TU Wien

Emergence in the Internet of Things

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The *Essence* of *Emergence*

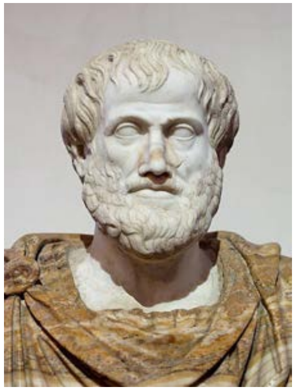
*The Whole is Greater than the Sum of its Parts**

The Level of the Whole: The *Internet of Things*

The Level of The Parts: The *Things*, i.e**,**
Cyber-Physical Systems (CPSs)

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

In the IoT, we are interested in *emergent behavior*.



***Aristotle**

Born: in Stageira, Greece February 20, 0384

Died: June 04, 0322

Outline

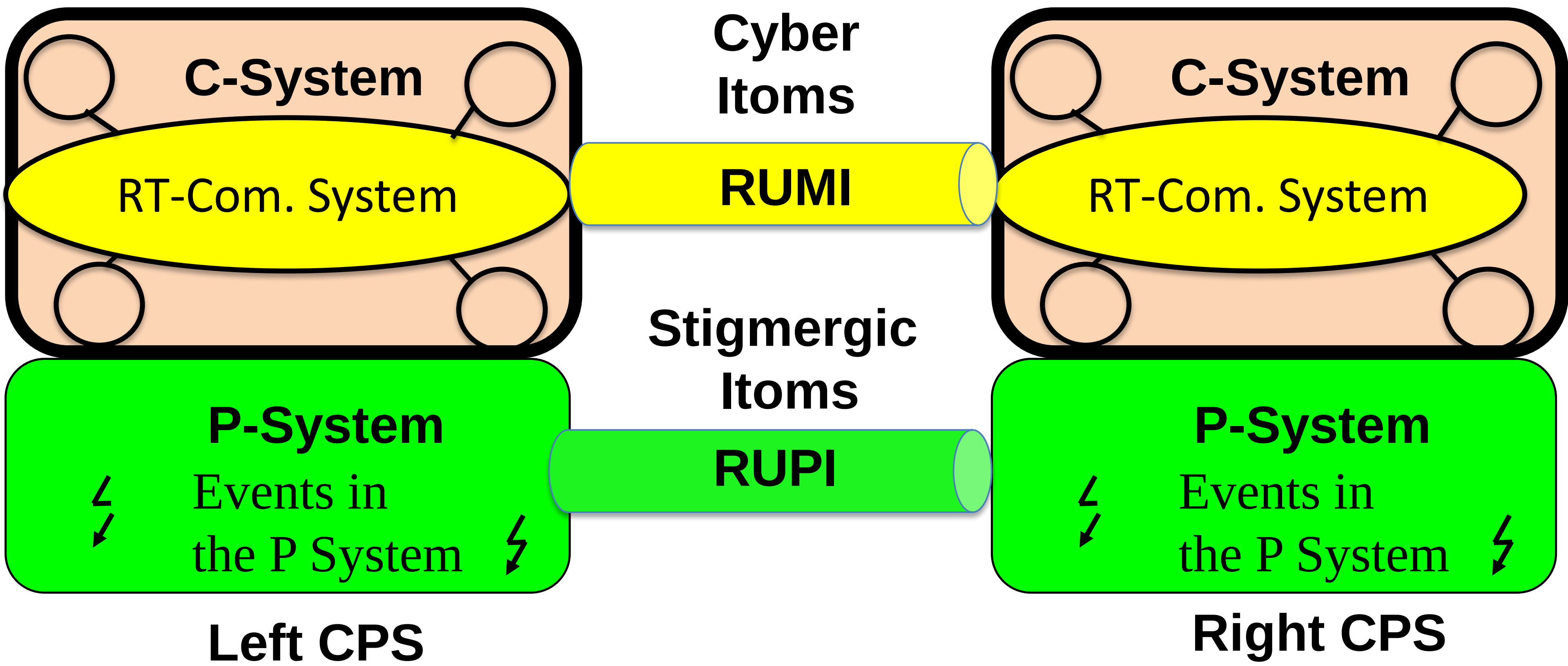
- Introduction
- Communication in Cyber-Physical Systems of Systems
- Multi-level Hierarchies
- Emergence
- Examples
- Consequences for System Design
- Conclusion

The IoT is an Enormous *System of Systems (SoS)*.

An SoS is an integration of a finite number *of autonomous constituent systems (CS) e.g., embedded systems,* which are independent and operable, and which are networked together for a period of time to achieve a certain higher goal (refer to Jamshidi, 2009, T-Area SoS)**.**

SoSs are qualitatively different from Embedded Systems

Information Flow in a CPSoS



Itom: Information Item
RUMI: Relied upon Message Interface
RUPI: Relied upon Physical Interface

Exchange of *Information Items* (*Itoms*), not pure *Data*

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

An *Itom* consists of ***timed data*** and an ***explanation of the data***.

- In cyber-space, *data* is represented by a *bit-pattern*.
- 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.

