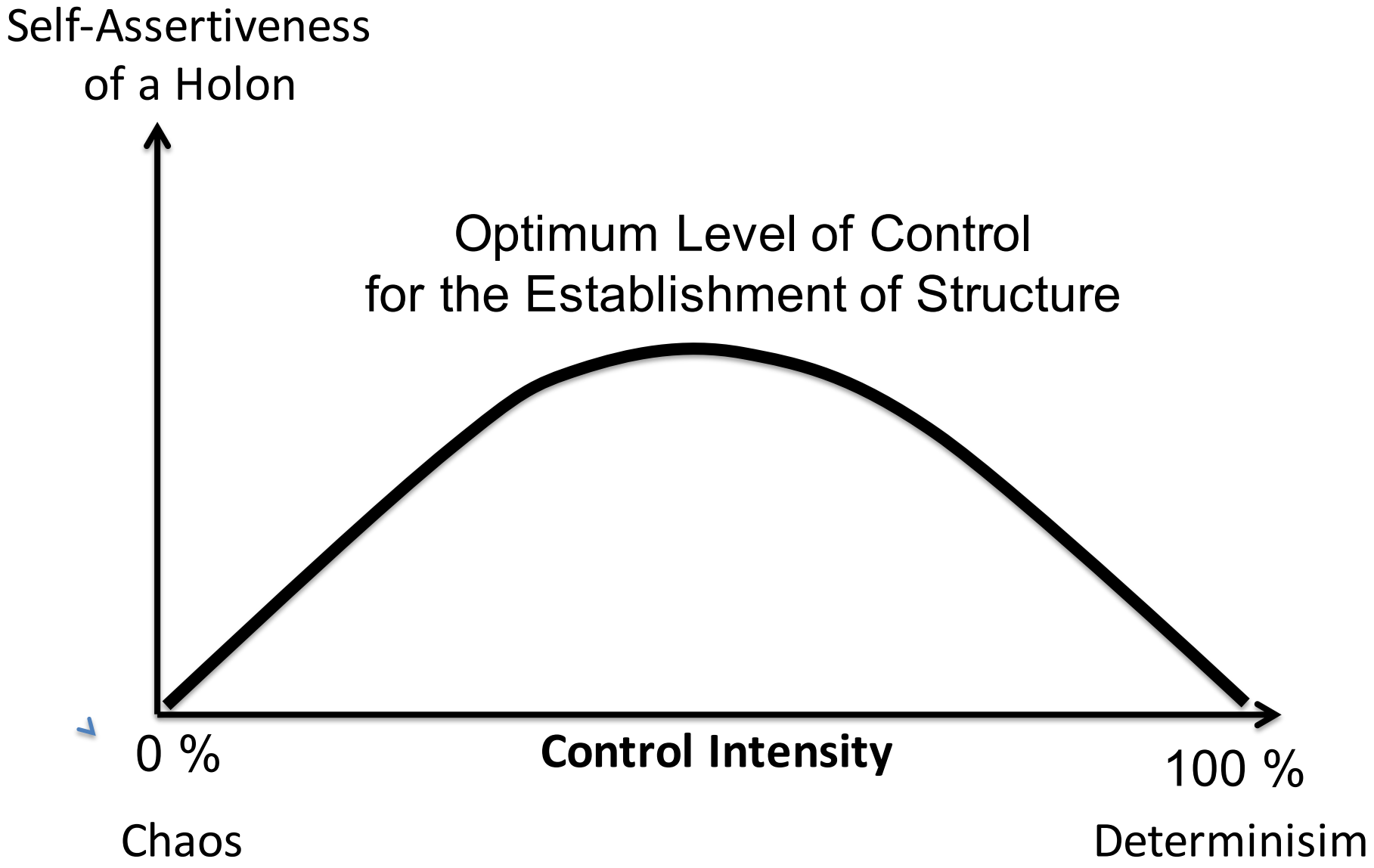
In order to support the simplification at the macro-level and establish a hierarchical control level, a *control hierarchy* must

- on the one side *constrain* some degrees of freedom of the behavior of the parts but
- on the other side must *abstract from*, i.e. *allow* some degrees of freedom of behavior to the parts at the micro-level.

