# On the Nature of Computing

ACM Summer School
Athens
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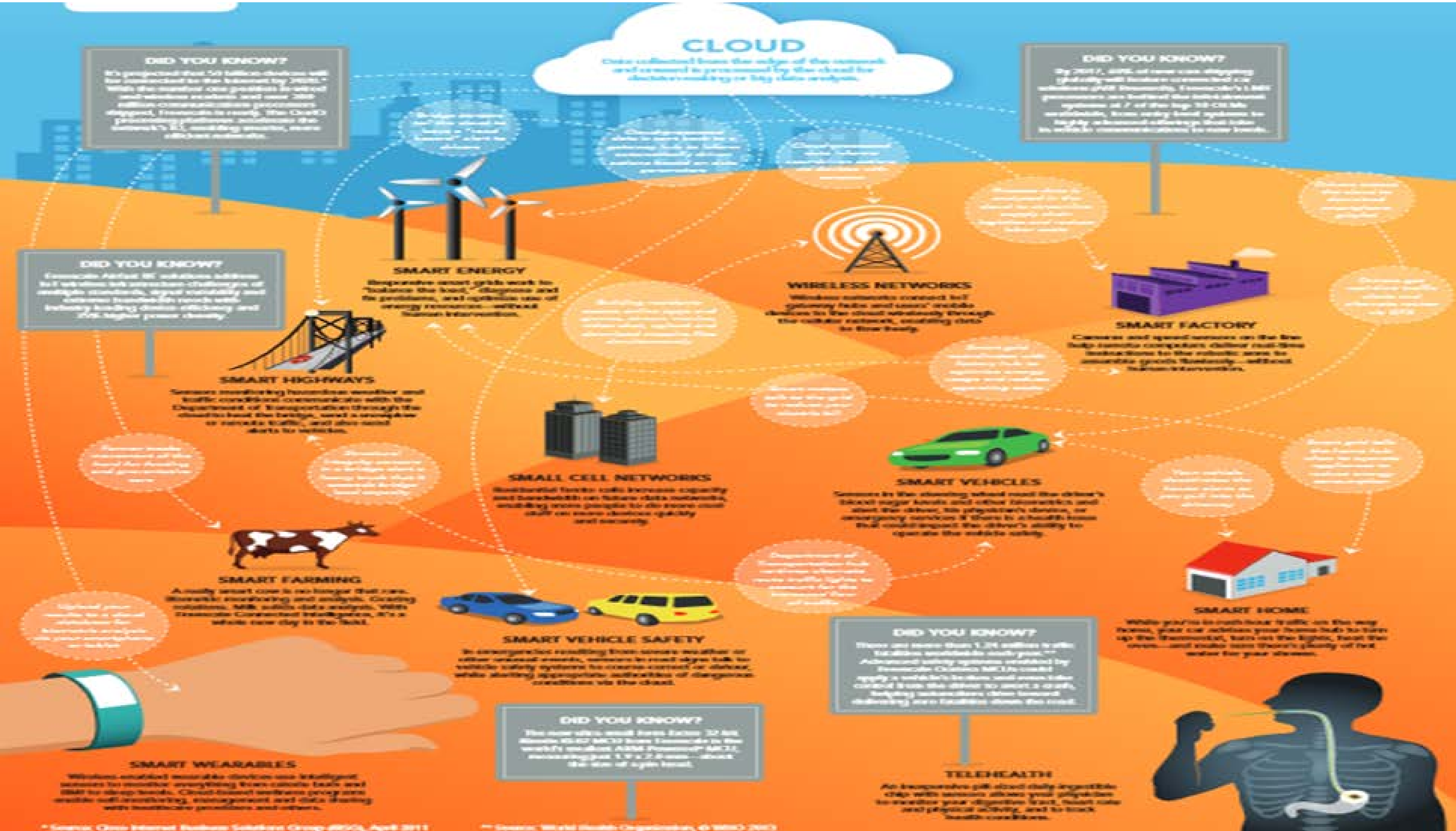
# Computing – The ICT Revolution

*The IoT allows objects to be sensed or controlled remotely across a network infrastructure, achieving more direct integration of the physical world into computer-based systems, and resulting in improved efficiency and predictability.*



# Computing – Relationship to Other Disciplines

- There is currently a lack of recognition of Computing as a discipline:
  - does not enjoy the same prestige as natural sciences and mathematics
  - secondary status in K-12 teaching curricula in most countries

- Physics (physicists) have dominated scientific thought until the end of the 20th century

- For decades the importance of Computing and Information have been underestimated or overlooked by a strongly reductionist view of the world: <u>understanding the nature of complex things by reducing them to the interactions of their parts, or to simpler more fundamental things.</u>

- *"My task is to explain elephants and the world of complex things, in terms of the simple things that physicists either understand, or are working on"*

- *"The capacity to do word-processing is an emergent property of computers"*

- *"Brain could exist outside body"*

# Computing – Some Important Questions

What is Computing?

*The discipline of Computing is the systematic study of algorithmic processes that describe and transform information: their theory, analysis, design, efficiency, implementation, and application. The fundamental question underlying all Computing is "What can be (efficiently) automated?" (ACM 1989)*

- Information and knowledge
- Computation - properties and limitations
- Is Computing a New Domain of Knowledge - Science, Engineering or both ?
- How is it related to basic disciplines, Mathematics, Physical Science, Biology

Linking Physicality and Computation

- Commonalities between physical and computational processes
- Main differences and limitations
- Natural Computing – Digital Physics

Linking Artificial and Natural Intelligence

- The concept of intelligence
- Commonalities and differences?
- Overcoming current limitations

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- What is Information
- What is Computing
- Domains of Knowledge
- Linking Physicality and Computation
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- Discussion

# What is Information?

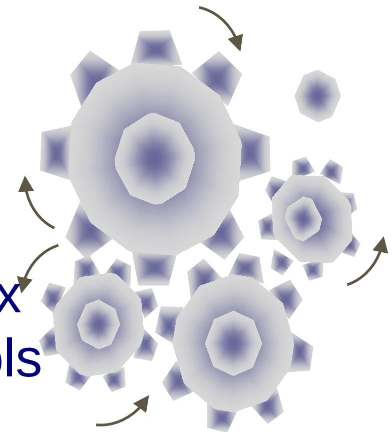
Information is a relationship between the syntax and the semantic domain of a given language

