Emergence in Cyber-Physical Systems of Systems (CPSoSs)

Credits to Hermann Institute of Computer Engineering, Vienna University of Technology

Outline

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

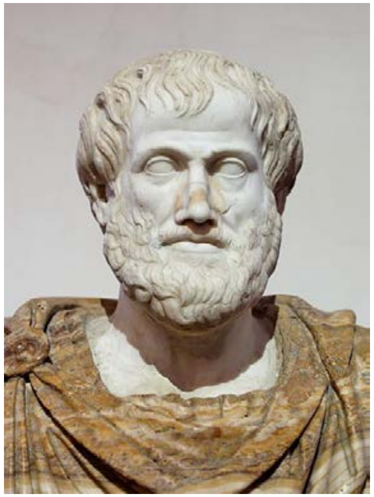
The *Essence* of *Emergence*

The Whole is Greater than the Sum of its Parts*

The Whole: The Cyber-Physical **Systems of Systems**

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 **humans** that **interact to provide a given service**

System-of-Systems (SoS)

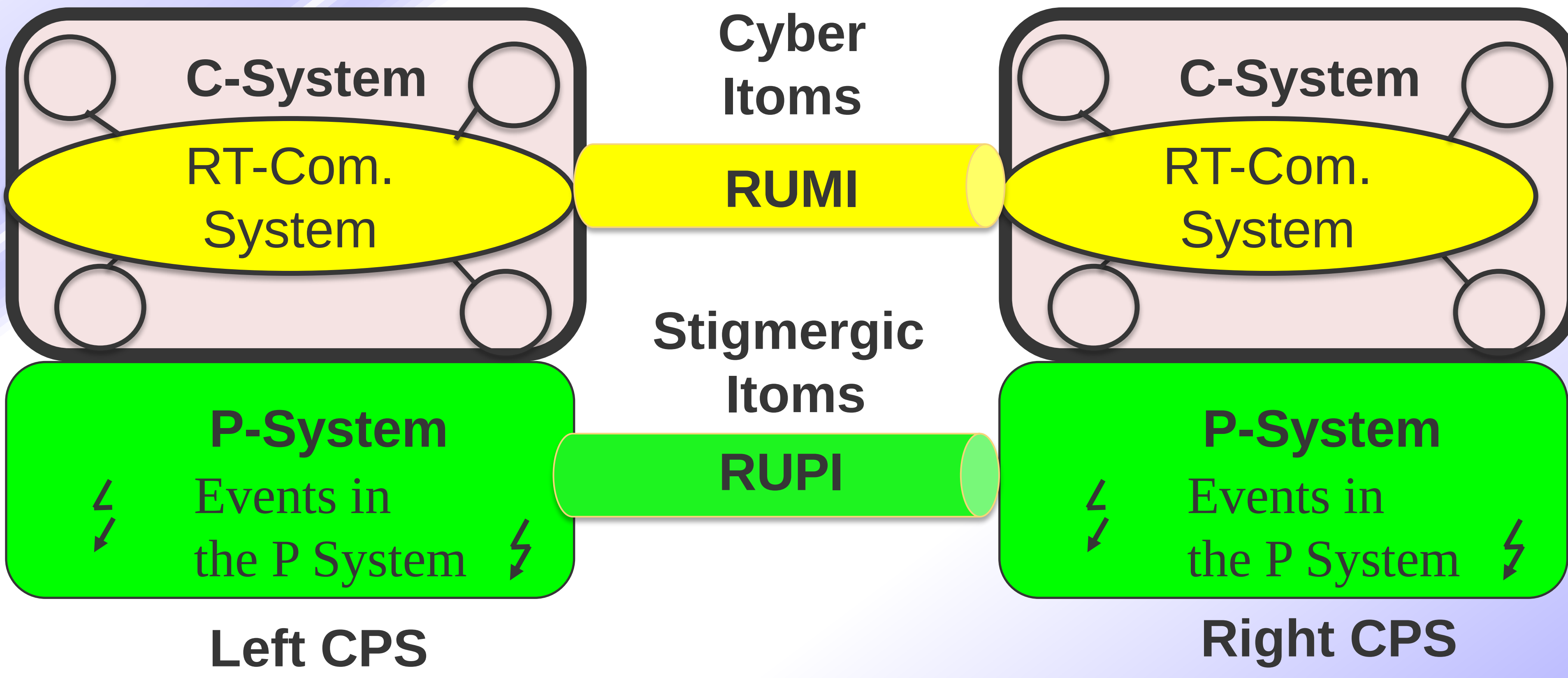
A System-of-Systems (SoS) is an **integration of a finite number of constituent systems** (CSes) which are independent and operable, and which are networked together for a period of time to achieve a **certain higher goal**.

CPS: 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.