The delicate borderline between *the constraints from above on the behavior of the parts* and *the freedom of the behavior of the micro-parts* is decisive for the proper functioning of any control hierarchy.

Conductor vs. Orchestra

Self Assertiveness in a Control Hierarchy



Sources of *Control*

We distinguish between two sources of control:

- *Authority from the outside*, e.g. the authority of a *General* over the *Soldiers* in a military hierarchy
- *Authority form the inside*: The ensemble of parts at the *macro level* exercises control over the individual parts at the *micro level*. This implies that the higher level is equipped with causal powers of its own so that it can inflict effects on the lower level that is causing it.

From the point of view of *emergence*, *authority from the inside* is most relevant.

Interaction Relations

- **Physical Interactions**: come about by force fields, (e.g, electromagnetic or gravitational fields). They are *synchronic*. Physical structures (e.g, a molecule) are mainly formed by force fields.
- **Informational Interactions**: come about the exchange of *Itoms*, either across message channels or stigmergic channels. They are *diacronic*. Emergent behavior in systems-of-systems is caused by informational interactions.

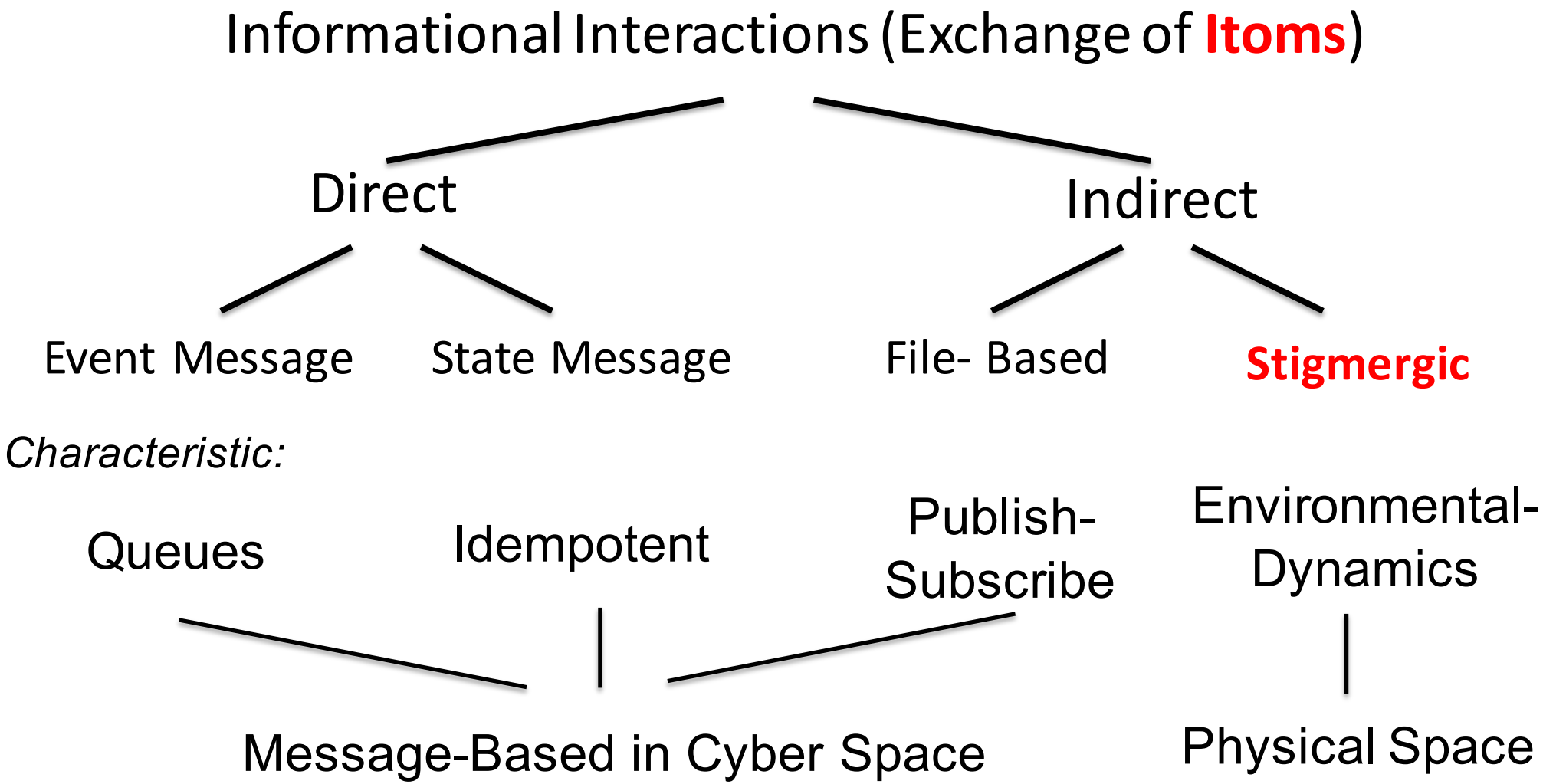
Physical Interactions

Physical interactions are characterized by

- ***distance*** among the parts,
- ***force fields*** among the parts,
- r**elaxation time** or ***frequency of interactions*** among the parts

When we move up the levels of a material hierarchy the *distances increases*, the *force-field decrease* and the *frequency of interactions* decrease.

Informational Interactions



Information Item: The concept of an *Itom*

An ***Information Item*** *(Itom)* is a ***timed proposition*** *about some state or behavior of the world*.

In cyber space, an *Itom* consists of an **atomic triple**: ***a bit pattern (the data),*** an ***explanation of the bit-pattern*** and an ***instant of time***.

- While the *data* is carried explicitly in a message, the ***explanation and the time*** **are often implied by context**.
- In a *SoS the* ***context and the time of the sender can be different from the context and the time of the receiver*****.**

If this is the case, then a message that carries *data* without an explanation can be interpreted differently by the sender and the receiver who reside in different contexts.