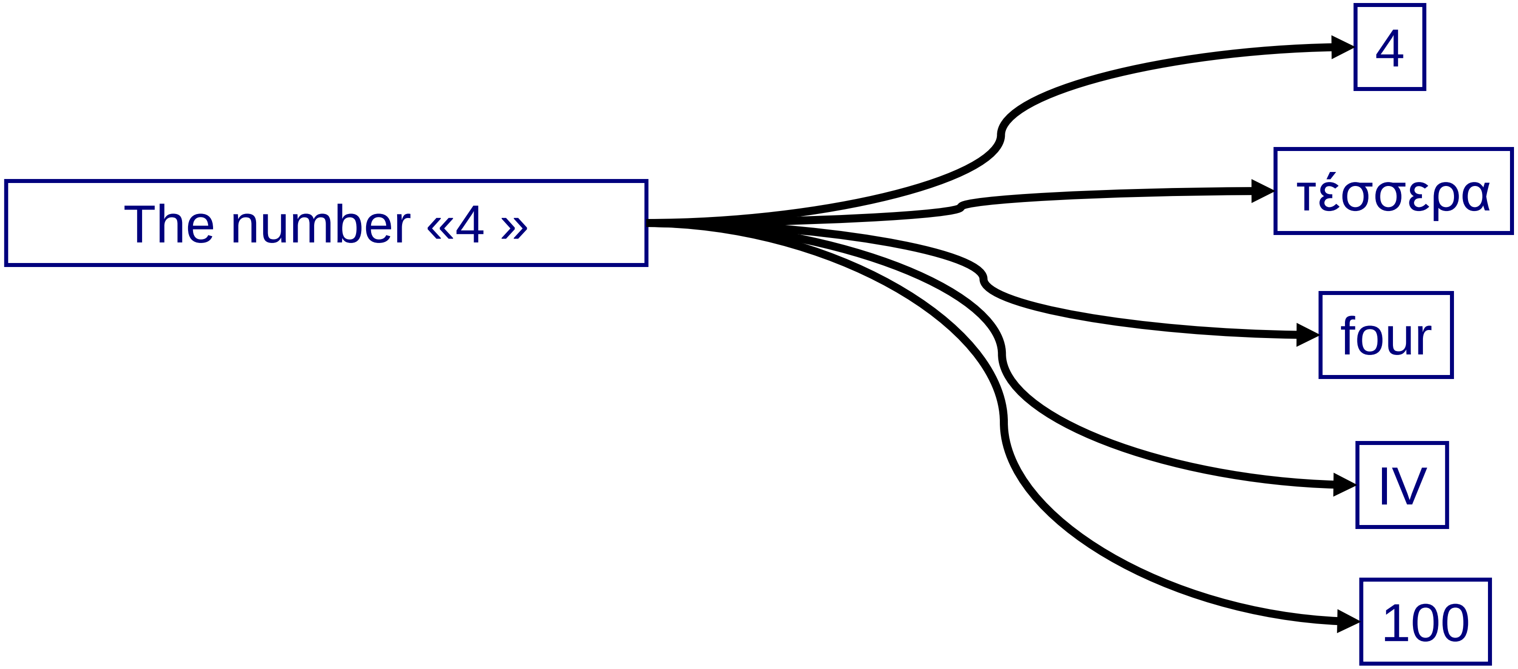
Representation

Semantic Domain
Concepts

Syntax
Symbols

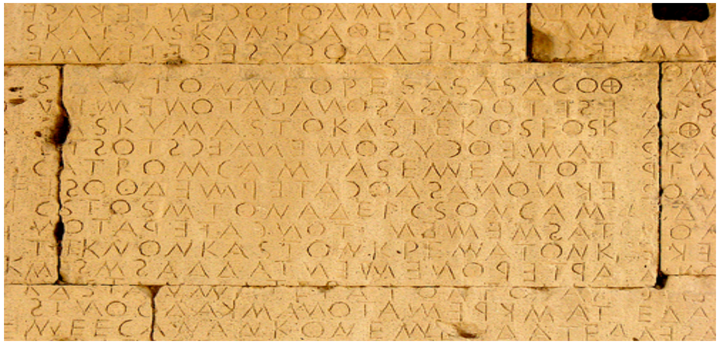
Denotation





# What is Information?–Information is in the Mind of the Beholder

No information



Information for a Hellenist

$$\oint \mathbf{E} \cdot d\mathbf{A} = \frac{q_{enc}}{\varepsilon_0}$$

$$\oint \mathbf{B} \cdot d\mathbf{A} = 0$$

$$\oint \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$$

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt} + \mu_0 i_{enc}$$

Information for a Physicist

Information

Information

- is an <u>entity</u> different from matter/energy
- is <u>non-physical</u> although it needs media for its representation.
- is not subject to physical space-time constraints - the Theory of Computation is time-ignorant
- is created by minds, <u>not</u> by machines

# What is Information – Syntactic Information

Syntactic information is measured as the quantity of symbols, pixels, bits needed for a representation of information.
According to Shannon's Theory, it

- characterizes the content of a message, not its meaning
- is *nlog(b)*, the number of yes/no questions one would have asked to completely resolve ambiguity for a word of length *n* on an alphabet of *b* symbols

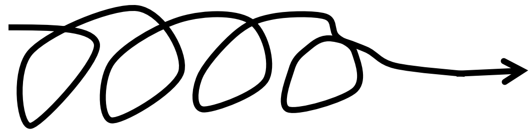
| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| g | o | o | d | m | o | r | n | i | n | g |
| g | d | r | d | o | m | o | n | o | g | i |

Syntactic information theory e.g. Shannon, Kolmogorov

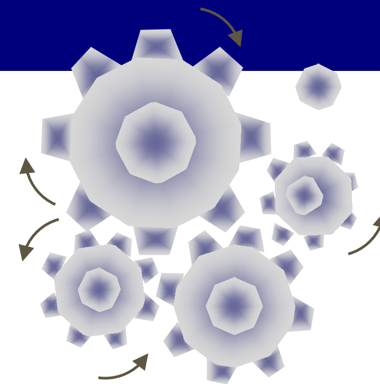
- finds application in data compression, channel coding, information representation techniques
- ignores meaning - It is like saying that one kilo of gold and one kilo of lead are equivalent!

