Emergence in Cyber-Physical Systems-of-Systems

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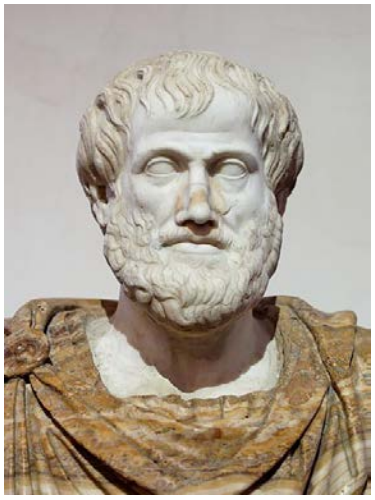
The Essence of Emergence

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

What is a System-of-Systems?

Constituent System (CS)

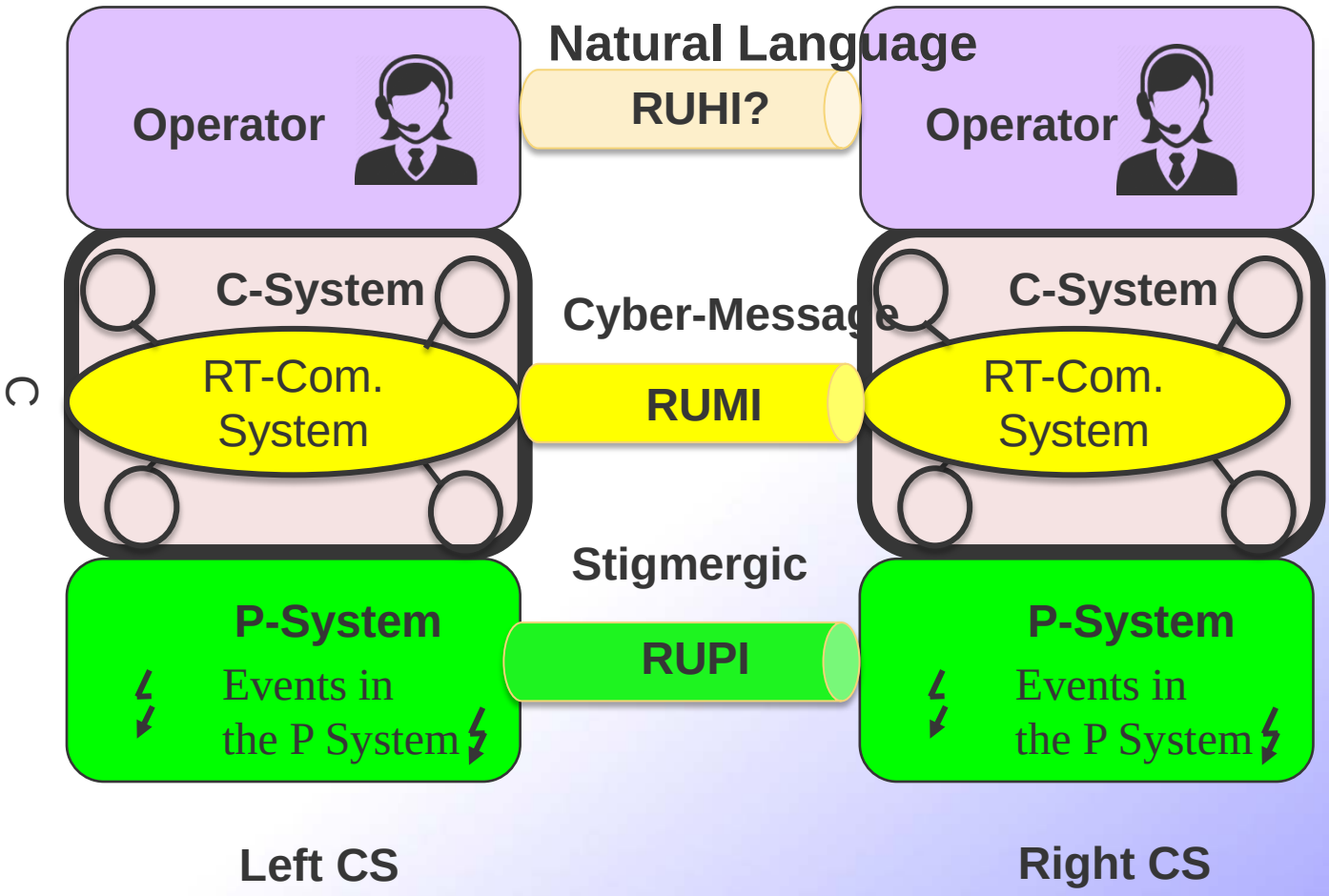
An **autonomous subsystem** of an SoS, consisting of **computer systems** and possibly of a controlled objects and/or human role players that **interact to provide a given service**