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

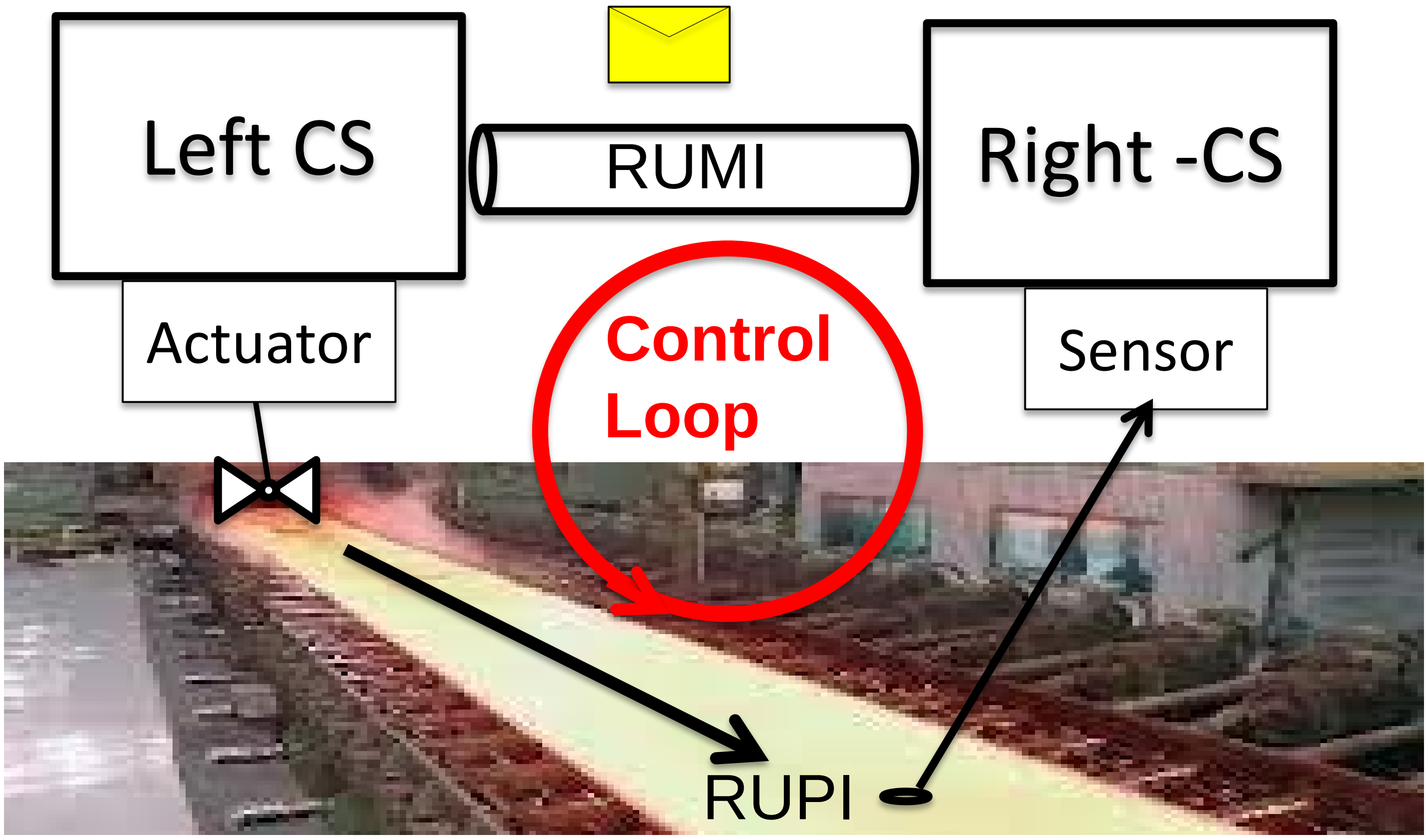
Stigmergic Channels

- The biologist *Grasse* introduced the term *stigmergy* to describe the indirect information flow among the members of a termite colony when they coordinate their nest building activities.
- According to the present understanding, the nearly blind ants orient themselves on the information captured by the *olfactory sense* following the intensity of the smell of the chemical substance *pheromone*.
- **A *stigmergic information channel* is present if one CPS 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.**
- Since stigmergic *Itoms* are derived from the state of the *physical environment* (not in cyber space) they are exposed to the full spectrum of ***environment dynamics***.

Traffic Flow

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

Control Loop Closed by Stigmergic Channel



A control loop of a CPS consists of message channels and stigmergic channels. Environmental Effects that disturb the operation of the system are masked.

Stigmergic versus Message Based Itoms

Characteristic	RUPI (Stigmergic)	RUMI (Cyber Message)
Information Type	Properties of Things captured by a sensor	No Restriction
Inform. Transfer	Pull	Push
Tense	Present	Past, Present, Future
Observation Mode	Direct	Indirect
Observation Delay	None	Existent
Comm. Delay	Unbounded	Bounded
Source	Unknown	Known
E-Dynamics	**Considered**	**Not Considered**
Representation	Single Context	Multiple Contexts

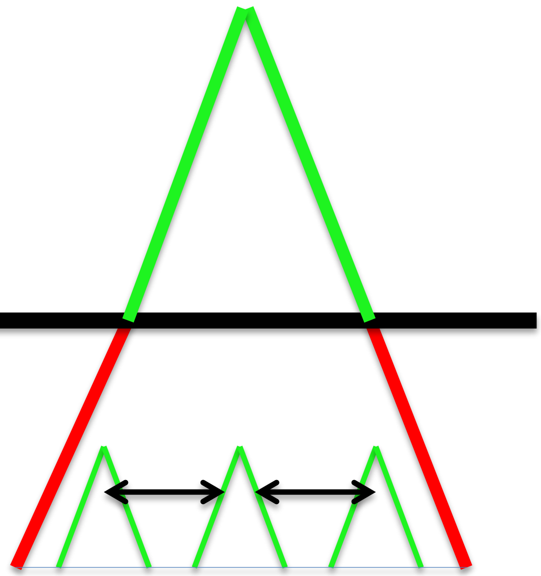
Multi-Level Hierarchy

- 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 found modeling structure is that of a *multi-level hierarchy.*
- Each level of a hierarchy possesses its *unique set of regularities, either natural laws or imposed rules (in the design of artefacts).*
- **The phenomenon of *emergence* is always associated with levels of a *hierarchy.***

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 (H. Simon, 1969, p.219]

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*.

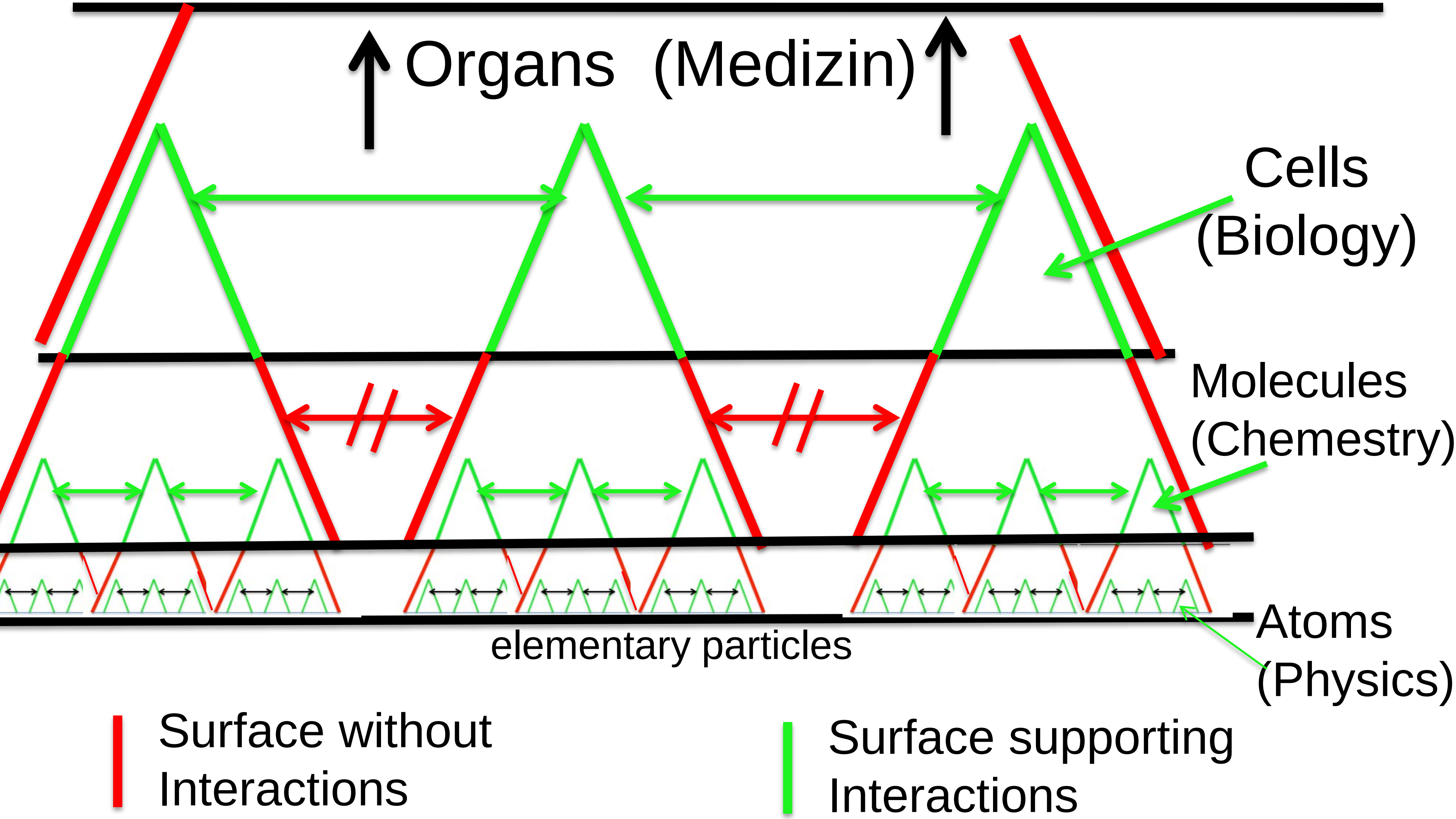
The word *holon* is a combination of the Greek "*holos*", meaning *all*, and the suffix "*on*" which means *part*.