# What is Information? – Algorithm

Semantics
Concepts

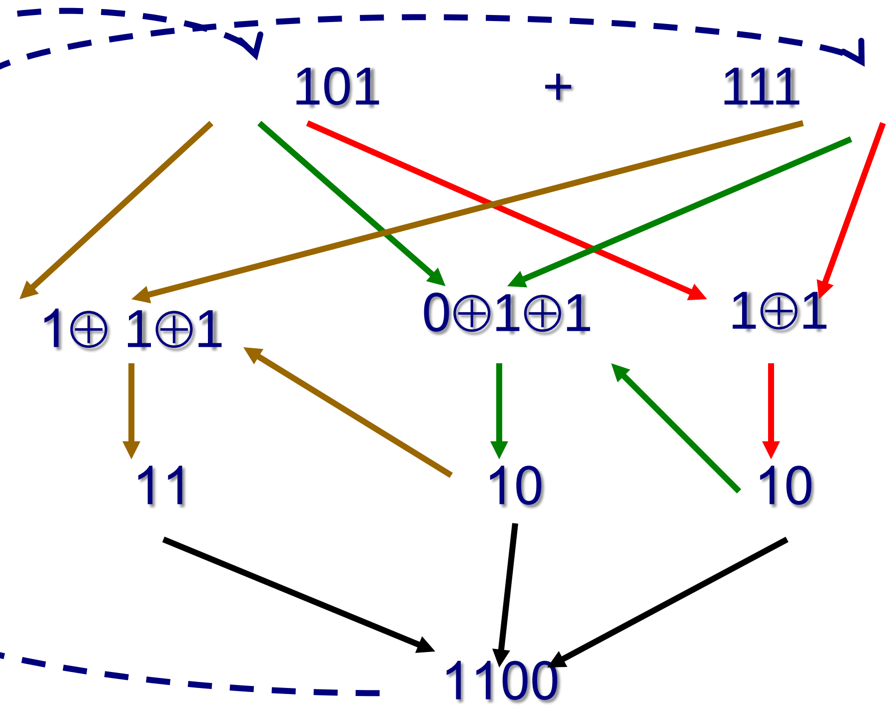


Algorithm



Syntax
Symbols

The sum of «5» and «7» is «12»



# What is Information? – Basic Laws of Computation

<u>Gödel's incompleteness theorem</u>

- For any formal system based on arithmetic, there will always be statements about the natural numbers that are true, but that are unprovable within the system
  Examples of propositions not provable mechanically: *"a program terminates"*, *"the variable x of a program is bounded by some value"*

This theorem sets limits to mathematical knowledge – a kind of "uncertainty principle" for Mathematics.

<u>Complexity</u>: Each problem admitting an algorithmic solution is characterized by its complexity, that is the amount of resources in time and memory needed for its solution.

- The same problem can be solved by algorithms of different complexity
- The complexity of a problem cannot be lower than a certain bound

OVERVIEW

- What is Information
- What is Computing
- Domains of Knowledge
- Linking Physicality and Computation
- Artificial vs. Natural Intelligence
- Discussion

# What is Computing – Science vs. Domain of Knowledge

Science is "*a branch of study concerned with the observation and classification of facts, especially with the establishment and quantitative formulation of verifiable general laws.*" (Webster dictionary)

Standard definitions focus on the discovery of facts and laws

- exclude Computing and many other disciplines such as Mathematics, Social Sciences
- overlook the fact that engineering is (or should be) grounded on rigorous methods involving the application of specific knowledge and its ultimate experimental validation

To understand the nature of Computing, the most pertinent concept is that of <u>domain of knowledge</u>.

*"Knowledge is truthful information that embedded into the right network of conceptual interrelations can be used to <u>understand a subject</u> or <u>solve a problem</u>."*

- Scientific theories, but also Mathematics, Engineering, Social Sciences, Medicine, Cooking are domains of knowledge

# What is Computing – Knowledge

- A priori knowledge is independent of experience e.g. Mathematics, Logic, Theory of Computing.
- A posteriori knowledge is dependent on experience or empirical evidence e.g. Natural Sciences, Engineering, Economics, Cooking.

  A posteriori knowledge comes in degrees – its validity may differ in testability, degree of abstraction and the way in which it is developed.

- Considering domains of knowledge avoids sterile discussions focusing on the scientific or non scientific nature of disciplines

.