Example: **30º F** is *different* from **30º C**

Data versus *Information in an SoS*:

Germany

90 €

ATM Transaction

United States

100 US $

The *time-dependent* monetary value, i.e, the *semantic content or the information* of the transaction, is the same in both contexts, but the *data* in the different constituent systems of the SoS are different

.

Stigmergic Channels

- **A *stigmergic information channel* is present if one CPS (Cyber-Physical System) acts on the environment common to many CPSs, changes the state of this physical environment and another CPS observes *relevant properties* of the changed state at some later point in time by a sensor.**
- *Itoms exchanged over stigmergic channels* are derived from the current state of the *physical environment* (not the cyber space) which is observed by a *sensor*. The design of a sensor provides the explanation of the bit pattern produced by a sensor.
- Stigmergic Itoms are exposed to the full spectrum of ***environmental dynamics***.

Traffic Flow

The information flow among drivers on a busy road is mainly of the *stigmergic* type.

Definition of Emergence

The essence for the occurrence of emergent phenomena at the macro-level lies in the *organization of the parts*, i.e., in the *static* or *dynamic relation among of parts* caused *by physical* or ***informational interactions*** among the parts at the micro-level.

A phenomenon of a whole at the macro-level is emergent if and only if it is *of a new kind* with respect to the non-relational phenomena of any of its proper parts at the micro level.

Conceptual Novelty at the macro-level relative to the *world of concepts at the micro-level* is thus the landmark of our definition of emergence.

Conceptualization at the Macro-Level

- Novel concepts must be formed and new laws may have to be introduced at the macro to be able to describe the emerging phenomena appropriately.
  Example: *liquidity*, *hydrodynamic laws.*
- Since the concepts at the macro level are new with respect to existing concepts that describe the properties of the parts, the established laws that determine the behavior of the parts at the micro-level will probably not embrace the new concepts of the macro-level.
- **It is necessary to formulate inter-ordinal laws (also called *bridge laws*) to relate the established concepts at the micro-level with the new concepts of the macro-level.**