System-of-Systems (SoS)

A System-of-Systems (SoS) is an **integration of a finite number of constituent systems** (CSes) which are **independent and operable**, and which are networked together for a period of time to achieve a **certain higher goal**.

Constituent Systems and Communication Channels

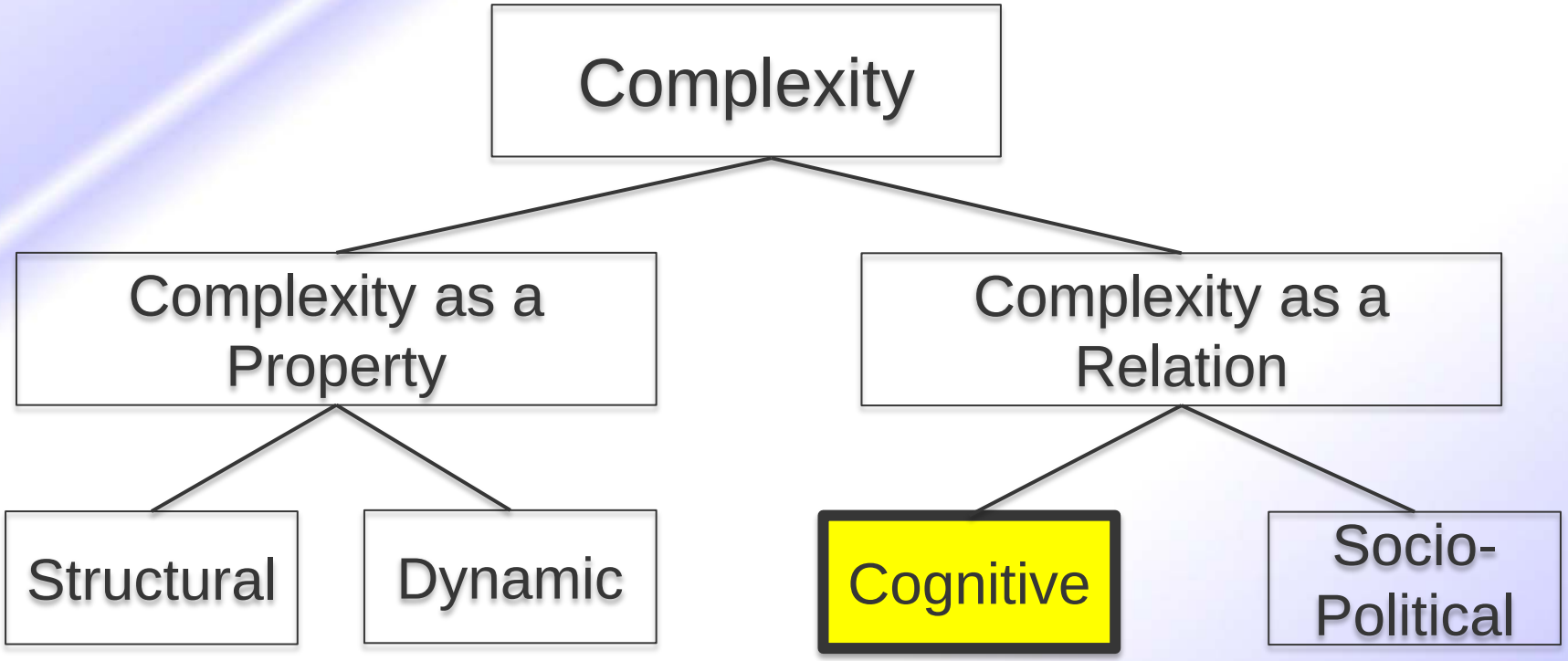
- C-System
  - Controlled by program execution
  - Execution time
  - Sparse Time-base
- P-System
  - Controlled by laws of physics
  - Physical time
  - Dense time