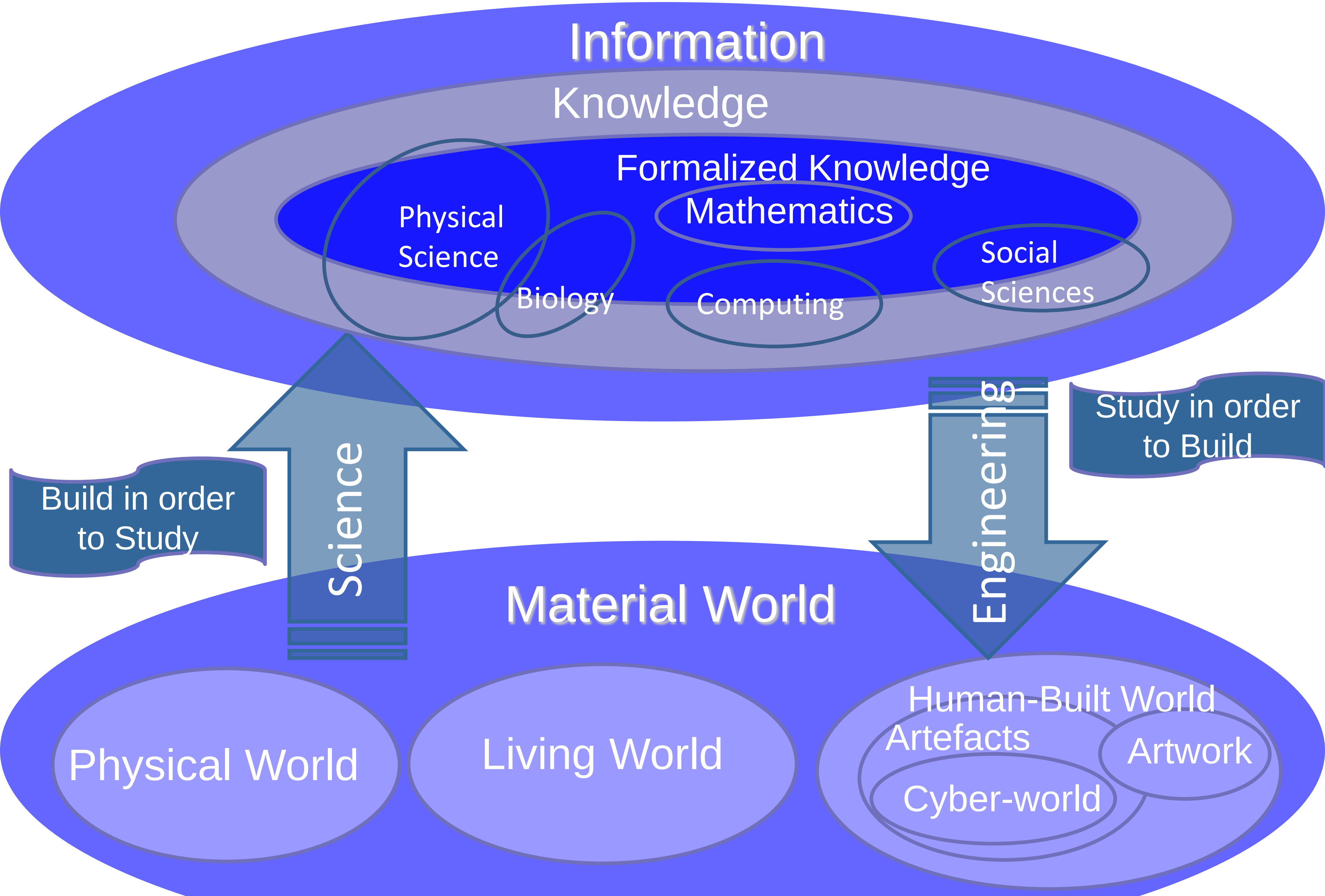
- The starting point in the pursuit of knowledge need not be observation.
  - The Theory of Relativity was motivated by a series of thought experiments rather than direct observation.
  - The development of Computing as a discipline started from prior knowledge about computation based on mathematics and logic.
  - If Computing had emerged through the study of natural computational processes e.g. quantum computing, bio-computing, would it have been deemed as “true” science?

# What is Computing – Science vs. Engineering

Knowledge acquisition and development combine Science and Engineering as well as a priori Knowledge including Mathematics, Logic and Linguistics.

- Science
  - is mainly motivated by the need for understanding the physical world.
  - privileges the analytic approach by connecting phenomena through abstractions to the world of concepts and mathematics.
- Engineering
  - is motivated by the need to master and adapt the physical world.
  - is predominantly synthetic and applies knowledge in order to build trustworthy and optimized artefacts.
- Interaction and cross-fertilization between Science and Engineering is key to the progress of scientific knowledge as shown by numerous examples.
  - A great deal of the foundations of physics and mathematics has been laid by engineers.
  - Today, more than ever, Science and Engineering are involved in an accelerating virtuous cycle of mutual advancement

# What is Computing – Science vs. Engineering



# What is Computing

- Computing is a domain of knowledge distinct from Natural Science. None of those domains is fundamentally concerned with the very nature of information processes and their transformations.

Computing is a science and associated with engineering disciplines

- Science: study of *information processes* both artificial and natural including the representation, transformation, and transmission of information.

Phenomena can be interpreted as information processes

  - DNA “translation” is an information process;
  - Neural networks

- Engineering: *design* of computing systems as the process leading from requirements to correct artefacts. As such, it studies all aspects from specification to implementation, including tradeoffs between physical resources and performance

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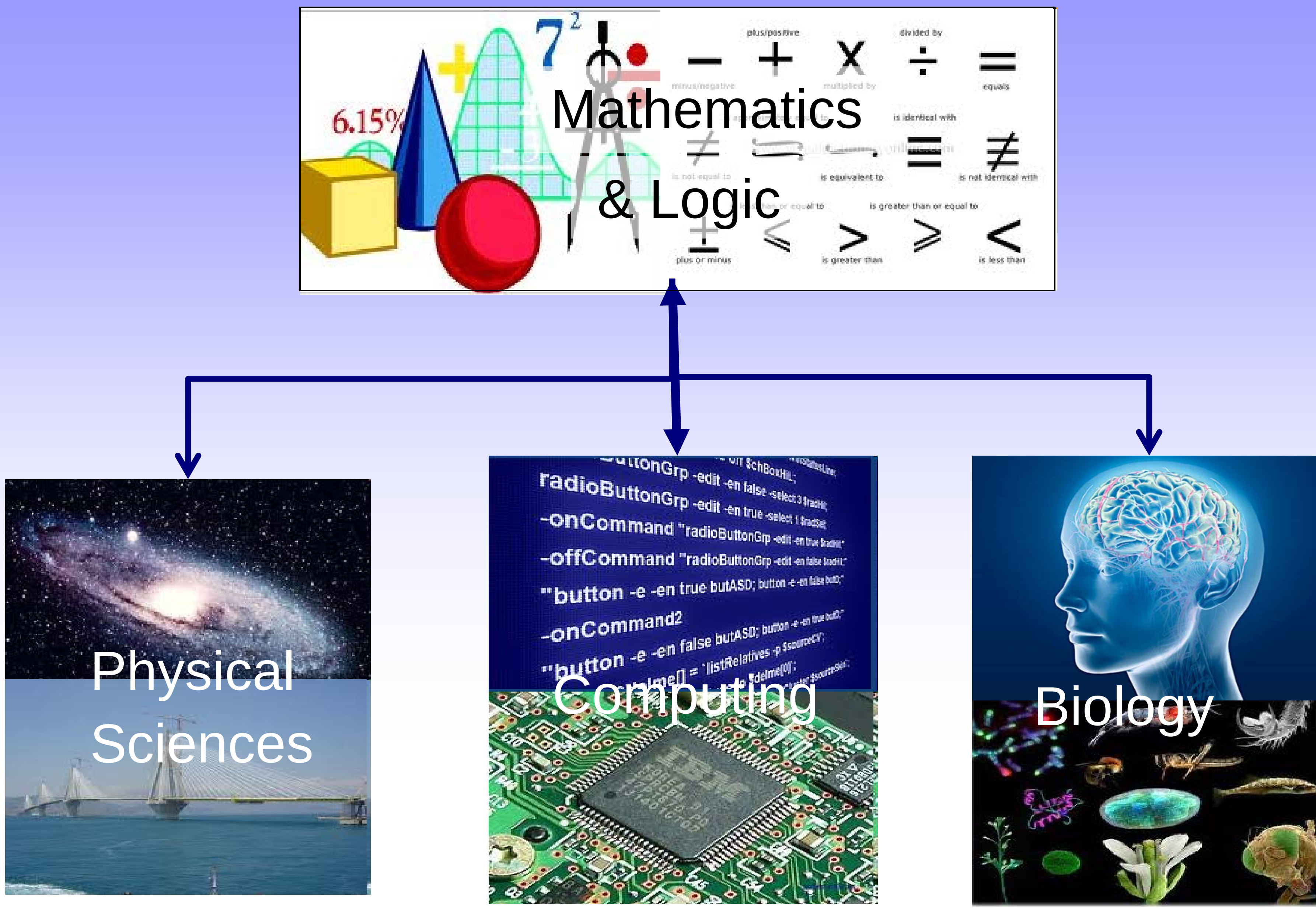
# Fundamental Domains of Knowledge