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.*

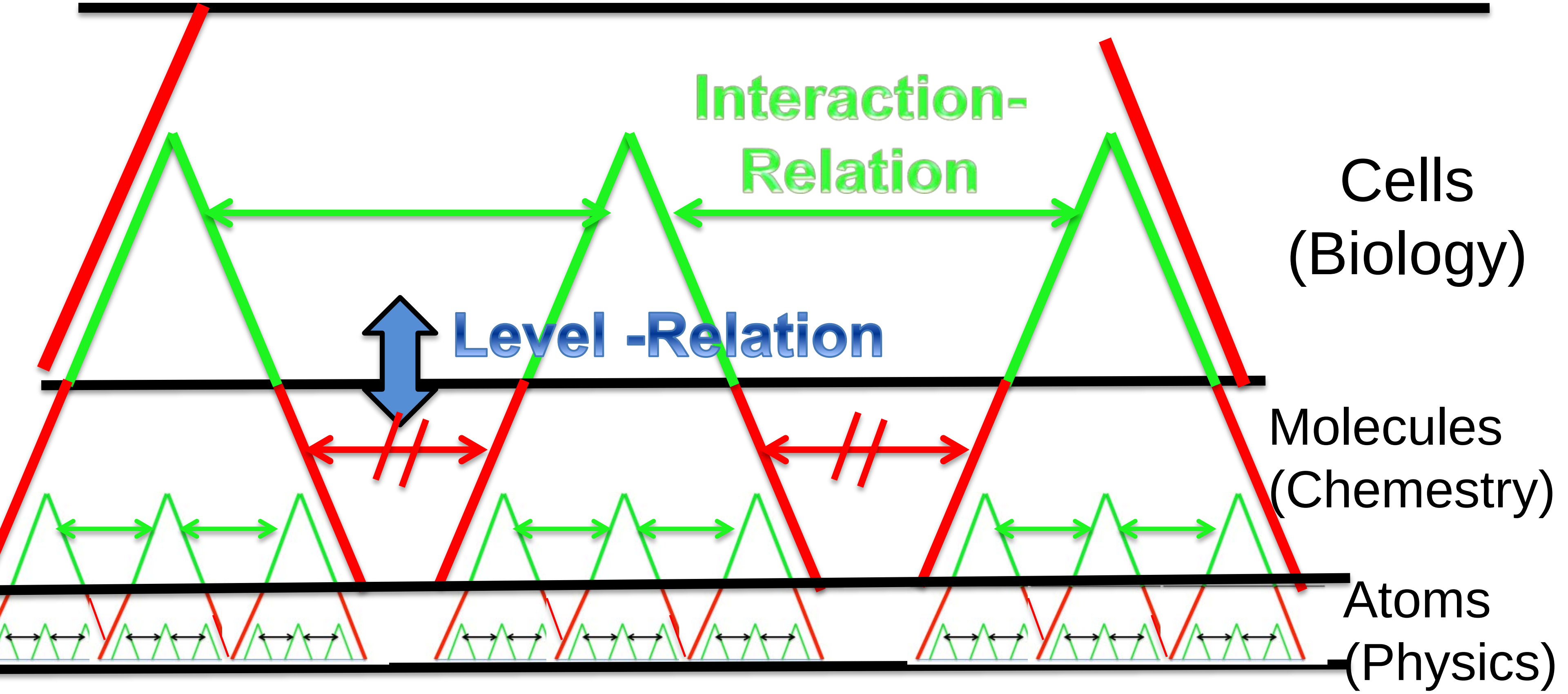
Recursion in a Multi-Level Hierarchy

- A *multi-level hierarchy* is a recursive structure where a system, the *whole (*the *holon)* at the level of interest (the *macro-level*), can be *taken apart* at the level below (the micro-level), into a *set of sub-systems* (the *parts)* and a *design* that that *controls* the interactions of the parts.
- Each one of these sub-systems (the *parts*) 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 Material Hierarchy (*Holarchy*)



Multi-level Hierarchy (*Holarchy*)



Surface without Interactions

Surface supporting Interactions

Level Relations

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

(ii) **Control:** The whole *constrains or (partially) controls* the behavior of the parts
Example: Blinking of Fireflies

(iii) **Description:** The parts and the design 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 relation* is most relevant.