Information Flow



Itom: Information Item

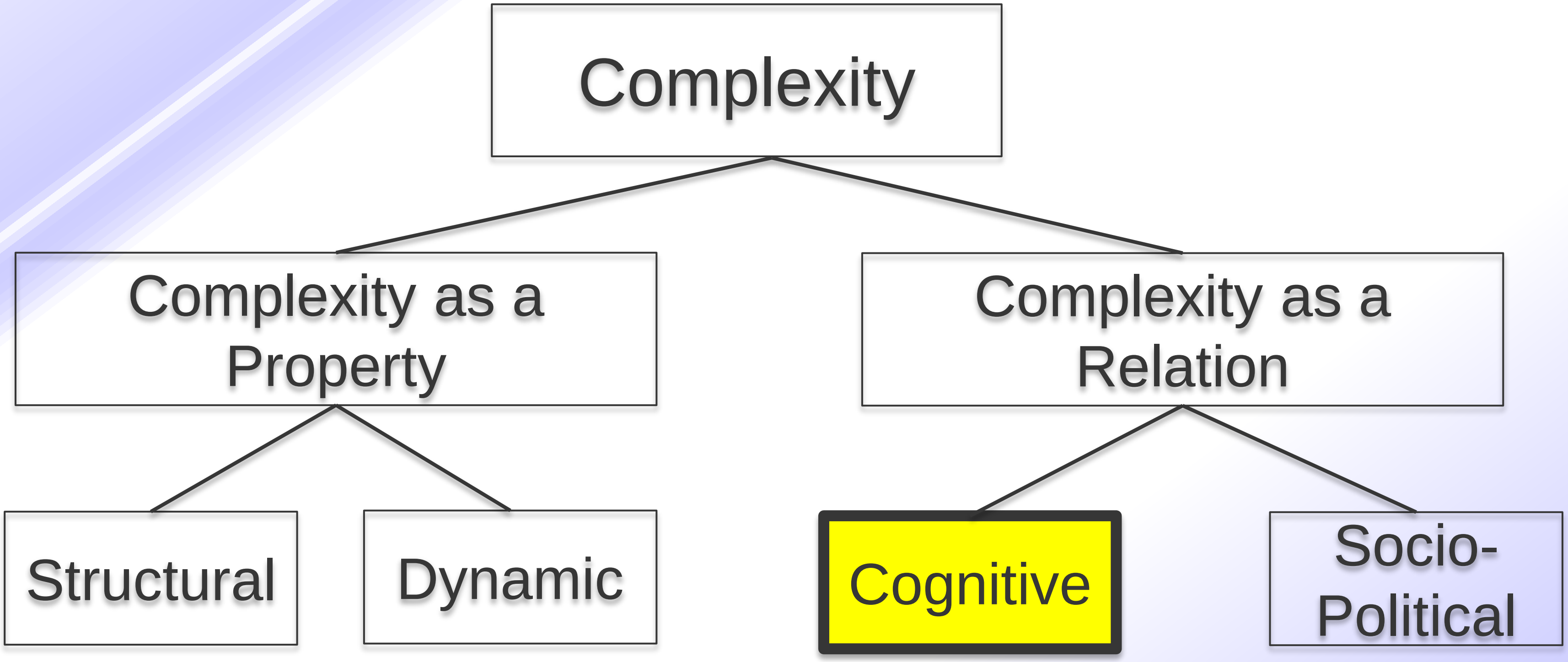
RUMI: Relied upon Message Interface

RUPI: Relied upon Physical Interface

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

According to Craig, *understanding the behavior* 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 <u>it is new with respect to the non-relational phenomena of any of its proper parts at the micro level</u>.

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

As Emergent properties may have beneficial or detrimental effects

- **Govern and manage the emergence so to have only ‘good’ emergence**

Multi-Level Hierarchy

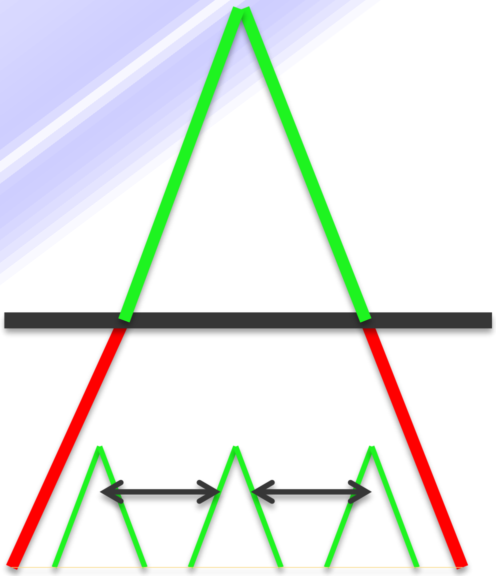
- The understanding and analysis of the immense variety of things and their behavior in the non-living and living world around us requires appropriate *modeling structures*.
- Such a *modeling structure* must limit the overall complexity of a *single model* and support the step-wise integration of a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

Multi-Level Hierarchy - 2

- 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.***

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]

Holon: the Entity of a Two-Levels Hierarchy



The term ***holon*** was introduced 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*.

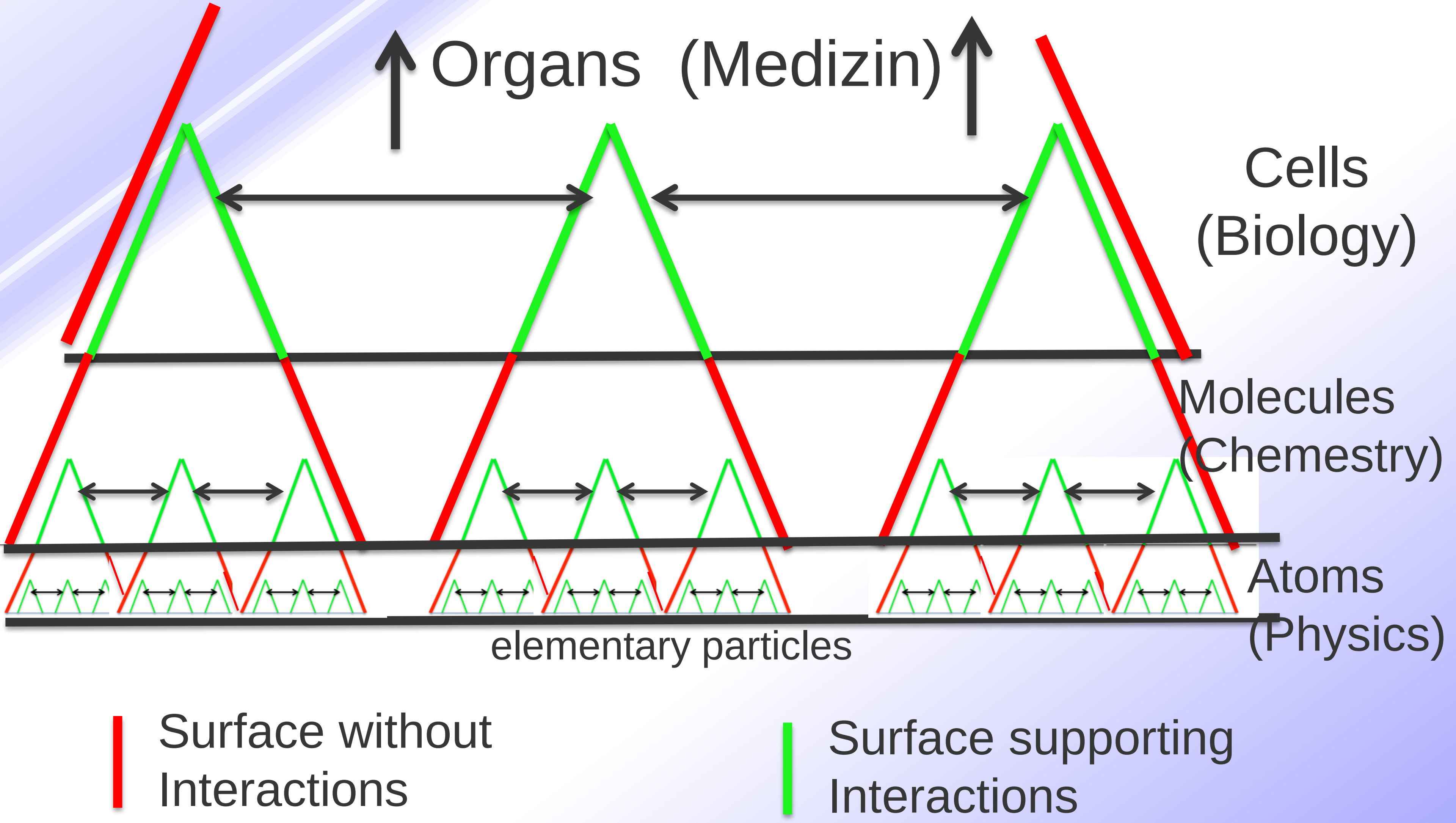
The word *holon* is a combination of the Greek "*holos*", meaning ***all***, and the suffix "*on*" which means ***part***.