# Domains of Knowledge – Abstraction Hierarchies

- Reality has depth and breadth. To cope with complexity, we study the physical world at different levels of abstraction, in scales
  - From $10^{-35}$m, the Planck length
  - To $10^{25}$ m, size of the observed universe

- Abstraction is a holistic way to break complexity by revealing relevant features of the observed reality
  *"Being abstract is something profoundly different from being vague … The purpose of abstraction is not to be vague, but to create a new semantic level in which one can be absolutely precise"* E.W. Dijsktra

- Abstraction hierarchies are a methodological simplification used to determine successive levels of granularity of observation at which relevant system properties can be studied.
  - The models of the hierarchy should be related through some adequate abstraction relation.
  - The abstraction relation should link the laws and properties at one layer to laws and properties of the upper layers.

# Domains of Knowledge – Abstraction Hierarchies

| The Physical Hierarchy | The Computing Hierarchy | The Bio-Hierarchy |
|---|---|---|
| The Universe | The Cyber-world | Ecosystem |
| Galaxy | Networked System | Organism |
| Solar System | Reactive System | Organ |
| Electro-mechanical System | Virtual Machine | Tissue |
| Crystals-Fluids-Gases | Instruction Set Architecture | Cell |
| Molecules | Integrated Circuit | Protein and RNA networks |
| Atoms | Logical Gate | Protein and RNA |
| Particles | Transistor | Genes |

We need theory, methods and tools for climbing up-and-down abstraction hierarchies

# Domains of Knowledge – Modularity

- <u>Modularity</u>: Complex systems can be built from a <u>relatively small number</u> of types of components (bricks, atomic elements) and glue (mortar) that can be considered as a composition operator.

  <u>Basic assumptions</u>:

  1. Any system of the considered domain can be built as the composition of a finite set of predefined types of components
  2. The behavior of each component can be studied separately.
  3. The behavior of a composite component can be inferred by composing the behavior of its constituents
  4. The behavior of the components is not altered or changes in a predictable manner when they are composed

     This assumption is valid in classical Physics but fails for bio-systems, programs, linguistic systems, etc.

- A specific problem for computing systems is *component heterogeneity* - This is a key limitation to mastering component-based construction of software

# Domains of Knowledge – Emergence of Properties

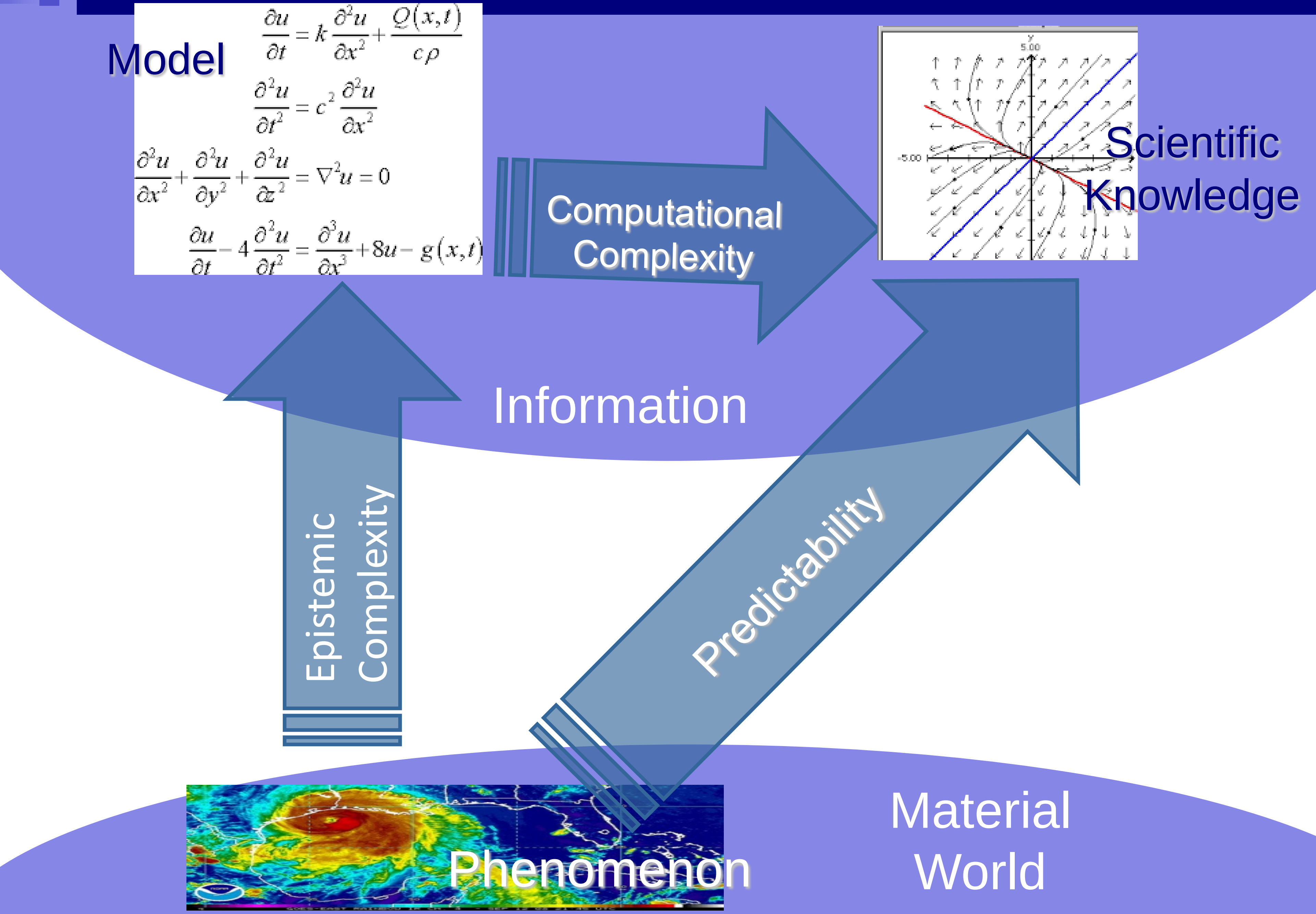
- Is it possible to unify knowledge in a domain using a compositionality principle: knowing the properties of components at one layer, is it possible to infer global properties of composite components at a higher level?
  - *properties of water from properties of the atoms of hydrogen and oxygen and rules for their composition?*
  - *properties of an application software from behavioral properties of the components of the HW platform on which it is running*?
  - *properties of mental processes from behavioral properties of components (neurons) of the brain*