Motivation: Reduce COST

- The major cost elements during the specification, design, operation, evolution and maintenance of a large CPSoS are accrued in the ***non-physical domain***
- Compared to the cost of the ***engineering effort,*** the hardware costs of a CPSoS are modest—and getting even smaller as the hardware technology moves forward
- The *engineering effort* depends to a considerable degree on the ***cognitive complexity***, i.e., the ***time needed to understand the behavior*** *of a system*
- Any **reduction of the cognitive complexity** of a large system is thus of utmost economic significance and reduces the probability of the occurrence of design errors

Complexity



- Topological
- Components
- Links

- Behavior
- Causality
- Feedback

Relation between a Scenario and an Observer

Relation between a Scenario and Society

Cognitive Complexity

Cognitive complexity is concerned with the question:

*How much mental effort is required in order to **understand** a **given scenario** for the given **purpose** by an **identified user?***

The *time* it takes for an *average representative* from the *intended user group* to *understand* the scenario is linked to the ***cognitive complexity*** of a scenario.

The time required for understanding will depend upon

- the *conceptual basis* of the intended user group
- the purpose of understanding
- the inherent characteristics of the scenario
- the representation of the scenario

Mental Model

Understanding the behavior of a systems means that a *mental model* that establishes *causal links* between

- the ***observable inputs***,
- the ***state***
- and the ***observable outputs***

of the system has been formed.

Emergence

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

Example: **positive emergence**

The ATM network results from the combination of smaller networks, standardized interface, agreements

Example: **detrimental emergence**

Blackouts may result from the independent and uncoordinated access of multiple consumers to an energy supplier

Emergence and SOSes

We design SOSes to obtain emergent behaviors that cannot be observed in any individual CS so emergence is the very fundamental essence of our design

In our Mental Models we wish to be able to manage emergent phenomena conciously and master their apparence

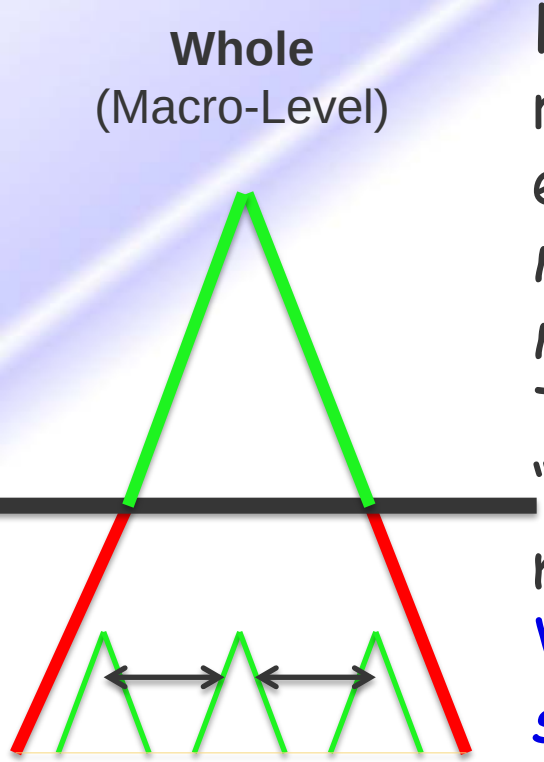
Emergent properties may have beneficial or detrimental effects.

- Govern and manage the emergence so to have only 'good' emergence

Emergence: 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*.
- The main (unique?) identified modeling structure is that of a ***multi-level hierarchy***.
- Each level of a hierarchy possesses its unique set of laws.
- **The phenomenon of *emergence* is always associated with levels of a *multi-level hierarchy*.**

Holon: the Entity of a Two-Levels Hierarchy



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***.