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.*

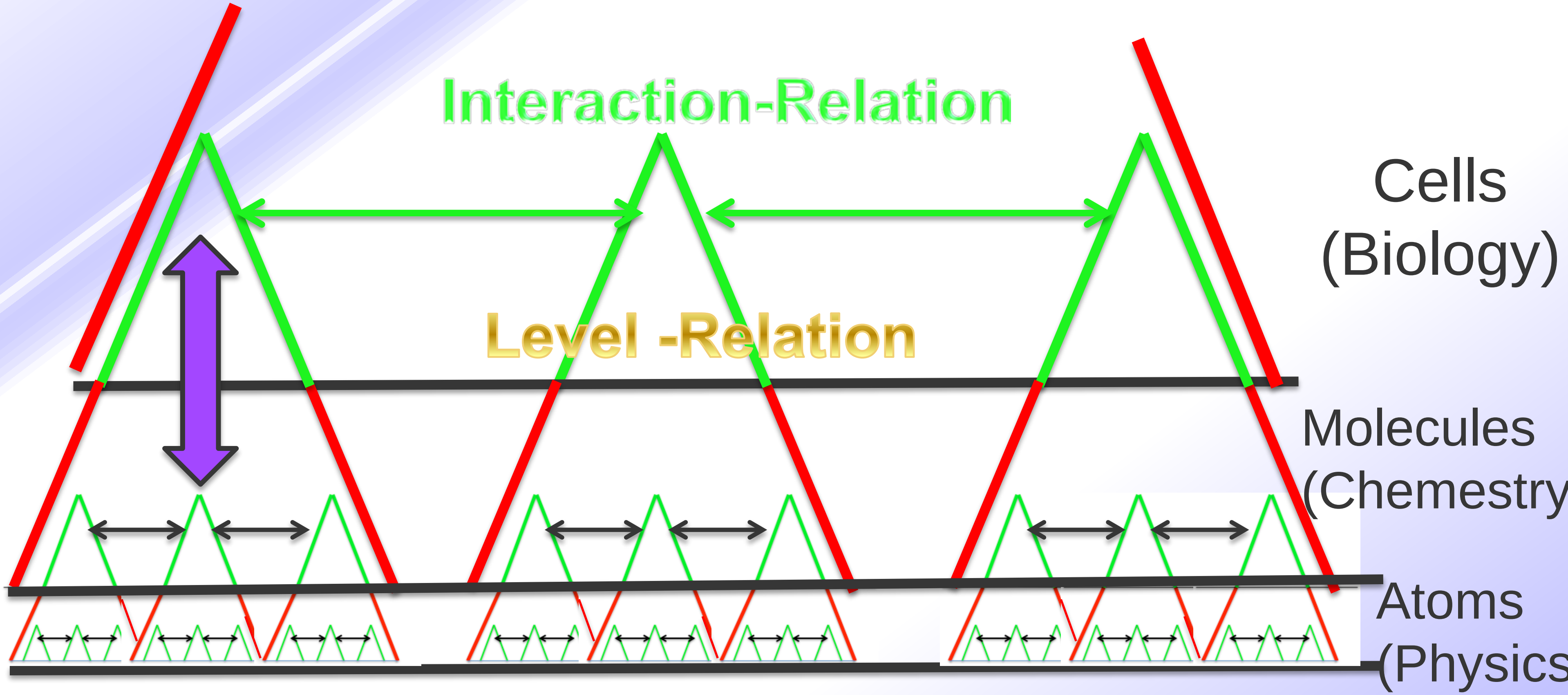
Recursion in a Multi-Level Hierarchy

- 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*)