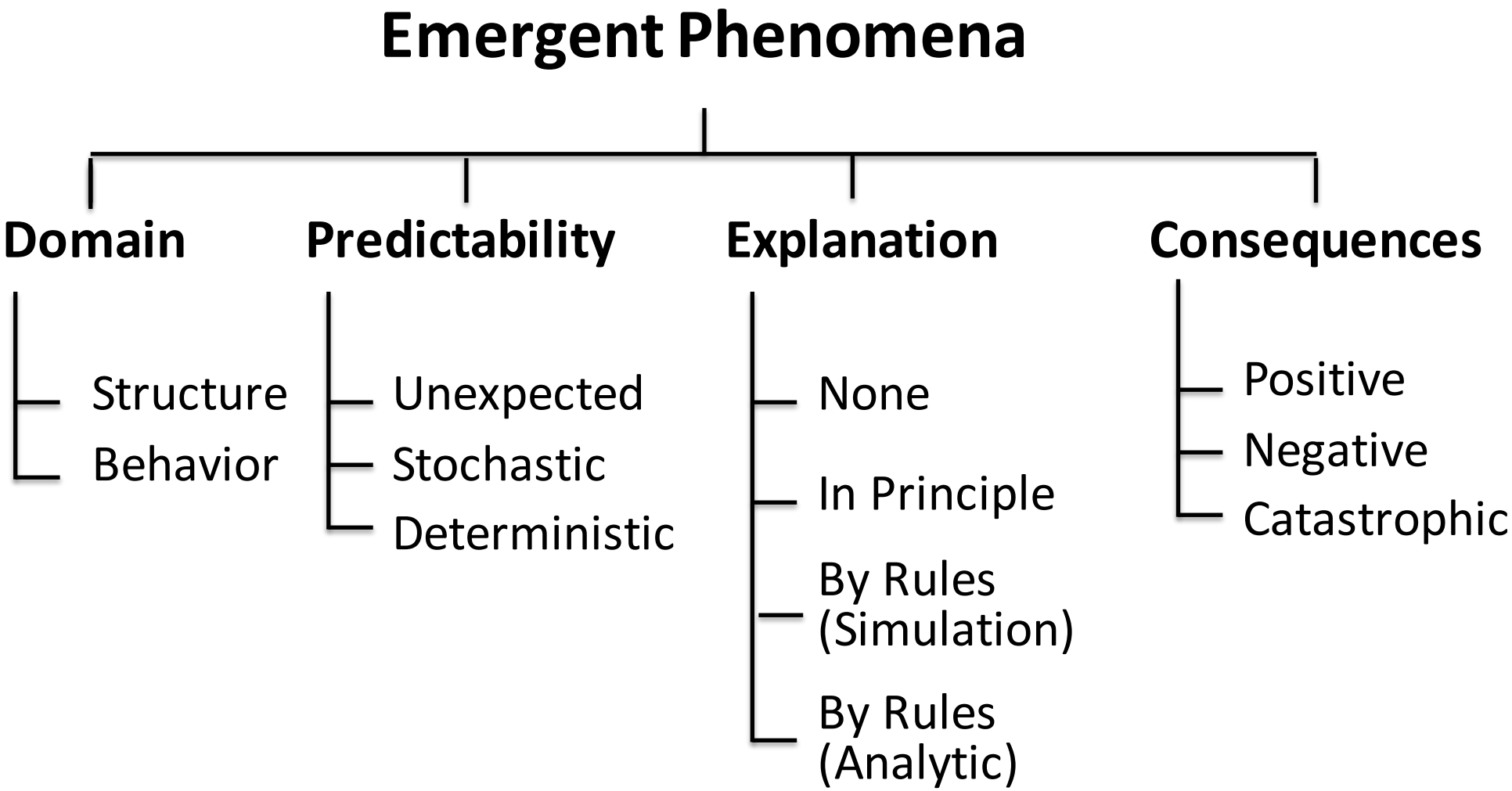
Emergence is our *Friend*, not our Enemy

The proper conceptualization of emergent phenomena can lead to an abrupt simplification at the next higher Level.

Examples:

- Fault-Tolerant Distributed Clock Synchronization → leads to the new concept of a *Dependable Global Time*
- The interactions among set of properly connected transistors → A *new whole* the behavior of which can be described by the concepts of *Boolean Logic.*
- A multitude of gas atoms leads to a *new whole* that can be characterized by the new concept *pressure*.