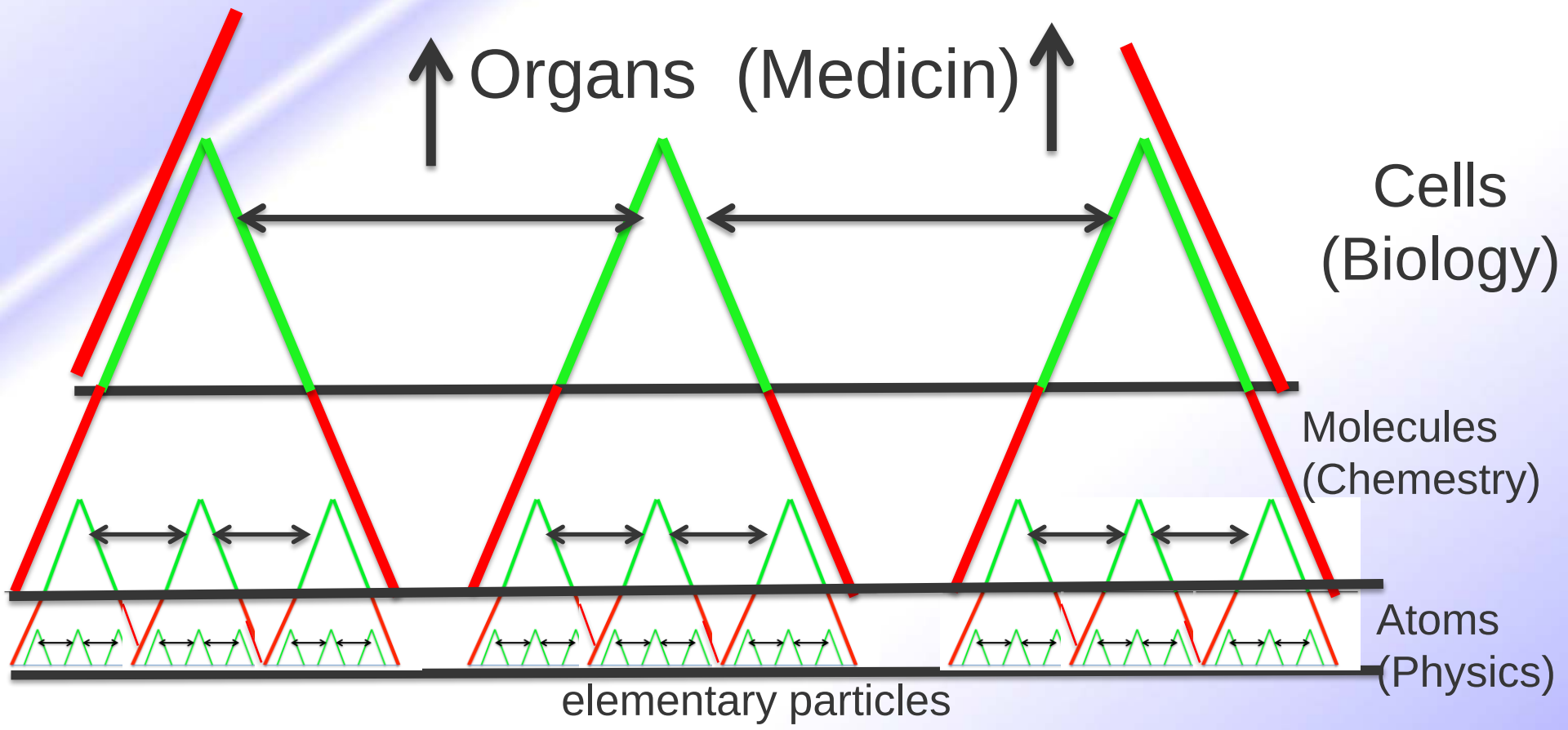
Viewed from the the *macro level*, a holon is a *stable whole* that can be accessed by an interface across its surface(green line).

Viewed from the *micro-level*, a holon is characterized by a set of *confined interacting parts*.