Control Hierarchy

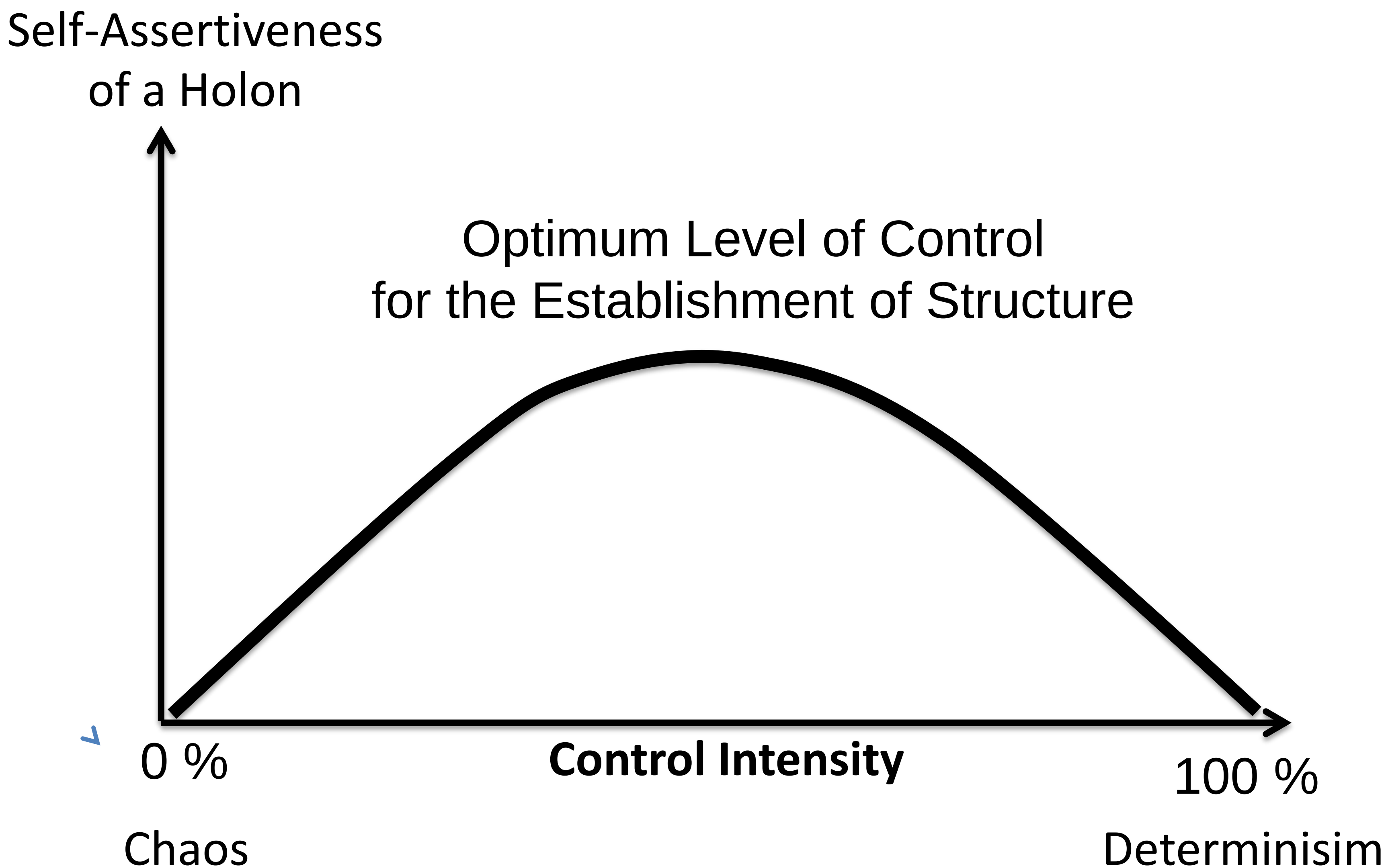
In order to support the simplification at the macro-level and establish a hierarchical control level, a *control hierarchy* must

- 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 of the holon*, e.g. the authority of a *General* over the *Soldiers* in a military hierarchy
- *Authority form the inside of the holon*: 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 formed by force fields according to *physical laws*.
- **Informational Interactions**: come about the designed exchange of *Itoms*, either across message channels or stigmergic channels. They are *diacronic*.

Emergent behavior in systems-of-systems is caused by informational interactions according to an algorithm. The *algorithm* that controls the informational interactions is part of the system design.