Types of Emergence



Classification of Emergence by *Explanation*

Classification by Explanation is relative to the state of *knowledge* (or the state of *ignorance*) —it may change as knowledge is increased:

- No explanation as of today — mind over neurons
- Explanation in principle—stock market crash
- Explanation by simulation—air traffic example
- Explanation by logic reasoning— clock synchronization

Explained vs. *Unexplained* Emergence

A number of philosophers take the view that a phenomenon at the macro-level is only emergent if it cannot be explained by (is not *reducible* to) the *state of knowledge* about the properties and laws that govern the parts at the micro-level.

There are two open questions concerning this definition:

- What constitutes an acceptable explanation?
- What is the reference for the *state of knowledge*?

If the state of knowledge of one person differs from the state of knowledge of another person, a phenomenon that is classified as emergent by one person is not called emergent by the other person.

Scientific Explanation

Hempel and Oppenheim outlined a general schema for a scientific explanation of a phenomenon as follows:

Given

Statements of the antecedent conditions

and

General Laws

then a logical deduction of the

Description of the empirical phenomenon to be explained

is entailed.

The *antecedent conditions* can be *initial conditions or boundary conditions* that are *unconstrained* by the general laws.

General Laws vs. *Rules*

A weaker form of explanation is provided if the *general laws* in the above schema are replaced by *established rules.* There are fundamental differences between general laws and established rules.

- General laws are *inexorable* and *universally* valid while established rules are *structure dependent* and *local.*
- Rules about the behavior of things are based on more or less meticulous experimental observations in *a limited context.*

A special case is the introduction of *imposed rules*, e.g., the rules of an artificial game, such as chess.

The degree of accuracy and rigor of various explanations differ substantially.

Explanation vs. Causation

Unidirectional cause-effect relations that *explain* a phenomenon play a prominent role in our subjective models of the world.

However, themeaning of the concept of *causation* is highly controversial in the field of modern physics, such as *quantum mechanics*.

To quote Pattee:

I believe the common everyday meaning of the concept of causation is entirely pragmatic. In other words, we use the word cause for events that might be controllable . . . the value of the concept of causation lies in its identification of where our power and control can be effective. . . . when we seek the cause of an accident, we are looking for those particular focal events over which we might have had some control. We are not interested in all those parallel subsidiary conditions that were also necessary for the accident to occur, but that we could not control . . . .

Downward Causation → *Causal Loop*

The interaction of the parts at the micro-level cause the whole at the macro-level while the whole at the macro-level can *constrain* the behavior of the parts at the micro-level. This *is downward causation*—resulting in a *causal loop*.

We conjecture that in a multi-level hierarchy emergent phenomena can only appear if there is a causal-loop formed between the micro-level that forms the whole at the macro-level and this whole (i.e., the ensemble of parts) that constrains the behavior of the parts at the micro-level.

According to our opinion *linear cause and effect relations cannot* provide an explanation for the occurrence of emergent phenomena.

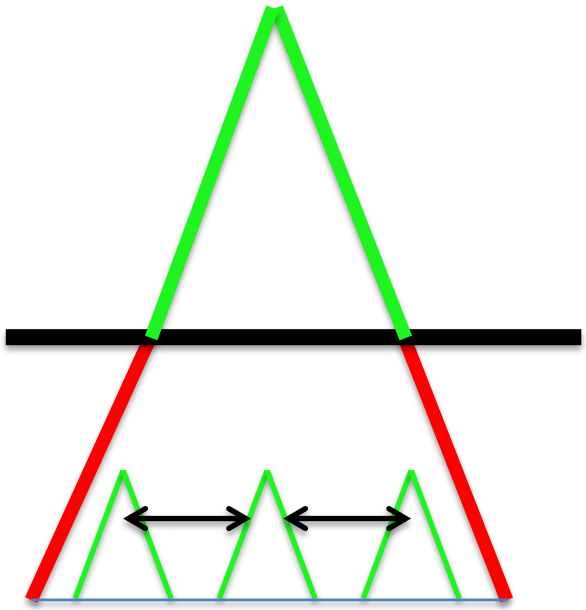
Example: Fault-Tolerant Clock Synchronization

In a fault-tolerant system with 3k+1 clocks, k clocks can fail in an arbitrary failure mode without a loss of the *global time*.

