



Emergence in Cyber-Physical Systems of Systems (CPSoS)

H. Kopetz



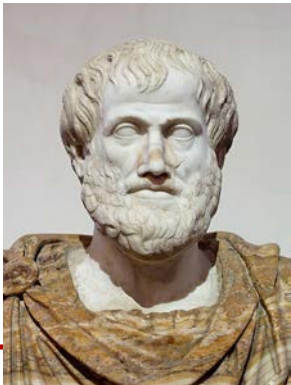
The *Essence of Emergence*

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.***

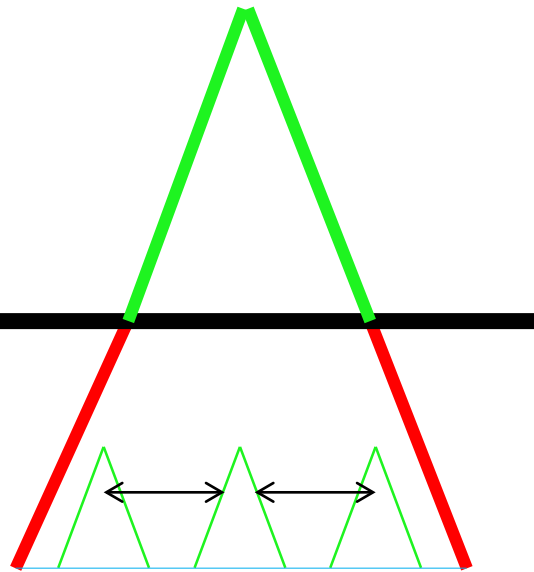


- ***Aristotle** Born: in Stageira, Greece February 20, 0384 Died: June 04, 0322
-



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

Whole
(Macro-Level)



Parts
(Micro-Level)

Holon

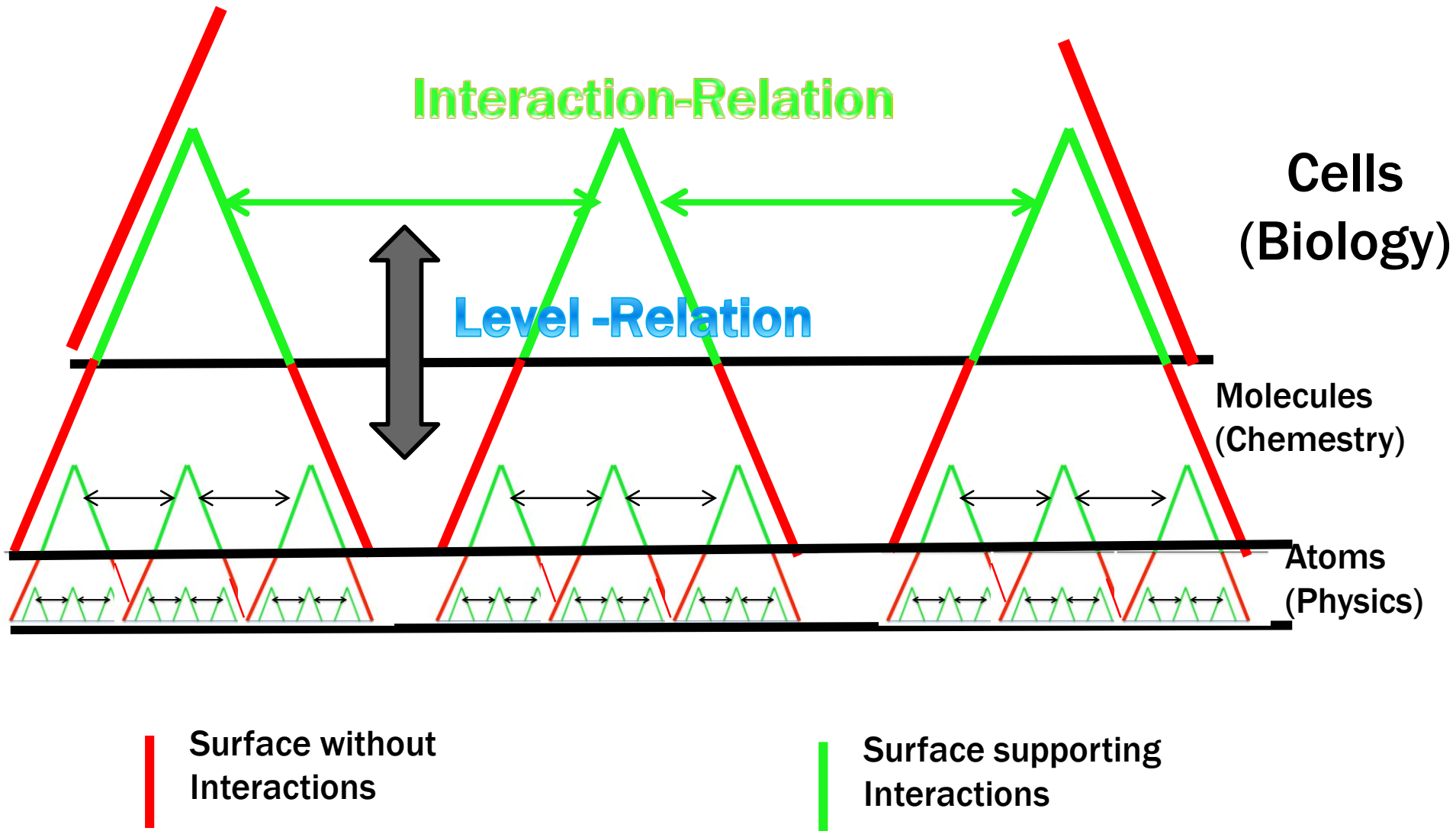
Koestler has introduced the term *holon* to refer to the *two-faced character* of an entity that is considered a **whole** at the *macro level* and an ensemble of **parts** at the *micro level*.