These questions are of the same nature, and will probably find no answers!

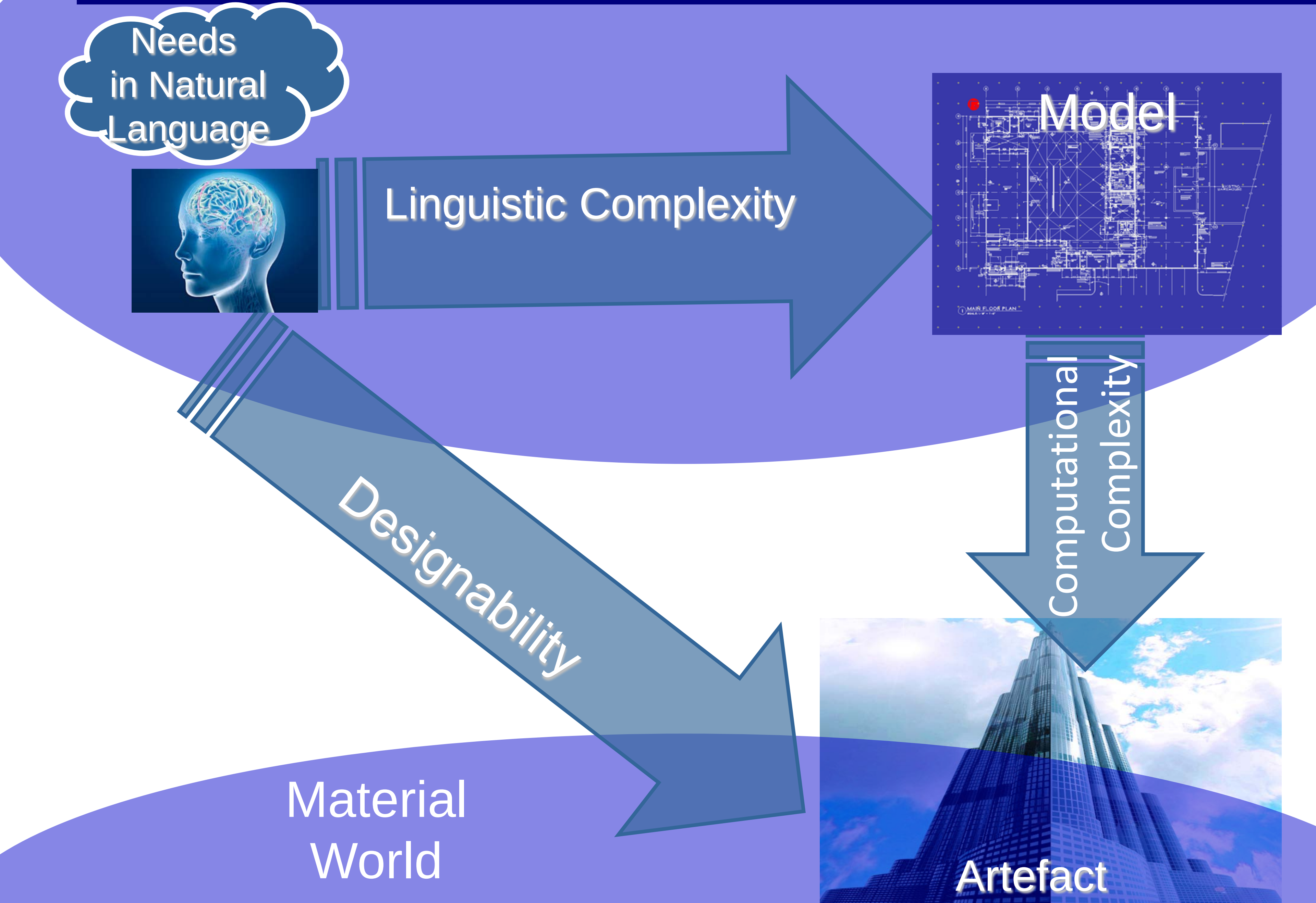
"*The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact, the more the elementary particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have to the very real problems of the rest of science, much less to those of society.*"

"More is Different", Philip Anderson, Science 1972.