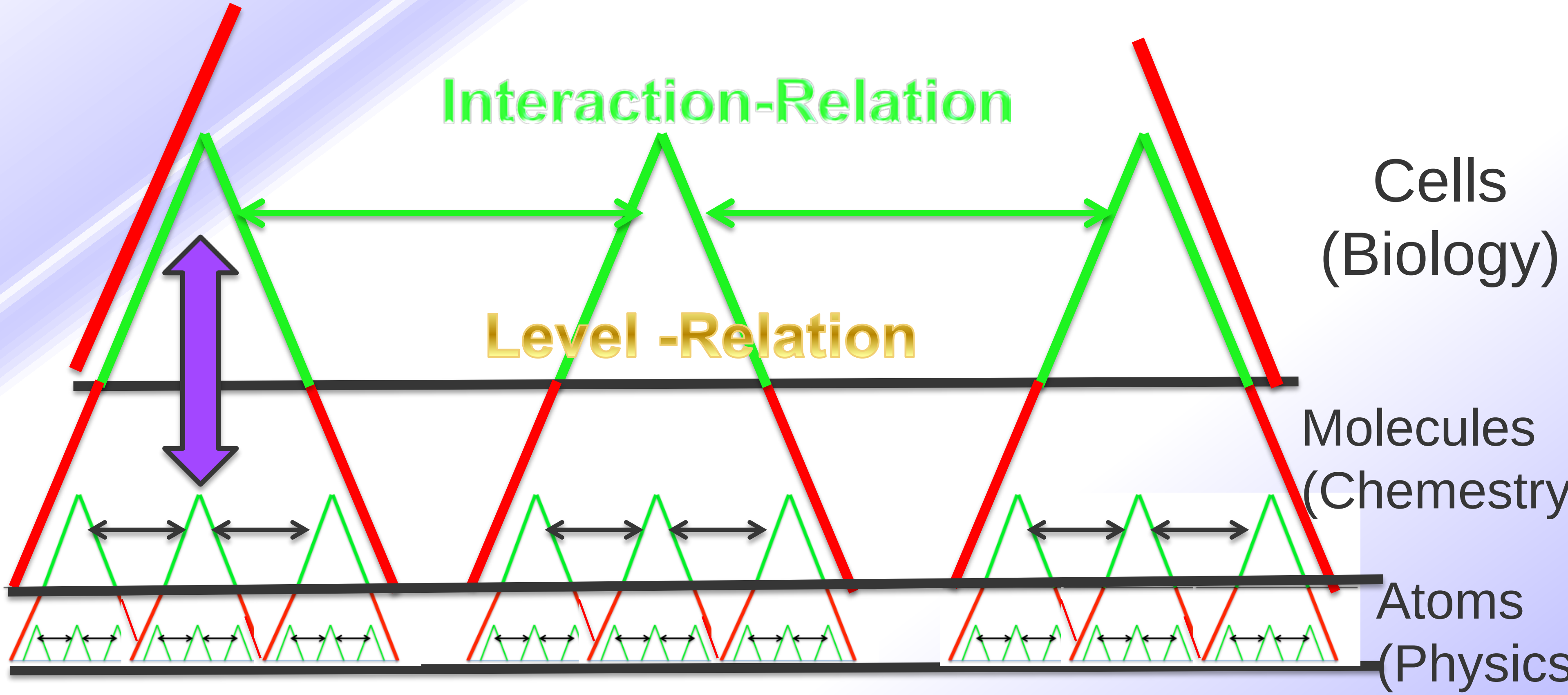
Holarchy relations



Surface without Interactions

Surface supporting Interactions

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

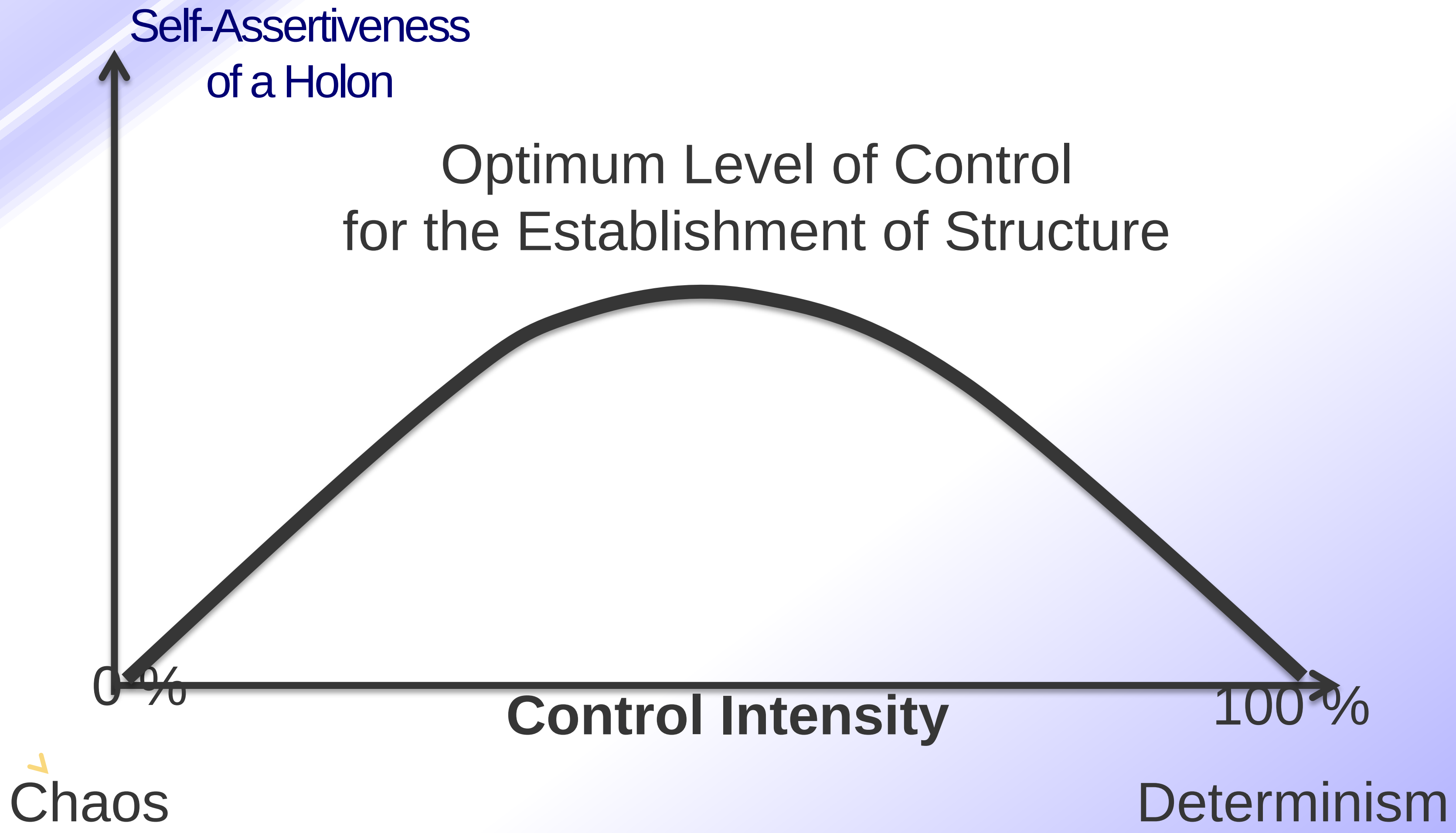
In order to support the simplification at the macro-level and establish a hierarchical control level, a *control hierarchy* must

- 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

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*. **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