- What is the novel phenomena? Tolerance of Clock Failures
- Is Fault-Tolerant Clock Synchronization explainable? yes
- *Downward causation:* the *time average* of the ensemble of clocks enforces a *state correction of a local clock.* The frequency of a *physical clock* cannot be changed (upward causation).
- Is the phenomenon predictable? Yes.
  If a local clocks does not work according to the rules of the synchronization algorithm, it is considered *failed* and expelled from the ensemble.

Upward and *Downward* Causation

Whole
(Macro-Level)



Parts
(Micro-Level)

Holon

Downward Causation by the ensemble of parts or from an outside authority.

Free behavior of the parts constrained by upward and downward causation.

Upward Causation by the laws of physics or from other imposed laws.

Supervenience

Supervenience is a relation between the emergent phenomena of adjacent levels in a hierarchy:

- **Sup_1:** A given emerging phenomenon at the macro level can emerge out of many different arrangements or interactions of the parts at the micro-level
- **Sup_2:** A difference in the emerging phenomena at the macro level requires a difference in the arrangements or the interactions of the parts at the micro level.

Because of *Sup_1* one can abstract from many different arrangements or interactions of the parts at the micro level that lead to the same emerging phenomena at the macro level.

Sup_1 leads to *Simplification*

The proper conceptualization of the new phenomena at the macro level is at the core of the simplifying power of a multi-level hierarchy with emergent phenomena.

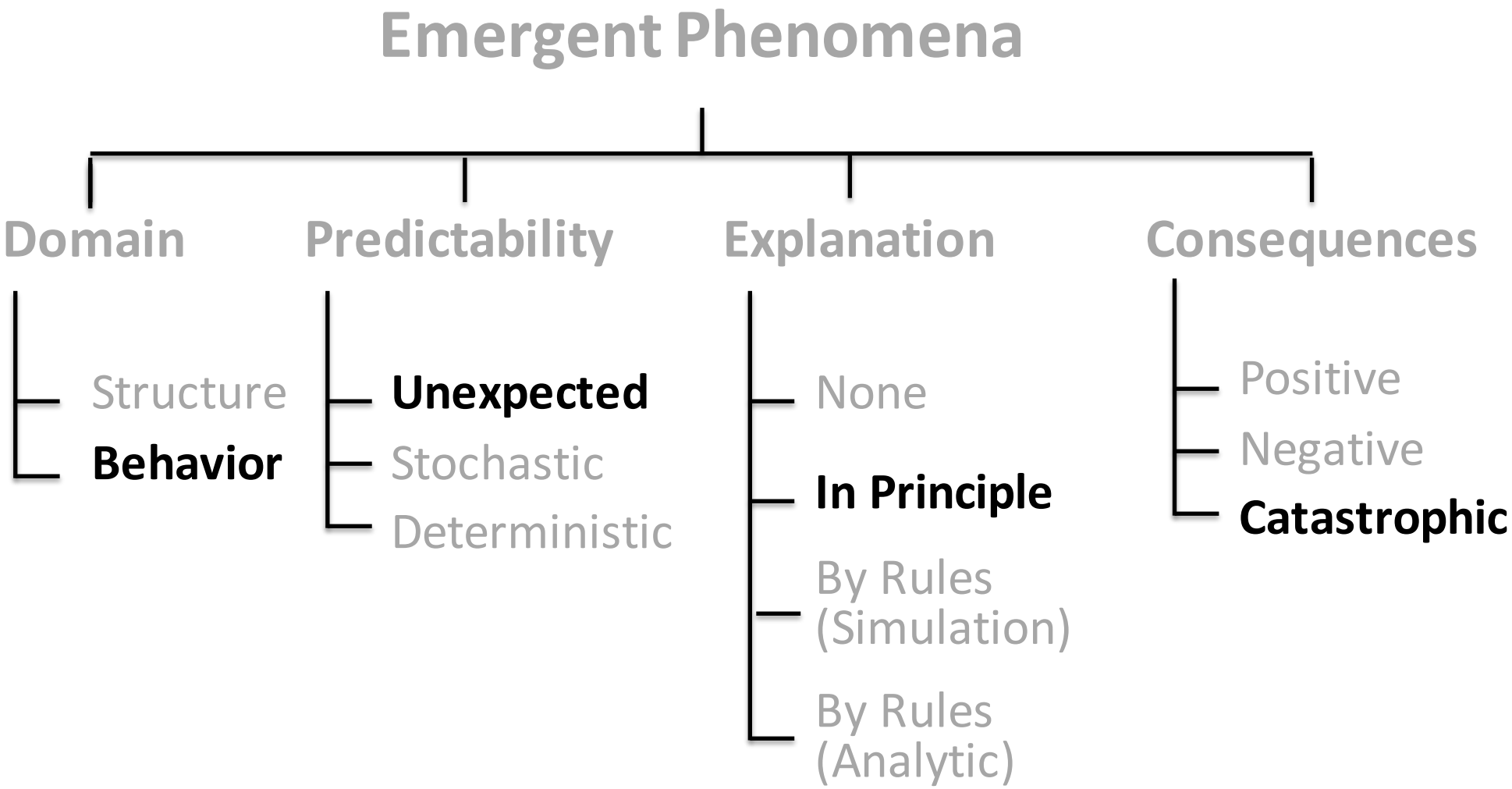
Let us look at the example of a transistor. The *transistor effect* is an emergent effect caused by the proper arrangement of dopant atoms in a semiconducting crystal. The exact arrangement of the dopant atoms is of no significance as long as the provided behavioral specifications of a transistor are met. In a VLSI chip that contains millions of transistor, the detailed microstructure of every single transistor is probably unique, but the external behavior of the transistors (the holons) is considered the *same* if the behavioral parameters are within the given specifications. It is a tremendous simplification for the designer of an electronic circuit that she/he does not have to consider the unique microstructure of every single transistor.