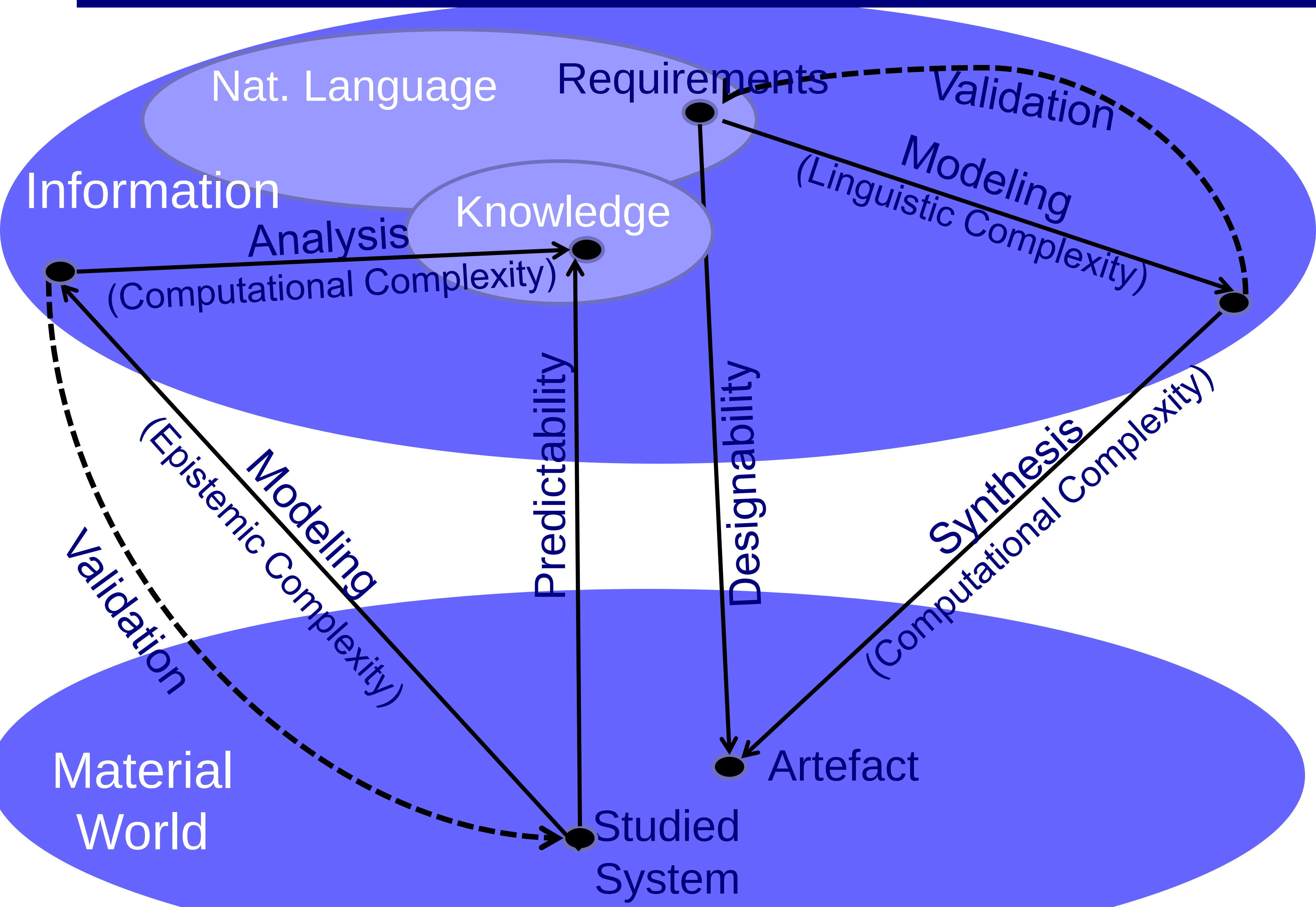
# Domains of Knowledge – Predictability



# Domains of Knowledge – Designability



# Domains of Knowledge – Predictability and Designability



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# Linking Physicality and Computation – Differences

Significant differences between models for Physical Phenomena and Computation Models

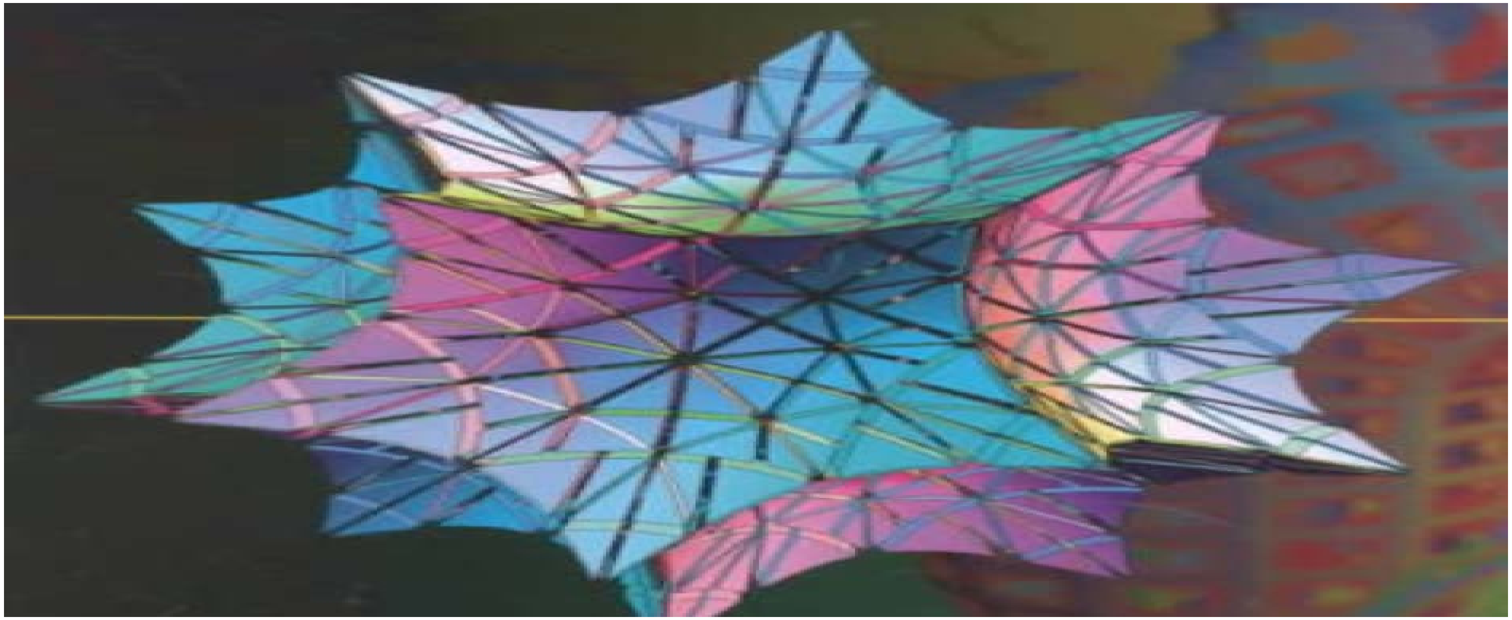
- Physical phenomena
  - cannot be understood without the concepts of space-time
  - regardless of the very nature of the physical world density of space-time has proven to be very convenient.