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*)





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.



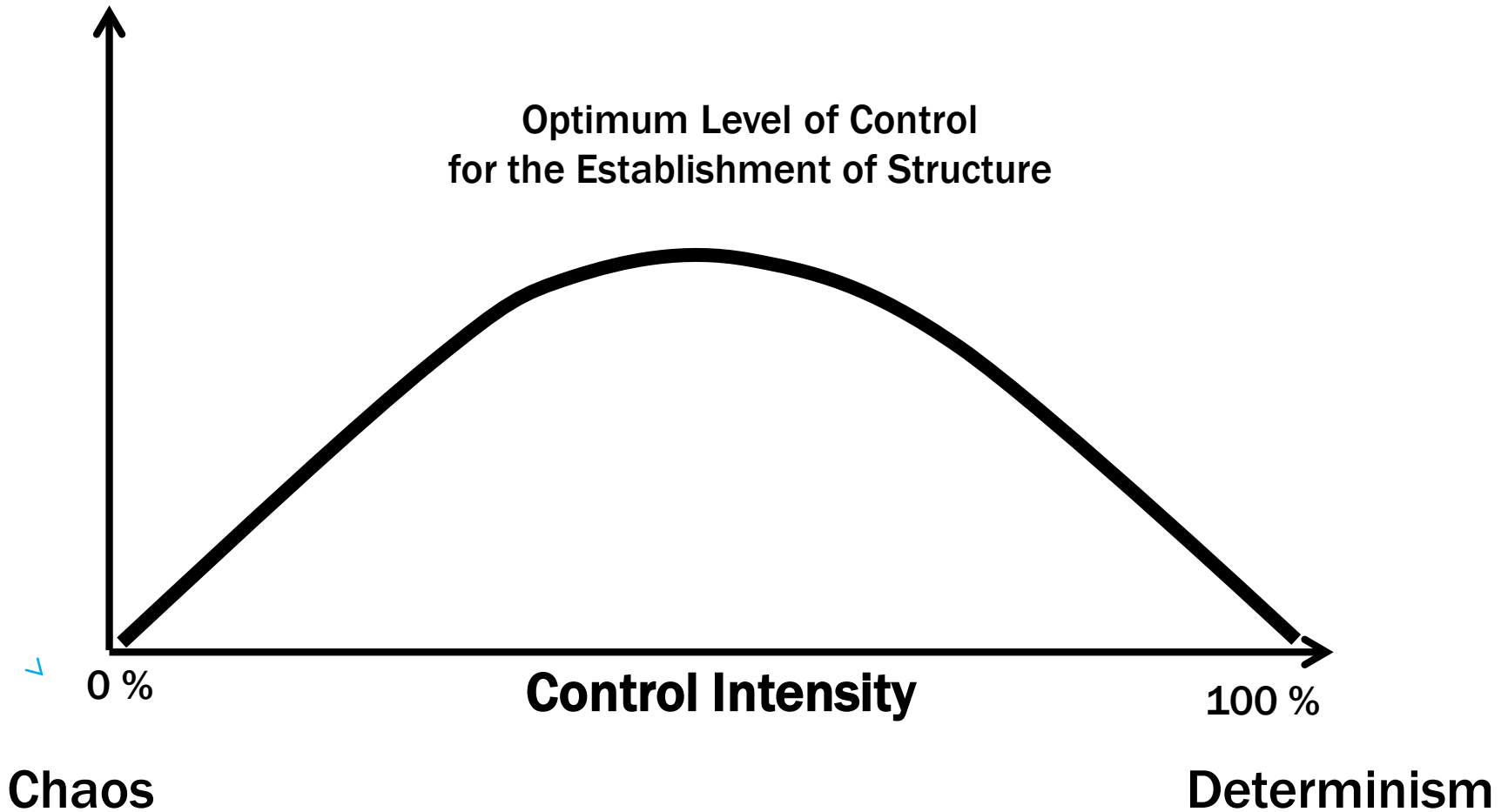
Conductor vs. Orchestra





Intensity of Control in a Control Hierarchy

- Measure of
- Structure





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.