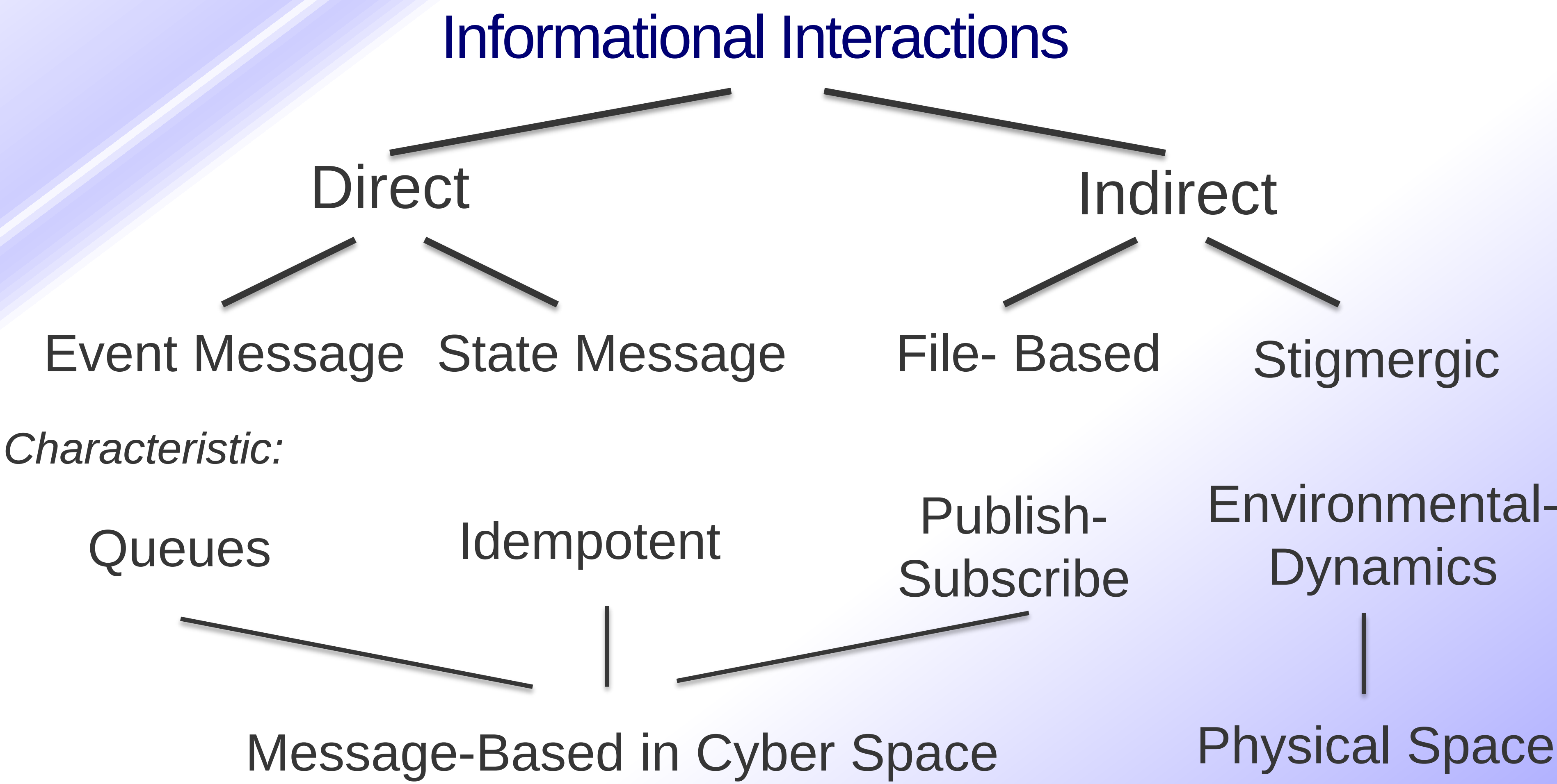
- **Physical Interactions**: come about by force fields, (e.g, electromagnetic or gravitational fields). They are *synchronic*. Physical structures (e.g, a molecule) are mainly formed by force fields.
- **Informational Interactions**: come about the exchange of *Itoms*, either across message channels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



Bedau’s Characterization

The Whole ***emerges*** from the parts

Two Hallmarks

(i) The Whole *depends* on the parts

(ii) The Whole Is *autonomous* from the parts

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.

Types of Emergence

Emergent Phenomena

- **Domain**
  - Structure
  - Behavior
- **Predictability**
  - Unpredictable
  - Stochastic
  - Deterministic
- **Explanation**
  - None
  - In Principle
  - By Rules (Simulation)
  - By Rules (Analytic)
- **Consequences**
  - Positive
  - None
  - Negative

Emergence is a powerful simplifier

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

Examples:

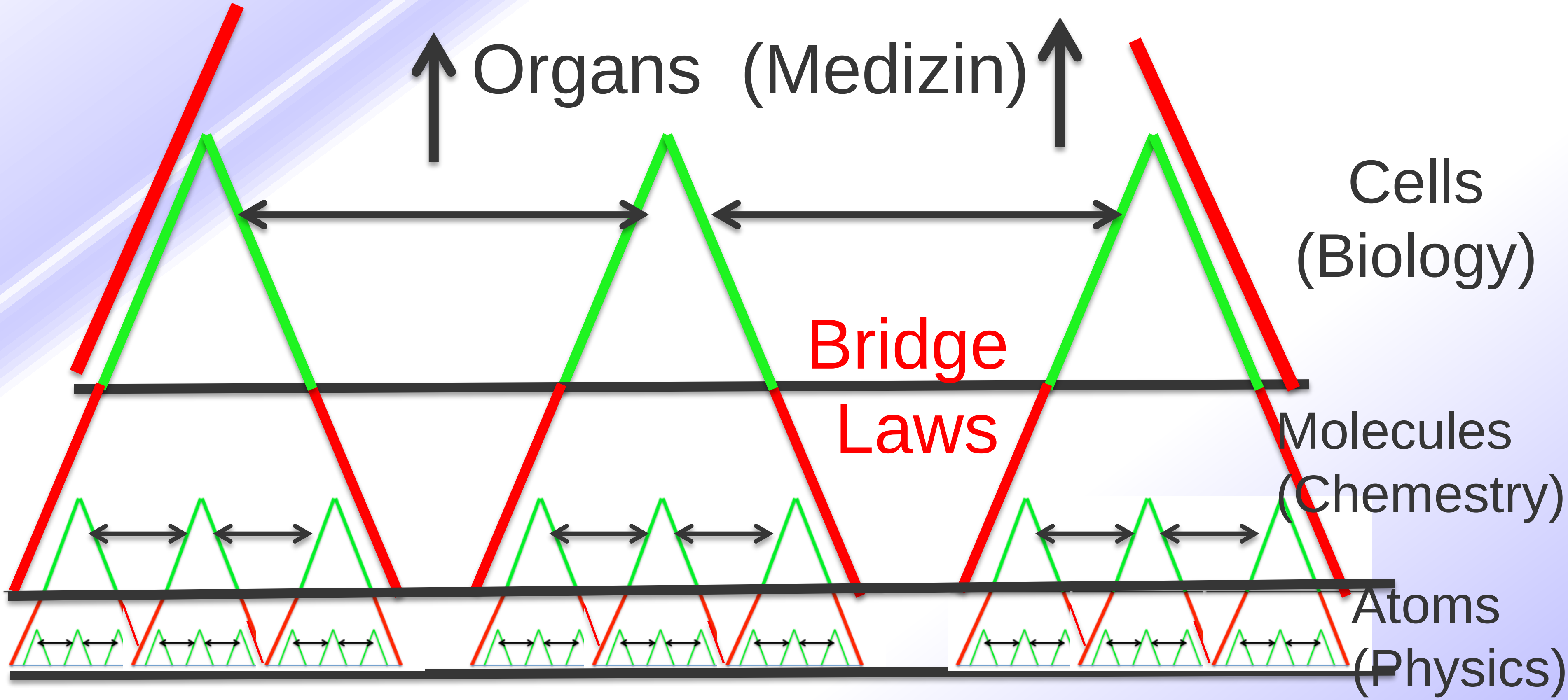
- Fault-Tolerant Distributed Clock Synchronization → leads to the new concept of a *Dependable Global Time*
- The interactions among set of properly connected transistors → A *new whole* the behavior of which can be described by the concepts of *Boolean Logic.*
- A multitude of gas atoms leads to a *new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

Nested Multi-level Hierarchy (*Holarchy*)



***Upward Causation* by the Laws of Physics**

Emergence is our *Friend*, not our Enemy

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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

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.