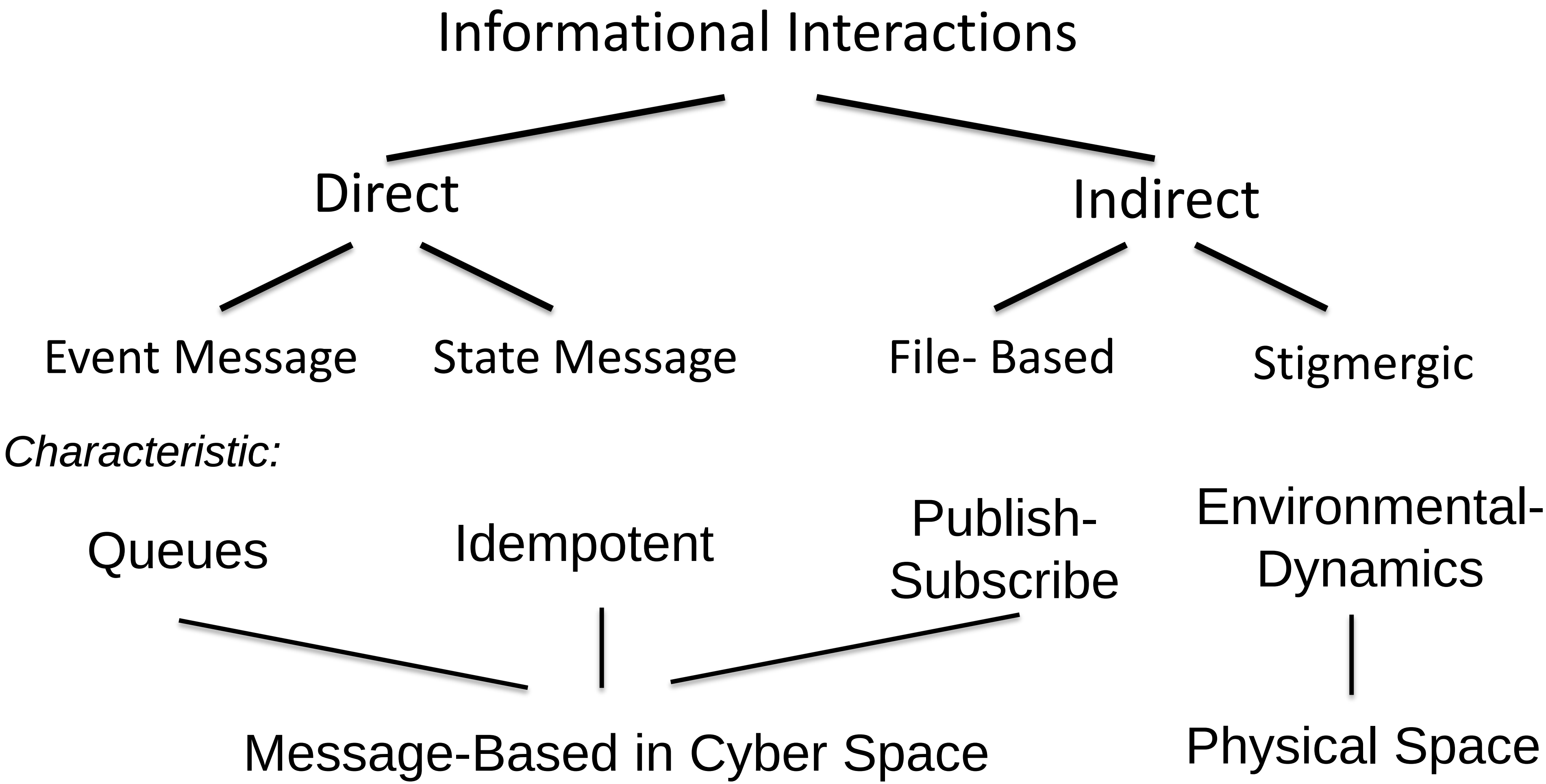
Physical Interactions

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 decreases* and the *frequency of interactions* decreases.

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 *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.

Emergent Structures vs. *Emergent Behavior*

- The novel phenomena can be *structures*, *behavior* or *properties*.
- In *System of Systems* we are primarily interested in *emergent behavior.*
- *Emergent behavior* is associated predominantly with *control hierarchies*.

Contribution of emergent behavior to the overall goal of a system **Emergent behavior**	**Beneficial**	**Detrimental**
Expected	Normal case	Avoided by appropriate rules
Unexpected	Positive surprise	Problematic case

Emergence is our *Friend*, not our Enemy

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

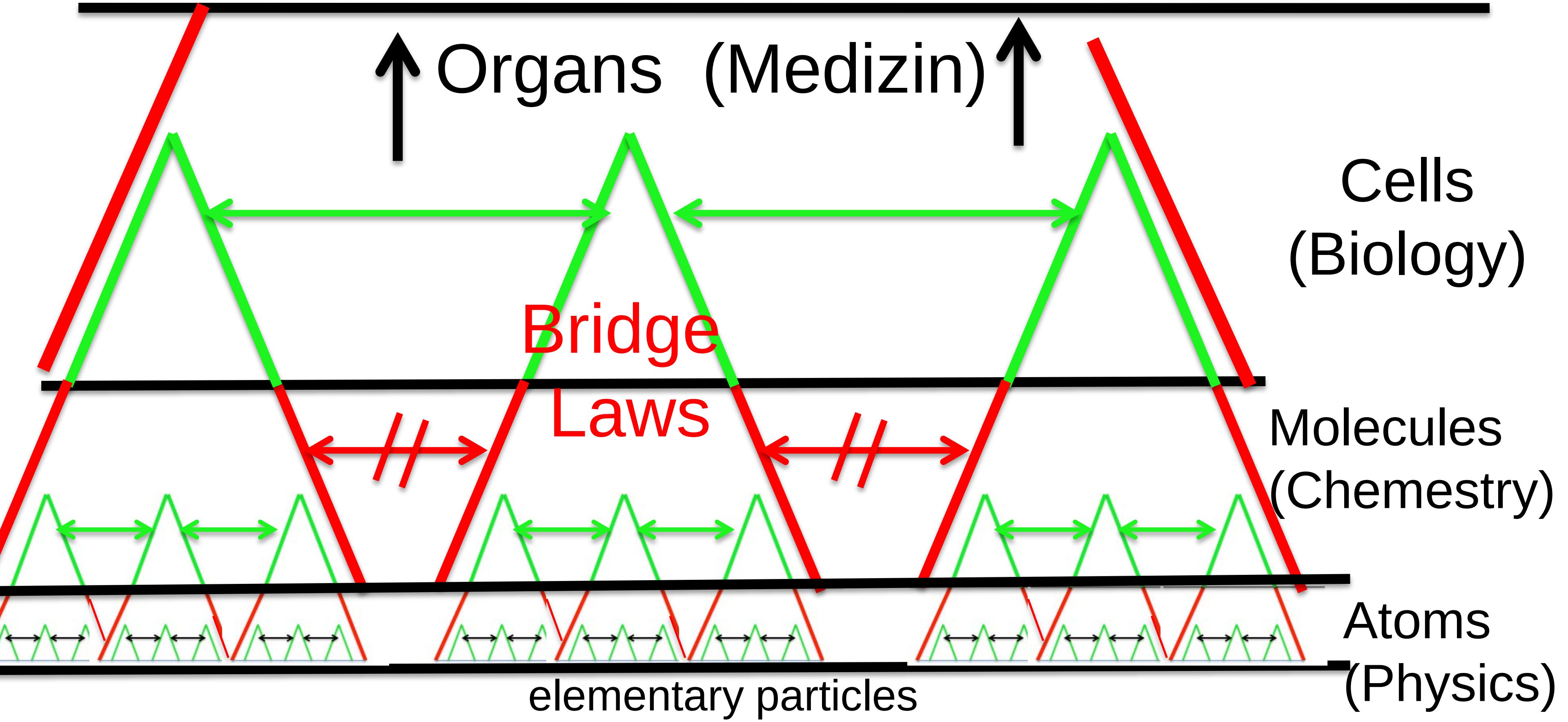
Examples:

- 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*.

Conceptualization at the Macro-Level

- Novel concepts must be formed and new laws may have to be introduced at the macro-level to be able to describe the emerging phenomena at the macro-level 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 may be possible to formulate *inter-ordinal laws* (also called *bridge laws*) to relate the new concepts of the macro-level to the established concepts at the micro-level.

Multi-level Material Hierarchy (*Holarchy*)



Surface without Interactions

Surface supporting Interactions

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 the *state of knowledge* about the properties and laws that govern the parts at the micro-level.

There are open questions concerning this definition:

- What constitutes an *acceptable explanation*?
- What is the reference for the *state of knowledge*?
- What is the difference between *explanation* and *reduction*?

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.

Explanation versus *Reduction*

The following quote about *Scientific Reduction* is taken from the *Stanford Encyclopedia on Philosophy*:

> *The term 'reduction' as used in philosophy expresses the idea that if an entity x reduces to an entity y then y is in a sense prior to x, is more basic than x, is such that x fully depends upon it or is constituted by it.* ***Saying that x reduces to y typically implies that x is nothing more than y or nothing over and above y.***

In an *artifact*, such as an SoS, emergent properties appear at the macro-level if the parts at the micro-level interact according to a *design provided by a human designer*—this is ***more*** than the parts considered in isolation.

Scientific Explanation

Hempel and *Oppenheim* outlined a 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 *eternal*, *inexorable* and *universally* valid while established rules are *context 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 *applicability* and *rigor* of various established rules differ substantially.