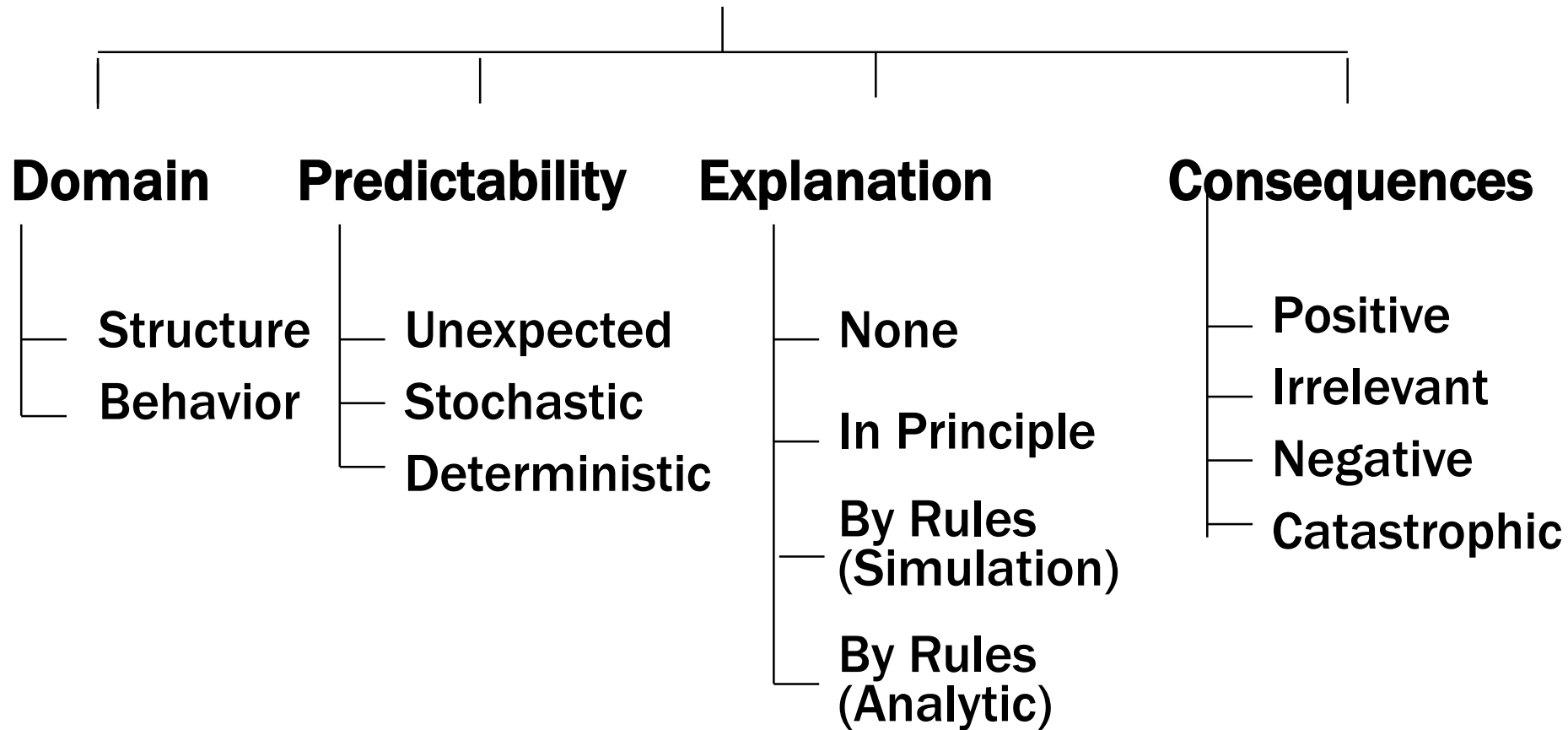
Conceptualization at the Macro-Level

- 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.**
-



Classification of Emergence

Emergent Phenomena





Fault-Tolerant Clock Synchronization

In a 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.
-



Downward Causation

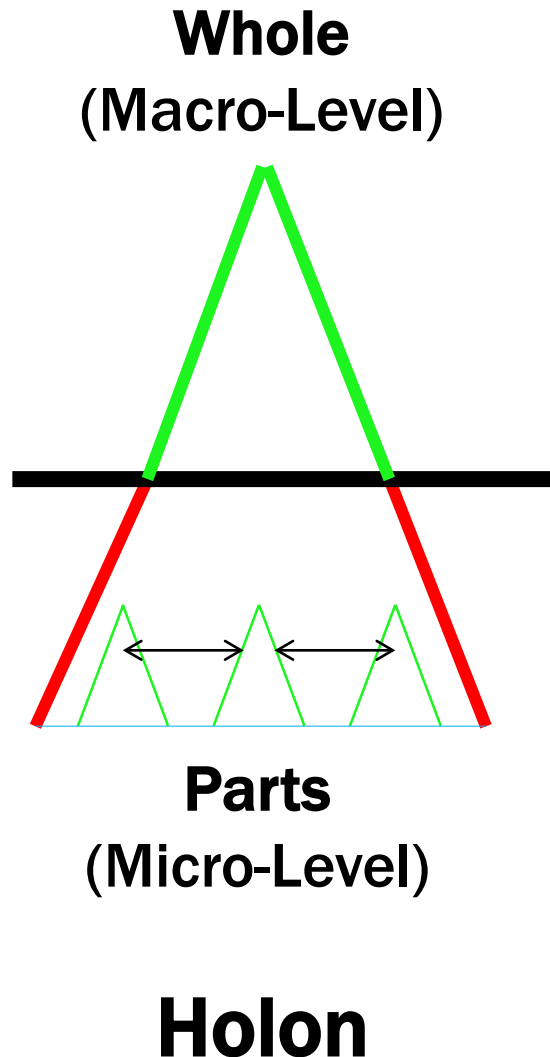
The interaction of the parts at the micro-level cause the whole at the macro-level while the whole at the macro-level can *constrain* the behavior of the parts at the micro-level. This is *downward causation*—resulting in a *causal loop*.

We conjecture that in a multi-level hierarchy emergent phenomena can 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.