Causation

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

However *unidirectional 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

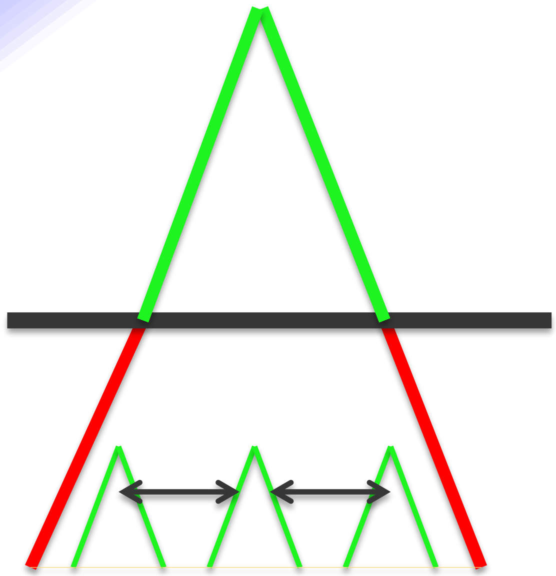
The interaction of the parts at the micro-level cause the whole at the macro-level while the whole at the macro-level can *constrain* the behavior of the parts at the micro-level. This *is downward causation*—resulting in a *causal loop*.

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 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.

Eexample 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*

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
- Thrashing
- ➢ *2001 Stock exchange flash crash (NOT EXPLAINED YET)*

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

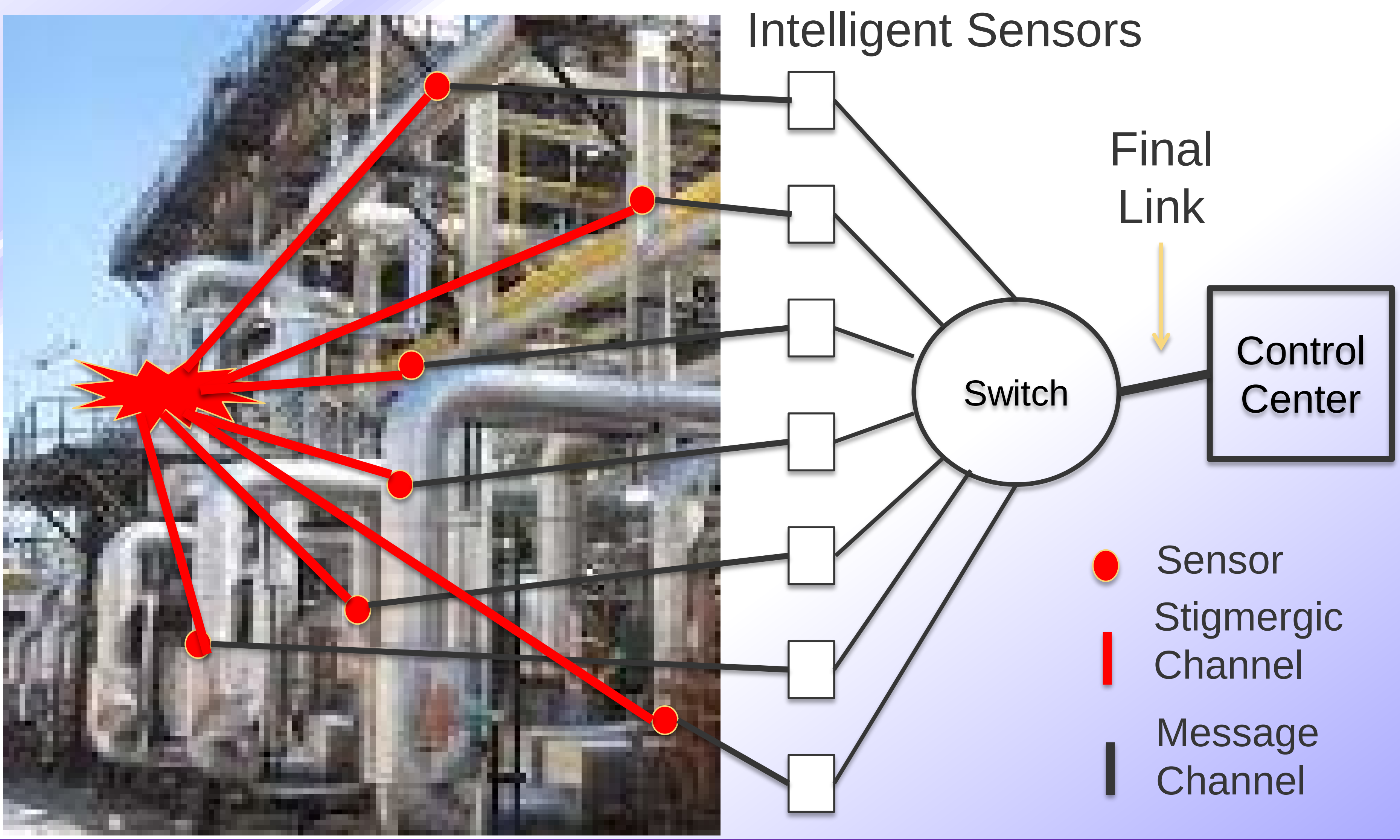
Discussion: Deadlock

- 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.