Causation

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

However *unidirectional temporal cause-effect* relations play a prominent role in our subjective models of the world. 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

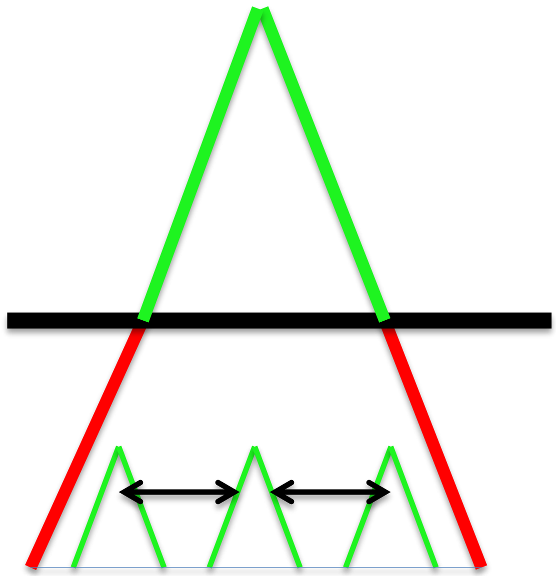
The interaction of the parts at the micro-level cause the whole at the macro-level while the whole at the macro-level can *constrain* the behavior of the parts at the micro-level. This *is downward causation*—resulting in a *causal loop*.

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
within the limits of upward
and downward causation.

Upward Causation
by *natural laws* or
from *imposed laws*.

Conductor vs. Orchestra

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

Examples of *Explained Emergence*

In this Section 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
- Thrashing
- Conway’s Game of Life

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.

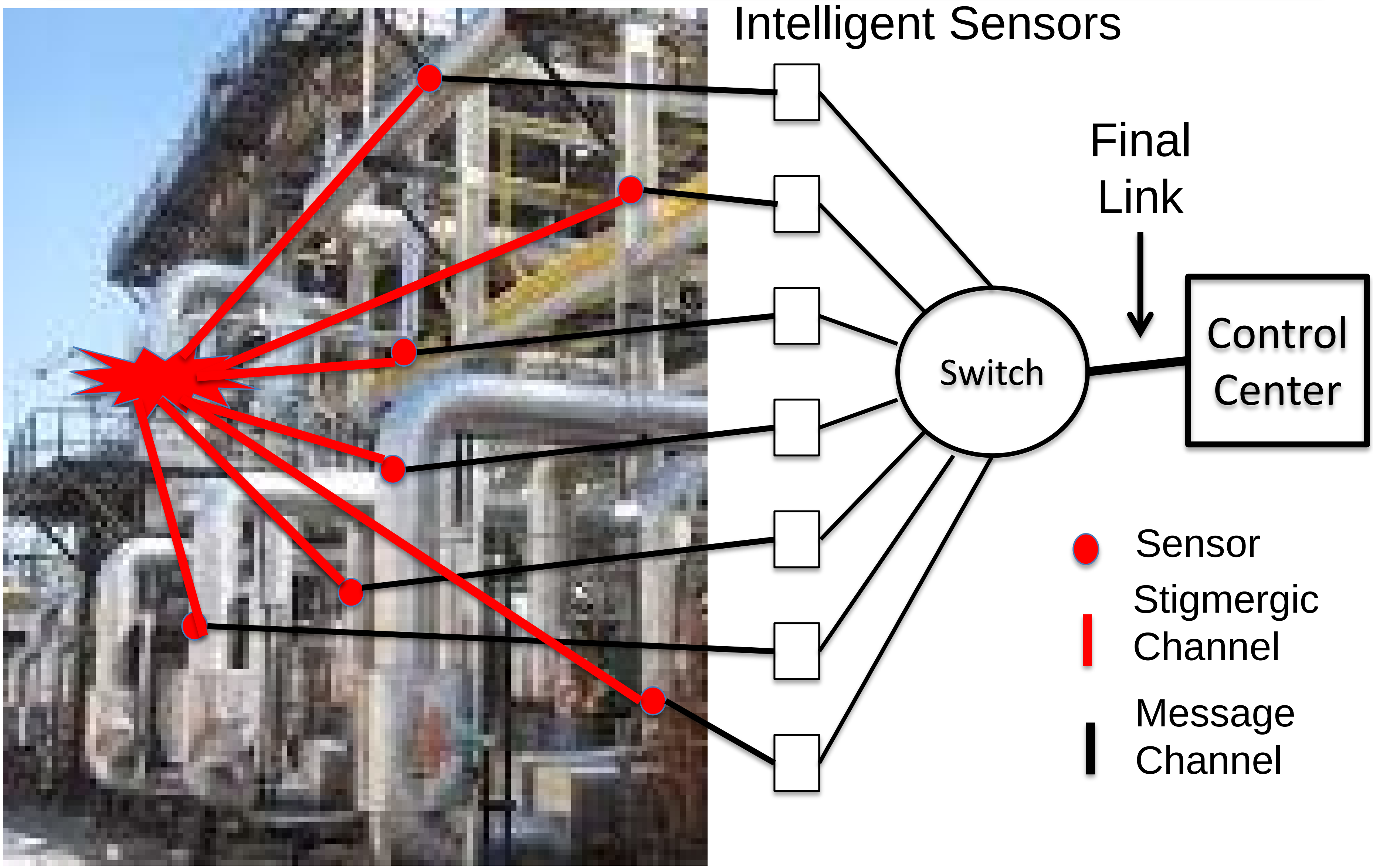
Discussion: Fault-Tolerant Clock Synchronization

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 of the design (the clock synchronization algorithm), it is considered *failed* and expelled from the ensemble.