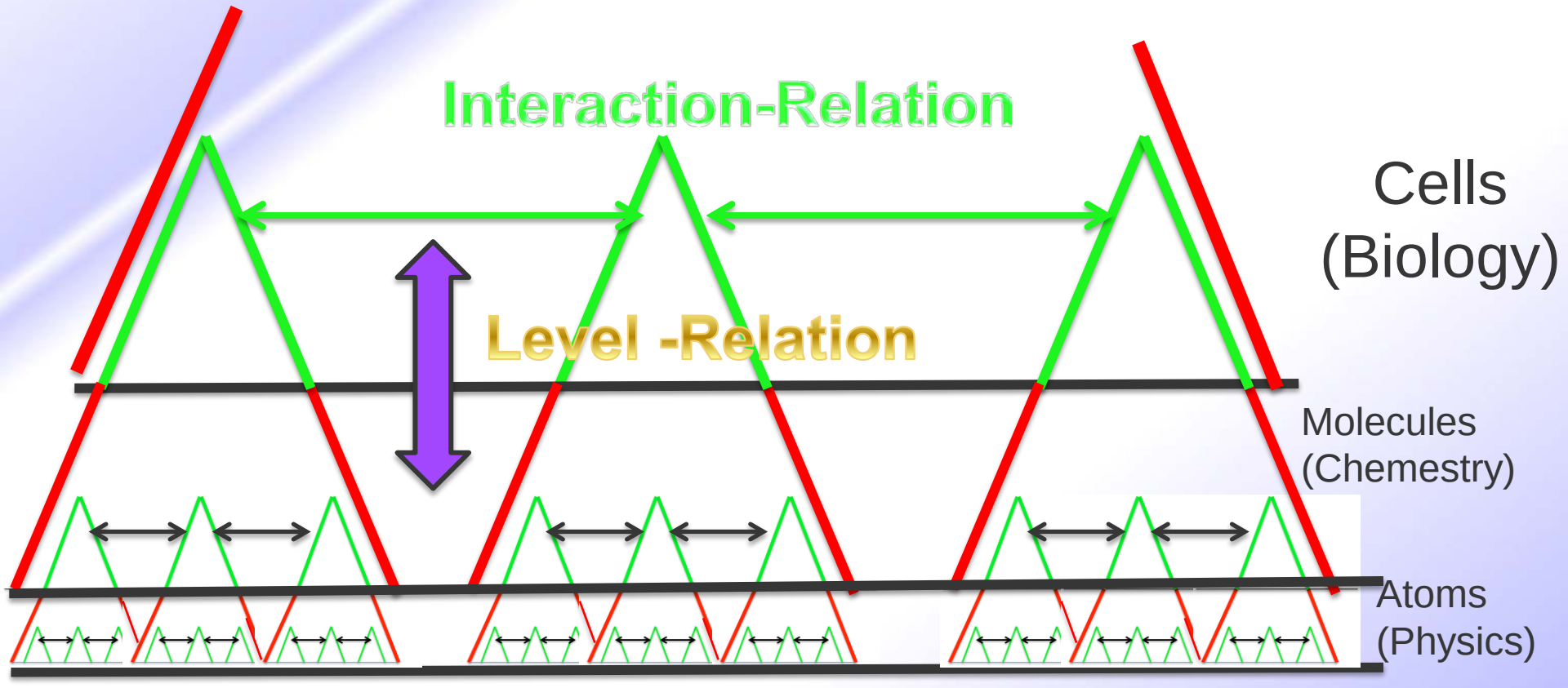
Recursion in a Multi-Level Hierarchy

- *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*.

Multi-level Hierarchy (*Holarchy*)



Holarchy relations



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 – Ants - Termites

(iii) Description: The Parts can be described at different levels of abstraction

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

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*. 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