Thrashing in Alarm Monitoring

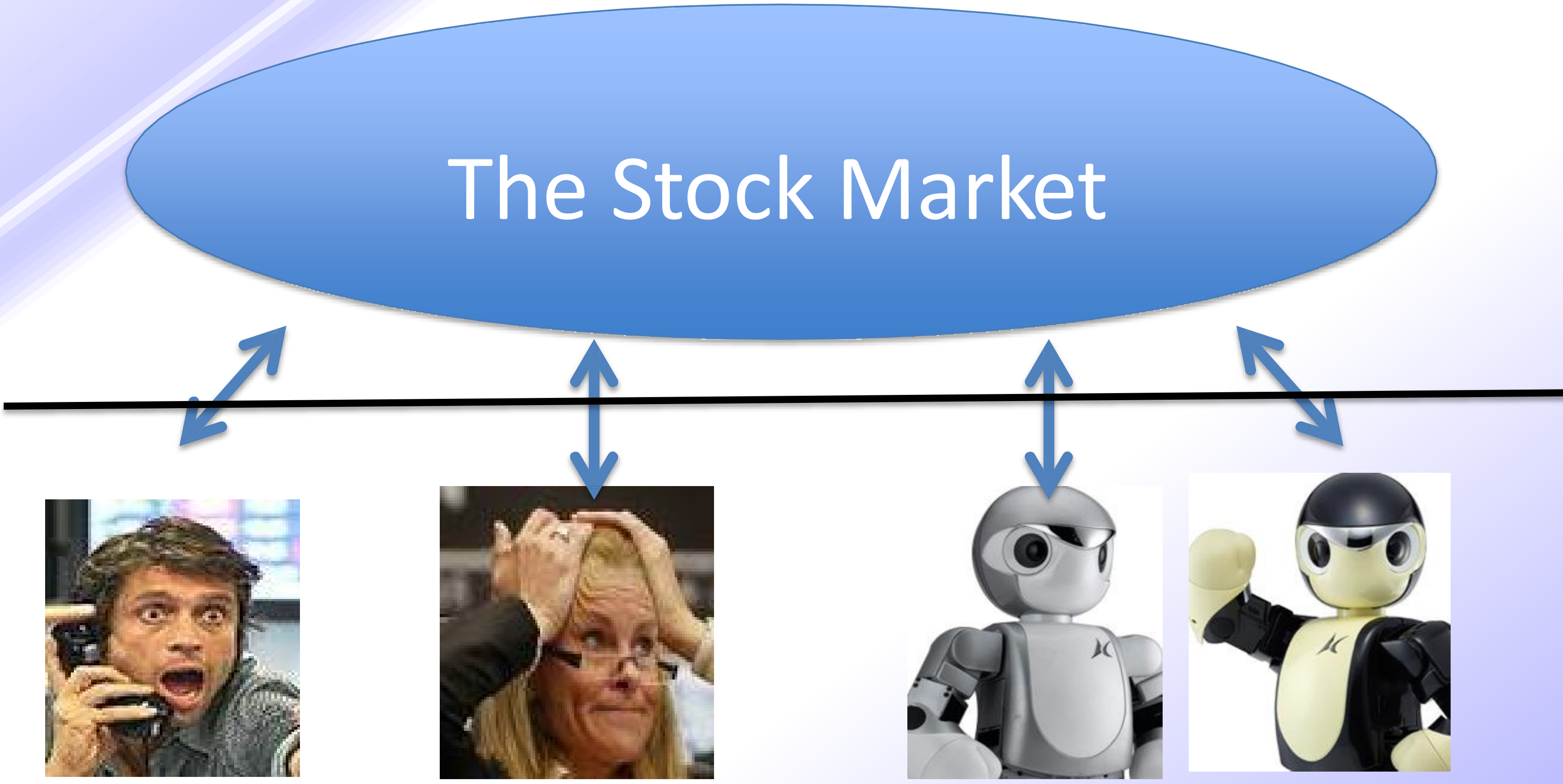


Discussion Thrashing

- 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

Unexplained emergence

Stock Market *2010 Flash Crash*



Reaction Time:
About 1 second

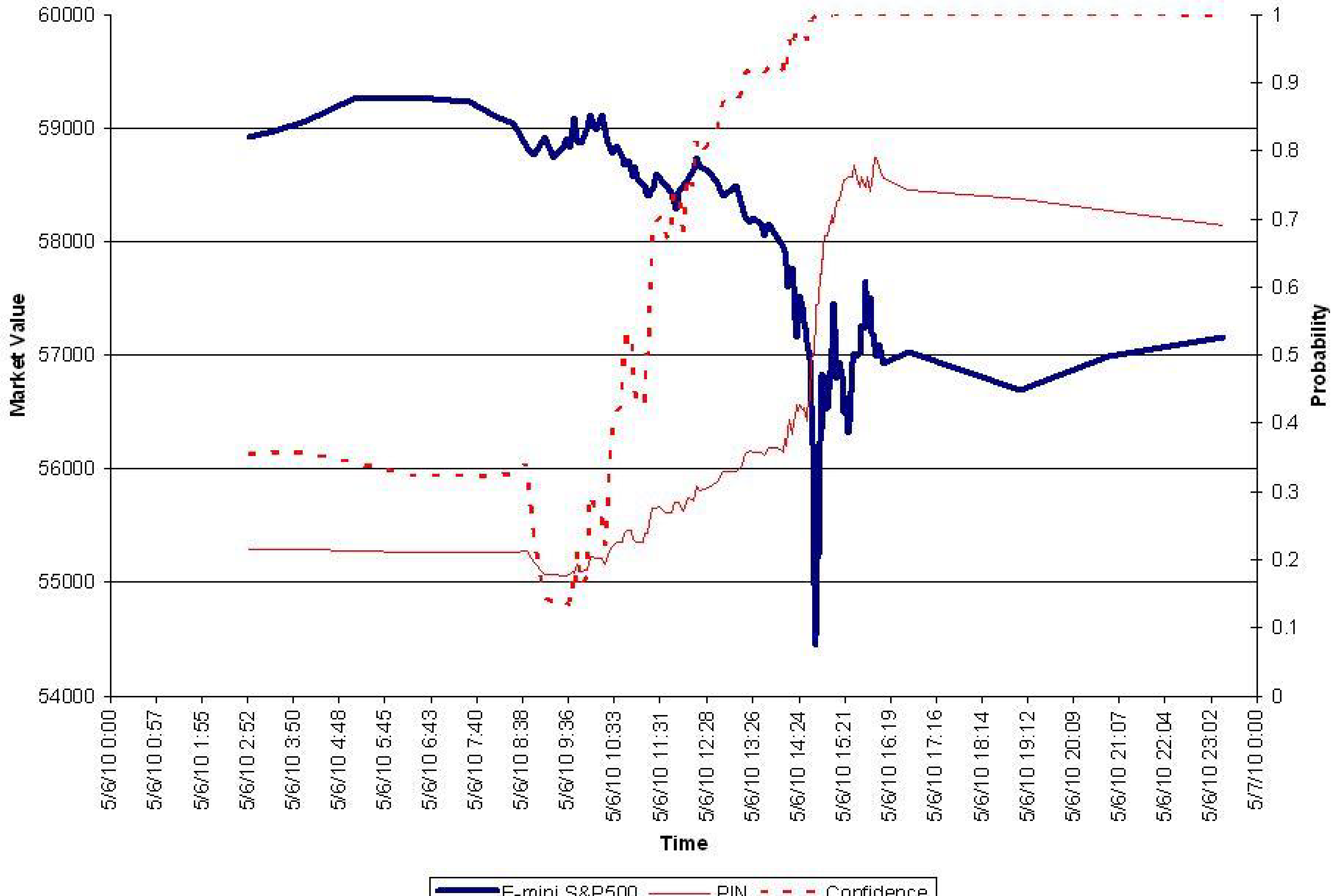
Reaction Time:
About 1 millisecond

High Frequency Trading

- In today's electronic financial markets, a single investor can execute more than 10,000 trades a second, meaning that more than 1,000 trades can happen in the blink of an eye.
- Electronic trading firms are willing to spend hundreds of
- millions of dollars to shave off even millionths of a second.
- This raises an important question for human welfare: If real economic activity depends on people doing things, and people can't possibly think or react this fast, who benefits from all the speed?
- Bloomberg View, Jan 25,2015

What happended on May 6,2010 ?