Sup_2 enables Fault-Diagnosis

Sup_2 states: *A difference in the emerging phenomena at the macro level requires a difference in the arrangements or the interactions of the parts at the micro level.*

Whenever the observed emergent behavior at the macro level *deviates* from the intended behavior, there must be *determinant* at the micro-level—the *cause* of the observed failure

Emergence in Safety-Critical Systems



Search for *Causal Loops*

A causal loop can only develop if there is a a direct or indirect information flow from the macro-level to the micro-level.

In many cases of CP-SoSs, a loop is closed by the transport for *Itoms* across a *stigmergic channel*.

A careful analysis of the exposed information flows, particularly across stigmergic channels, can lead to the detection of potential causal loops that can produce undesired emergent effects.

Expose all Information Flow Channels

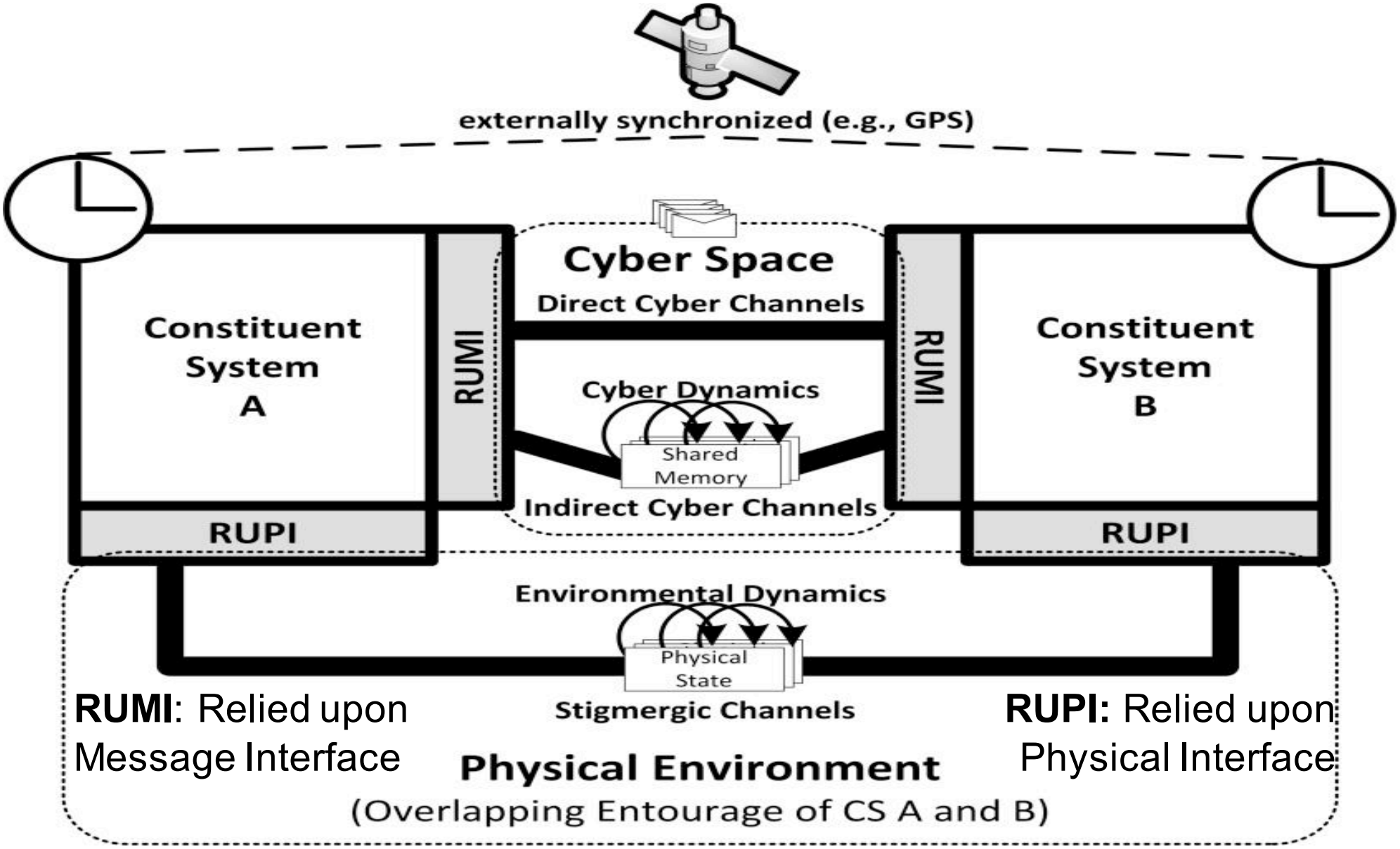
Emergent phenomena in System-of-Systems are caused by the information flow among the Constituent Systems. The information flow consists of

- Direct message channels for state and event messages
- Indirect information transfer via files
- Stigmergic channels that exist in the physical environment
  Be aware of *unplanned hidden channels*.

Since the scope of an SoS is often undefined, it may be impossible to find all hidden information flow channels, particularly the stigmergic channels in the environment.

This is a fundamental limitation in a CPSoS.

Information Flows in a CPSoS



Detect the Onset of Emergence

- The behavior of a safety-critical system should conform to the *design model* that is the basis for the safety argument.
- The des*ign model* may not take into account emergent effects that cause a deviation of the actual behavior from the intended behavior.
- Since emergent behavior is *diachronic,* (i.e. it develops over time) it is far-sighted to continually observe the system behavior to
  - Detect the start of an *anomalous behavior* that deviates from the intended behavior
  - Find an explanation for every observed anomalous behavior
  - Eliminate Emergency by Design

Conclusion

- *Emergence* is always associated with levels of a *multi-level hierarchy.*
- A phenomenon of a whole at the macro-level is emergent if and only if it is *of a new kind* with respect to the non-relational phenomena of any of its proper parts at the micro level.
- We conjecture that in a multi-level hierarchy emergent phenomena can only appear if there is a causal-loop formed between the micro-level that forms the whole at the macro-level and this whole (i.e., the ensemble of parts) that constrains the behavior of the parts at the micro-level.
- The proper conceptualization of the new phenomena at the macro level is at the core of the simplifying power of a multi-level hierarchy with emergent phenomena.

Further Information:

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Chapter

Emergence in Cyber-Physical Systems of Systems

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