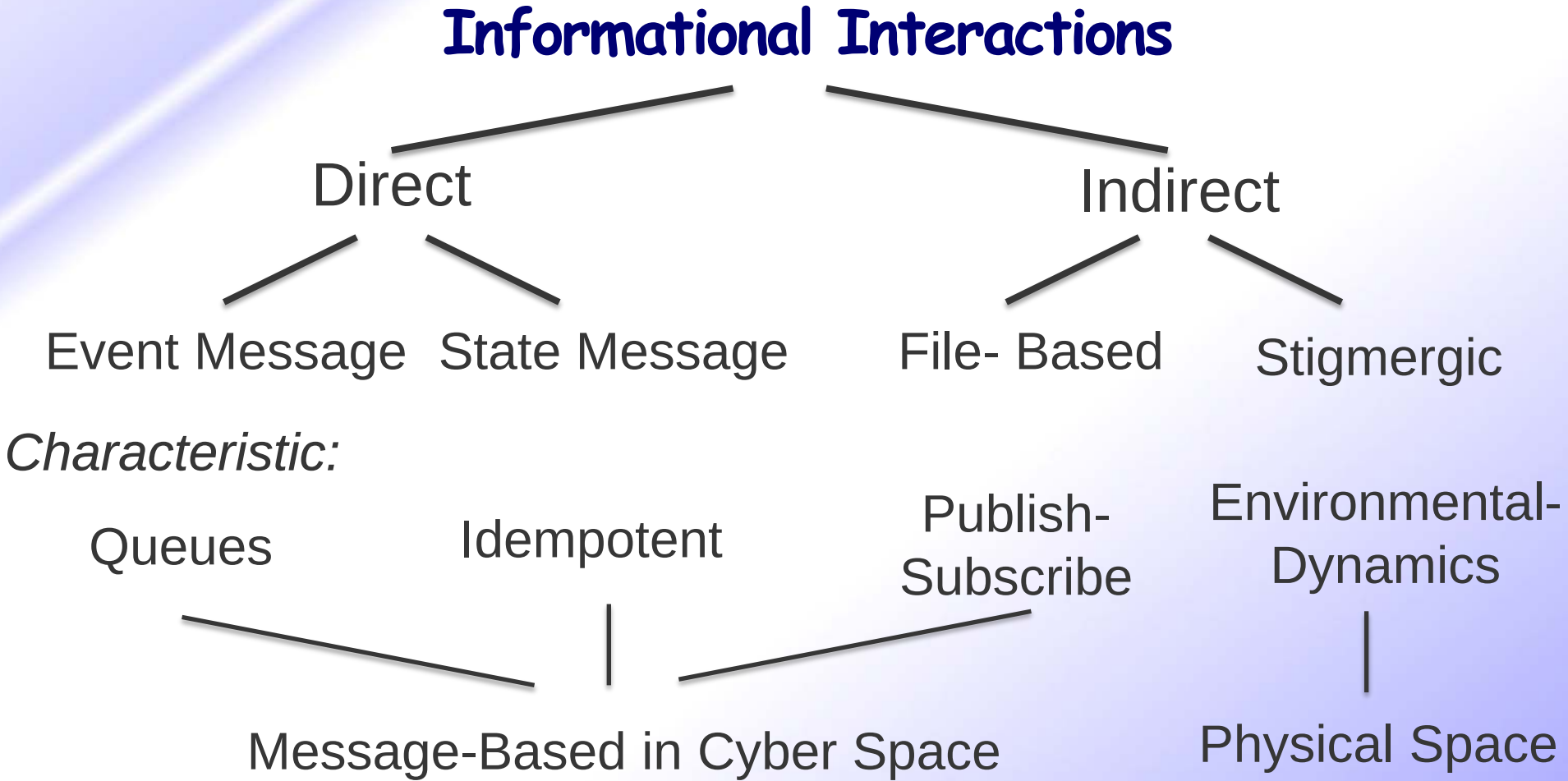
- **Physical Interactions**: come about by force fields, (e.g, electromagnetic or gravitational fields). They are *synchronic*. Physical structures (e.g, a molecule) are mainly formed by force fields.
- **Informational Interactions**: come about the exchange of *Itoms*, either across message channels 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,
  - **relaxation 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



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 *relation among 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.

Emergence is a powerful simplifier

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.*

Conceptualization at the Macro-Level

- Novel concepts and new laws may be needed at the macro level to describe the emerging phenomena appropriately.

  Example: *liquidity, hydrodynamic laws.*

- 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 concepts at the micro-level with the new concepts of the macro-level.**

Downward Causation

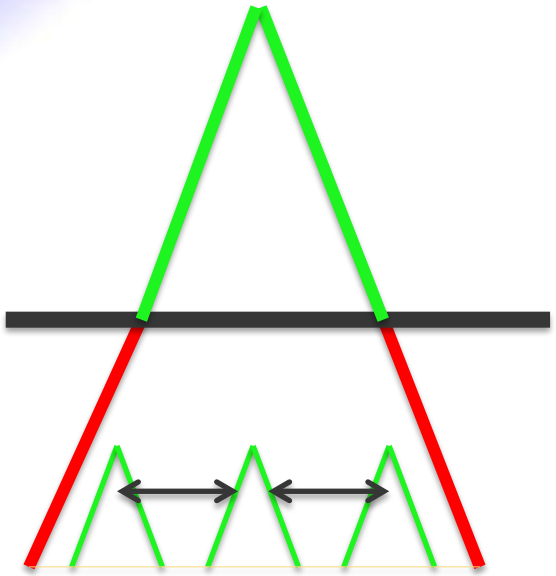
The interaction of the parts at the micro-level cause the whole at the macro-level while the whole at the macro-level can *constrain* the behavior of the parts at the micro-level. This *is* *downward causation*—resulting in a *causal loop*.