- The US trillion dollars stock market crash started at 2:32 and lasted for about 36 minutes.
- *As computerized high-frequency traders exited the stock market, the resulting lack of liquidity causes shares of some prominent companies to trade down as low as a penny or as high as $100.000* (N.Y Times, October 1, 1. 2010.)
- *The absurd result of valuable stocks being executed for a penny likely was attributable to the use of a practice called "stub quoting." When a market order is submitted for a stock, if available liquidity has already been taken out, the market order will seek the next available liquidity, regardless of price* Wikipedia.
- Intense investigations and congressional hearings followed, but conclusive evidence is still missing.


60000
59000
58000
57000
56000
55000
54000
Market Value
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Probability
5/6/10 0:00
5/6/10 0:57
5/6/10 1:55
5/6/10 2:52
5/6/10 3:50
5/6/10 4:48
5/6/10 5:45
5/6/10 6:43
5/6/10 7:40
5/6/10 8:38
5/6/10 9:36
5/6/10 10:33
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5/6/10 17:16
5/6/10 18:14
5/6/10 19:12
5/6/10 20:09
5/6/10 21:07
5/6/10 22:04
5/6/10 23:02
5/7/10 0:00
Time
E-mini S&P500
PIN
Confidence

More than 5 years later The *INDEPENDENT*, wrote on Friday, Febr. 15, 2016:

A British financial trader accused of triggering the 2010 Wall Street "flash crash" made more than £600,000 profits on the day, a court was told. Navinder Singh Sarao, 37, who operated from his parents' home in Hounslow, west London, manipulated the market by making "false" and "fictitious" orders on the Chicago Mercantile Exchange (CME) for years, the court heard.

Mark Summers, QC, for the US government, said the futures trader made $875,000 (£615,000) on the day of the Flash Crash on 6 May 2010, when the Dow Jones Industrial Average plunged 600 points in five minutes, wiping tens of billions of dollars off the value of US shares.

More than 5 years later The *INDEPENDENT*, wrote on Friday, Febr. 15, 2016 (ctd.):

*Mr Sarao, who has been dubbed the "Hound of Hounslow", **is fighting extradition to the US where he faces 22 charges including wire fraud, commodities fraud, market manipulation and "spoofing"** – the practice of bidding or offering with the intent to cancel the trade before actually executing the deal. If found guilty of the offences, he could face jail sentences in the US totalling a **maximum of 380 years**.*

At the extradition hearing at Westminster magistrates court in London, Mr Summers claimed Mr Sarao was a prolific trader who earned $4m through his trades on another single day –4 August 2011 – and, in total, made $40m illegally over five years.

Spoofing

Spoofing is a **disruptive algorithmic trading entity employed by traders** to outpace other market participants and to manipulate commodity markets. Spoofers feign interest in trading futures, stocks and other products in financial markets creating an illusion of exchange pessimism in the futures market when many offers are being cancelled or withdrawn, or false optimism or demand when many offers are being placed in bad faith. (Wikipedia)

The Flash Crash: *A New Deconstruction*

Aldrich, E.M, UC Santa Cruz, Grundfest, Stanford Laughlin, U Santa Cruz Published Jan 25, 2016, revised Febr 2, 2016

From the *abstract*:

On May 6, 2010, in the span of a mere four and half minutes, the Dow Jones Industrial Average lost approximately 1,000 points. *In the following fifteen minutes it recovered essentially all of its losses. This "Flash Crash" occurred in the absence of fundamental news that could explain the observed price pattern and is generally viewed as* ***the result of endogenous factors related to the complexity of modern equity market trading****. We present the first analysis of the entire order book at millisecond granularity, and not just of executed transactions, in an effort to explore the causes of the Flash Crash. …… we suggest that it is* ***highly unlikely*** *that, as alleged by the United States Government, Navinder Sarao's spoofing orders, even if illegal,* ***could have caused*** *the Flash Crash, or that the crash was a foreseeable consequence of his spoofing activity. (Bolds added)*

From Aldrich et al. p. 3

- The Flash Crash raises difficult, policy-relevant questions of **causation**. As is the case with most market events, the circumstances of the Flash Crash cannot be replicated.
- Analysts lack access to the specifications of the automated trading algorithms that were active in the markets prior to and during the crash, and cannot replicate the strategies implemented by human traders active during the relevant period.

- These limitations are compounded by significant identification issues attributable to complex market interactions and to the simultaneous presence of multiple potentially interactive causal factors. **In this environment, correlation is easily confused for causation.**

Conclusions onthe Flash Crash

- We do not fully understand the mechanisms that govern the operation of the stock market, although this market is **an *artifact*** (not a *natural system) and* a central mechanism in our free market economy.
- High Frequency Trading (HFT) shifts the *causes for market actions* from *human intervention to computer intervention*.

The Flash Crash of 2010 is an *ill-understood emergent phenomenon*.

Emergence in Safety-Critical Systems

Emergent Phenomena

- **Domain**
  - Structure
  - **Behavior**
- **Predictability**
  - **Unexpected**
  - Stochastic
  - Deterministic
- **Explanation**
  - None
  - **In Principle**
  - By Rules (Simulation)
  - By Rules (Analytic)
- **Consequences**
  - Positive
  - Negative
  - **Catastrophic**

AWARENESS about emergence

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

Consequences for System Design

Emergent phenomena in a System-of-Systems are caused by interactions among the Constituent Systems that close a *causal loop* such that 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**

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 with the other CS 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.
  - Others??

Considering components behaviour

- Components behavior
  - Software/hardware systems operate in an unexpected way. Among possible reasons:
    - wrong design or implementation
    - inappropriate use and inclusion in a system (Software **WRONG** reuse)
  - Problem of COTS and legacy CPSs used in CPSystem of Systems design
    - may come with unknown development faults
    - may contain unknown faults (bugs, vulnerabilities, etc.)
    - their specifications may be incomplete or even incorrect

Expose all Information Flow Channels

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

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 ones 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 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

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.

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➢ UK Pound Flash Crash Oct, 7, 2016