Thrashing in Alarm Monitoring



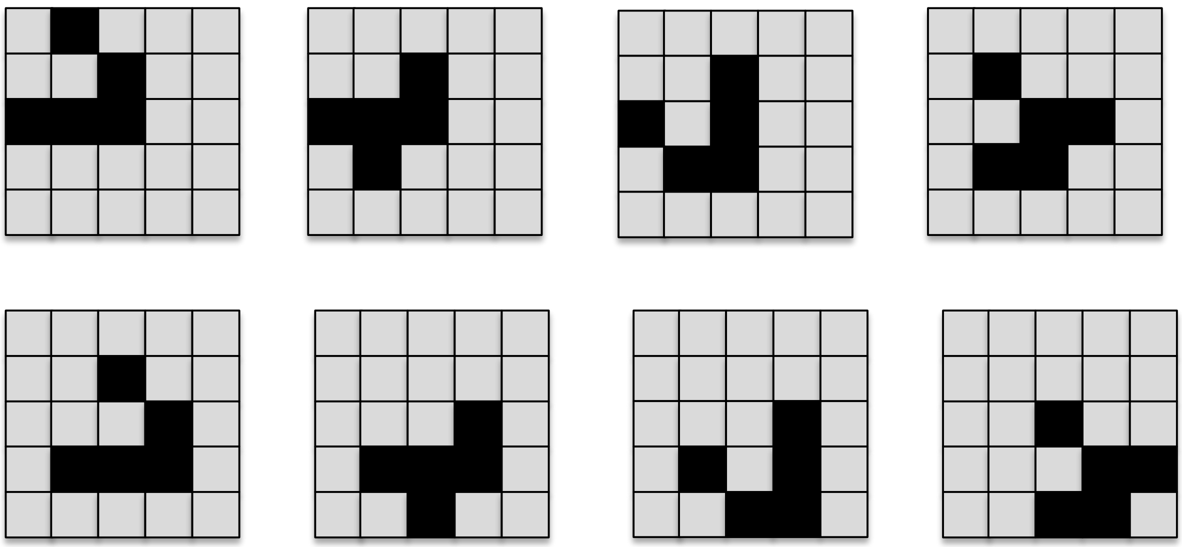
Discussion Thrashing

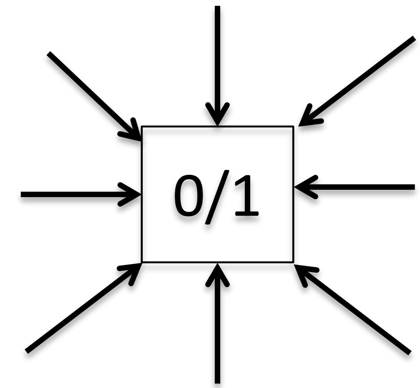
The event of a physical failure (e.g., the rupture of a pipe) causes a correlated concurrent stigmergic information flow to a set of sensors.

The *resource limitation* on the *final link* causes the retry-mechanism of event-based transmission protocols to kick in which further increases the traffic

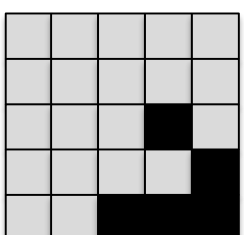
- What is the novel phenomena? Breakdown of real-time communication
- Is *Thrashing* explainable? yes
- *Downward causation:* The delay, caused by the *ensemble of concurrent messages* in a link of finite capacity causes the real-time communication to break down.
- Is *Thrashing* predictable? Yes

Conway's *Game of Life: The Glider*





A *cell* has 2 states (gray=0, black= 1) and 8 neighbors



Conway's ***Rules of Life***:

If state = 0 **and** exactly three neighbors are in state 1
then the state becomes 1, **else** it remains 0
If state = 1 **and either** two **or** three neighbors are in state 1
then the state remains 1, **else** it becomes 0

After four cycles, the pattern has moved along the diagonal.

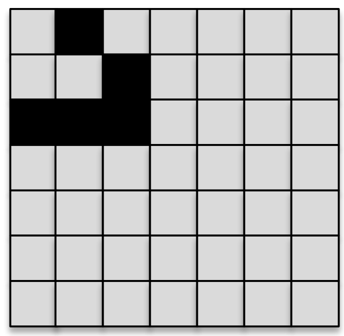
Discussion: Conway's Game of Life

If we select a *grain of observation* that observes the evolving patterns only after every four rounds then we observe the *glider* moving down diagonally. Holland calls this an *emergent phenomenon*.

The hierarchy of Conway's Game of Life is a *Description Hierarchy* where the macro-holons are *epi-phenomena*.

- What is the novel phenomenon? Moving glider
- Is the phenomenon explainable?   yes
- *Downward causation* is realized the cumulative effects of a round on the next round.
- Is the *phenomenon* predictable? Yes

Conway's *Game of Life: The Glider*



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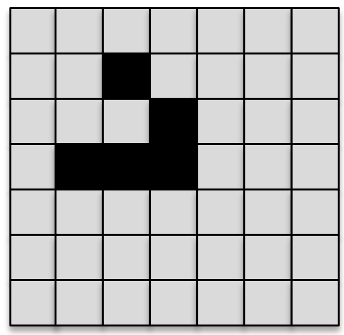

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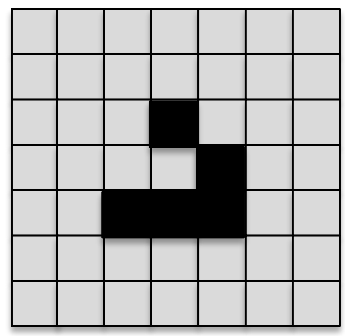

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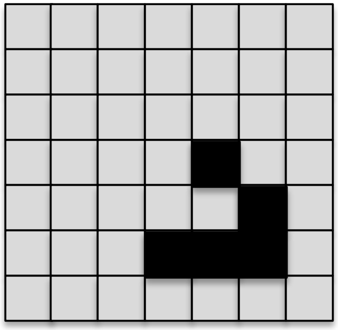

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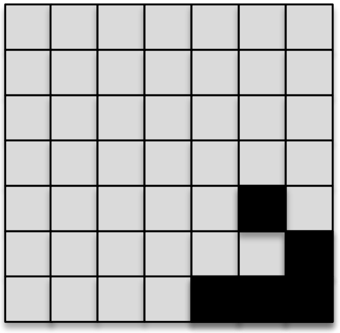


Consequences for System Design

Emergent phenomena in a System-of-Systems are caused by *designed* or *unplanned* interactions among the Constituent Systems that close a *causal loop* such that the behavior of the *ensemble of parts at the macro-level* effects the behavior of *an individual part at the micro-level*.

In order to detect actions that can lead to emergence

- **Expose all Information Flow Channels**
- **Search for Causal Loops**
- **Identify Capacity Limits**
- **Analyze Dynamic Mechanisms**
- **Maintain the *Integrity* of the Multi-level Hierarchy**

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.

CPS versus a *CP-SoS*

Characteristic	CPS	CP-SoS
Scope of System	**Fixed (known)**	**Not known**
Requirements and Spec.	Fixed	Changing
Context	Single	Multiple
Evolution	Version control	Uncoordinated
Testing	Test phases	Continuous
Implementation Technology	Given and fixed	Unknown
Faults (Physical, Design)	Exceptional	Expected
Control	Central	Autonomous
Emergence	Insignificant	Important

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 be 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.

Identify Capacity Limits

Whenever the usage of a resource approaches a capacity limit then the delay of an expected response to service request is increased. In many cases a *retry operation* is executed, in case this delay increases beyond a set *time-out*. The resulting increase in resource usage can produce an *avalanche effect*, such as trashing (an *emergent effect*).

It is therefore a good design practice to analyze the system behavior under peak load conditions and look for mechanisms that can lead to an avalanche effect..