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

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 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

Examples of *Emergence*

Here we present *very simple examples* of phenomena that have been called *emergent* in the computing literature to further clarify the concepts introduced so far

- Deadlock in Computer Systems
- Fault Tolerant Clock Synchronization

Deadlock Example: Seat Reservation

Process Type A

1. $S^{money} = 1$, $S^{seat} = 1$
2. Client selects seat and provides credit card
3. **Wait** (S^{money})
4. Get *Money*
5. If *No-Money* Then **Signal** (S^{money}) Print *No Money* Goto 2
6. **Wait** (S^{seat})
7. Get *Seat*
8. If *No-Seat* Then *Return Money* **Signal** (S^{money}) **Signal** (S^{seat}) Print *No Seat* Goto 2
9. **Signal** (S^{money}) **Signal** (S^{seat})
10. Print *Seat Ticket*
11. Goto 2

Process Type B

1. $S^{money} = 1$, $S^{seat} = 1$
2. Client selects seat and provides credit card
3. **Wait** (S^{seat})
4. Get *Seat*
5. If *No-Seat* Then **Signal** (S^{seat}) Print *No Seat* Goto 2
6. **Wait** (S^{money})
7. Get *Money*
8. If *No-Money* Then *Return Seat* **Signal** (S^{money}) **Signal** (S^{seat}) Print *No Money* Goto 2
9. **Signal** (S^{money}) **Signal** (S^{seat})
10. Print *Seat Ticket*
11. Goto 2

Discussion: Deadlock

- Gligor (and others) considers the occurrence of a *deadlock* in a computer system an *emergent phenomenon* [Gli06].
- Let us assume that in the small world of the micro-level everything is perfect—the *notion of permanent* halt does not exist at the micro-level but appears at the macro-level.
  - What is the novel phenomena? Permanent halt
  - Is Deadlock explainable? yes
  - *Downward causation* is realized by the indirect information Transfer (file-based information flow) via the semaphore variables
  - Is *Deadlock* predictable? No, neither in *praxis* nor in *theory* due to the *indeterminism* caused by simultaneity.

Discussion: Fault-Tolerant Clock Synchronization

- In a properly designed 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 ***inflicts*** a *state correction to a local clock*. The frequency of a *physical oscillator* cannot be changed (upward causation).
  - Is the phenomenon predictable? Yes.
- If a local clocks does not work according to the rules it is considered *failed* and expelled from the ensemble.

Emergence in Safety-Critical Systems

Emergent Behaviour	Beneficial	Detrimental
Expected	Normal case	Avoided by appropriate rules
Unexpected	Positive surprise	Problematic case

- With proper observation and documentation of interactions among the CSs the occurrence of the emergent phenomena in SOSes can be explained.

- Still as SoS designers and or users we would like to gain a complete **awareness** of emergent phenomena and be able to **CONTROL** (or mitigate the effects of) the detrimental one

Interactions between Constituent Systems

- Cyber-Physical Constituent systems interact via two types of channels
  - *Channels at Cyber level* that transport messages and can be observed
  - *Channels* in the Physical environment Stigmergic channels

•What about the impact of the environment on CS?
•Should we have to consider the environment itself as a particular kind of CS interacting through stigmergic channels??
•How to define and understand its behavior??

Causes of unexpected Emergence

- We believe all come down to our ignorance
- We are ignorant about the full set of system's behaviors even at micro level (CS level)
- Things exacerbate when scaling to SoS…
- More particularly, we may be ignorant about
  - The complete set of requirements we need to address in the SoS
  - The complete set of behaviors of each CPS
  - The complete set of interactions among the CPSs
  - The impact of the environment.
  - ……

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.

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* 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

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 parts at micro-level that forms the whole 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.