Upward and Downward Causation



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

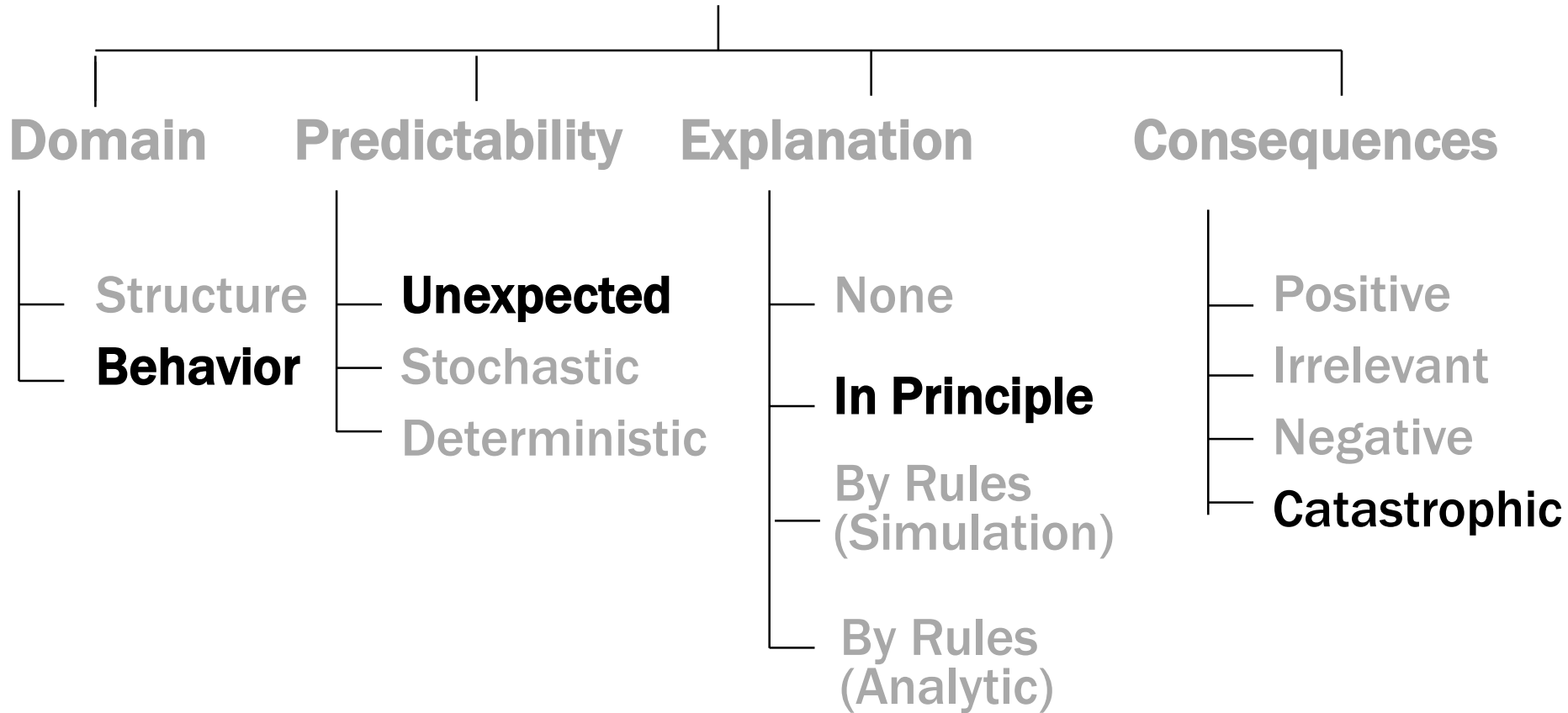
Free behavior of the parts
constrained by upward and
downward causation.

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



Emergence in Safety-Critical Systems

Emergent Phenomena





Search for *Causal Loops*

A causal loop can only develop if there is 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.



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 *design model* cannot take into account *unknown 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 Emergence by Design
-



Conclusions

- *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.
-