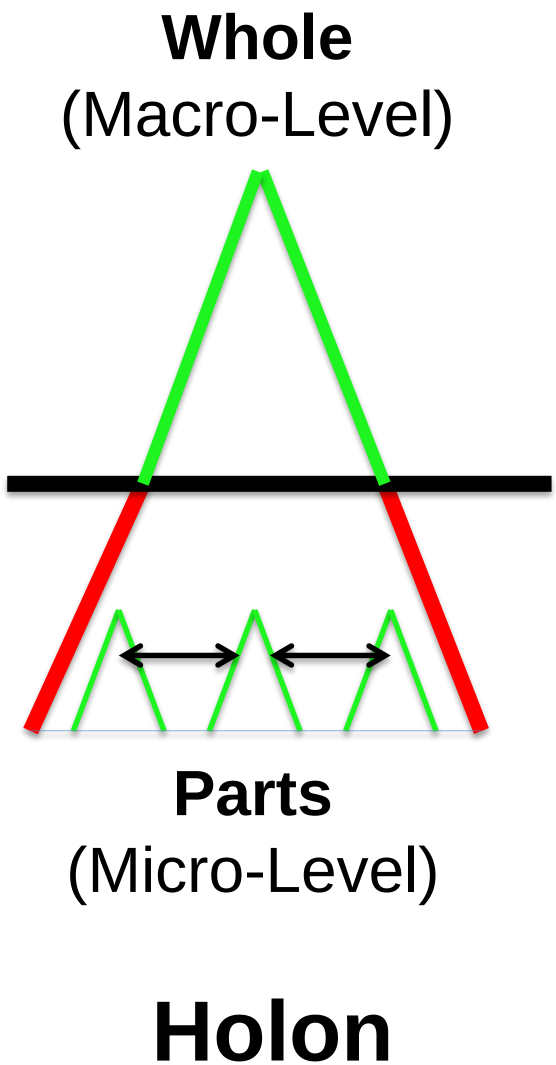
Analyze Dynamic Mechanisms

A Holon at any given level is an autonomous entity that tries to implement its functionality within the behavioral constraints imposed by upward and downward causation.

In order to maintain its *service* in a changing environment it may resort to *dynamic adaptive mechanisms* that are *productive* at the level of the holon but *unproductive* at the higher system levels (Example: *retry mechanism*).

It is therefore good practice to analyze the dynamic mechanisms within the holons with respect to their effect on the system properties.

Maintain the *Integrity* of the Multi-level Hierarchy



Maintain the Integrity of the Multi-level hierarchy by avoiding any *outside interaction* of the parts of a holon at the micro-level.

Any such interaction destroys the abstraction provided by a holon.

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.

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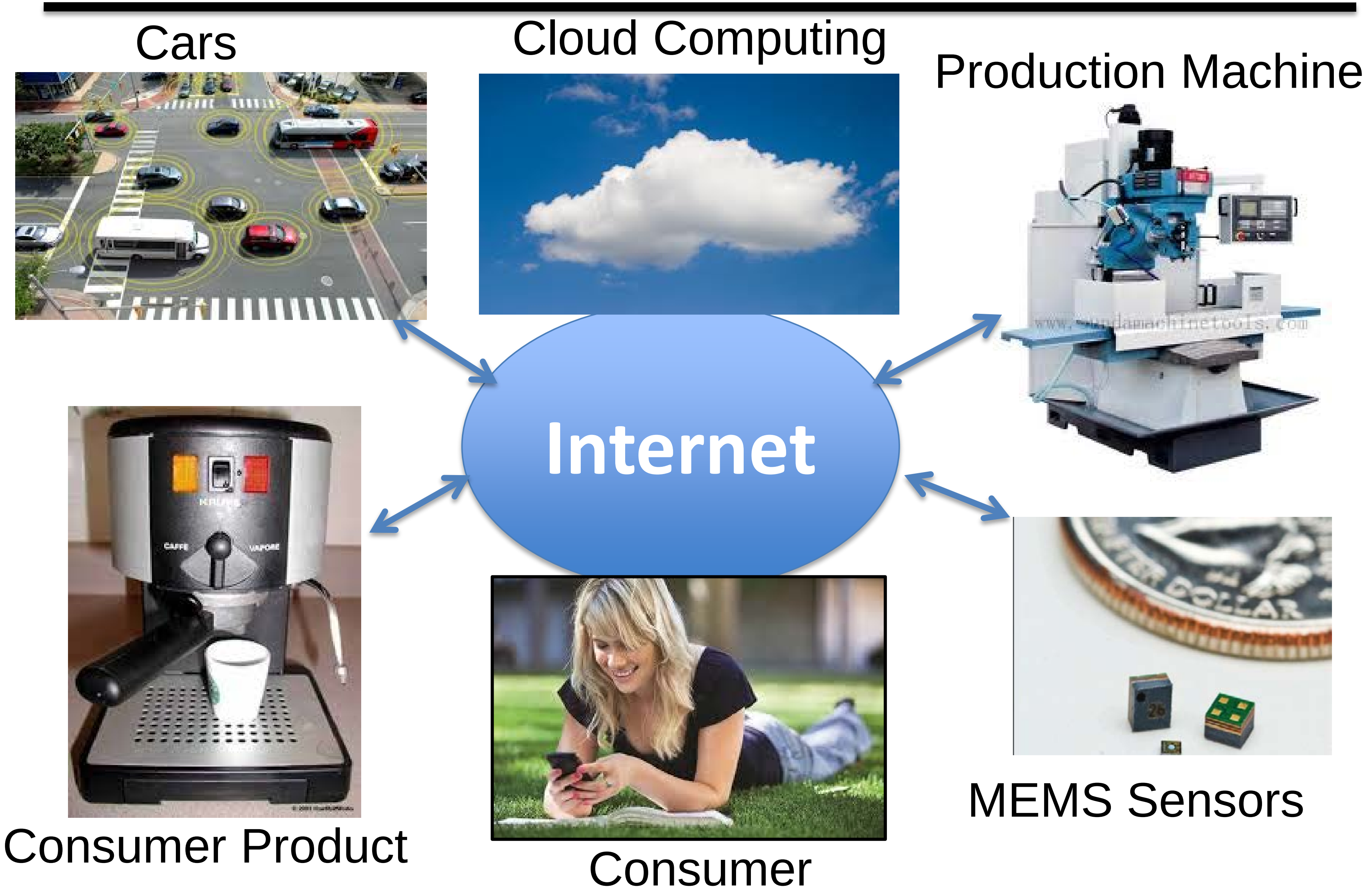
The *Internet of Things (IoT)*



IoT: Cyber Space* meets *Physical Space

Cyber Space	**Physical Space**
World of *Constructs*	World of *Things*
Program execution	Laws of physics
Execution time	**Physical time**
Time-base sparse	Time base dense

We need a computational model, where physical time and execution time are properly integrated.