- Computation models
  - are discrete as they are founded on arithmetic and logic.
  - algorithms involve a finite number of steps (are terminating).

- Two main approaches attempting to link physicality and computation.
  - <u>Digital Physics</u> considers that the universe can be adequately modeled using computing machines.
  - <u>Natural Computing</u> considers natural processes as computational processes e.g. analog computing, quantum computing, biocomputing

# Linking Physicality and Computation – Two Approaches

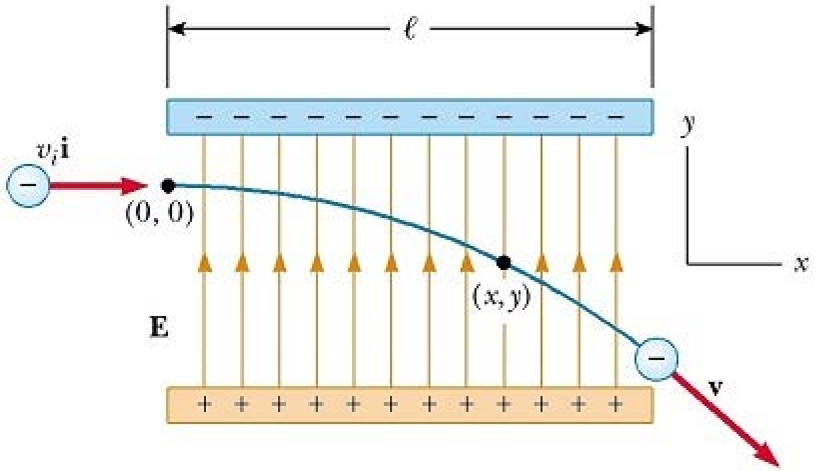
- Digital physics suggests that there exists, at least in principle, a program for a universal computer that computes the evolution of the universe.
- The computer could be, for example, a huge cellular automaton, or a universal Turing machine



Criticism: Known physical laws are very much infused with real numbers and the mathematics of the continuum.

# Linking Physicality and Computation – Two Approaches

Natural Computing: each well-understood physical phenomenon involves a computation described by the underlying physical law e.g. quantum, bio-inspired, analog computing.




An electron projected horizontally into a uniform electric field “computes” a parabola

Can Natural Computing be encompassed by the Theory of Computing?

We need to extend Turing machines to account for basic properties of analytic models used in Natural Sciences:

- consider machines that do not terminate, to model natural phenomena involving endless change.
- investigate how the concept of parallelism inherent to time-space and natural phenomena can be adequately modeled by concurrency of computation
- define a concept of computation for dense state space

# Linking Physicality and Computation – Commonalities

Both Physical Science and Computing deal with dynamic systems X'= f(X,Y)

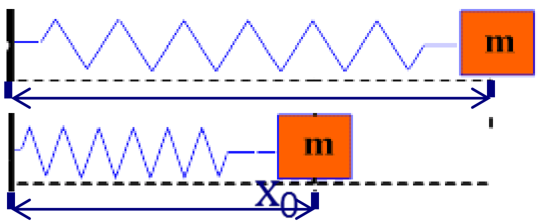
**Physics**

X' = dX/dt

X is the current state

Y is the current input

Variables are functions of time




$$m\frac{d^2x}{dt^2} = -kx$$

Law: $kx_0^2 - kx^2 = mv^2$

Physical system models

- are declarative
- inherently synchronous (physical time)
- driven by uniform laws

**Computing**

X' is the next state

X is the current state

Y is the current input

Discrete variables

<u>while</u> x≠y

<u>do</u> <u>if</u> x>y <u>then</u> x:=x-y

<u>else</u> y:=y-x

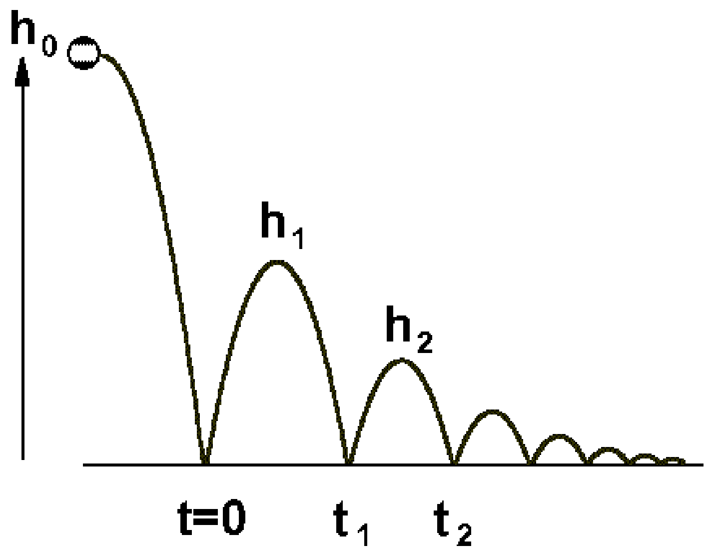
<u>Law</u>: $GCD(x,y)=GCD(x_0,y_0)$

Computation models are

- procedural
- ignore physical time
- driven by specific laws defined by their designers

# Linking Physicality and Computation – Zenoness

Limitations of Computing appear when we try to faithfully simulate physical processes involving an infinite sequence of converging discrete events.




Computers cannot faithfully simulate such processes

- they are discrete and they cannot compute infinitesimal quantities!
- finding $\lim_{n\to\infty} (t_n - t_0)$ requires discovery and application of an induction hypothesis - and this cannot be automated because of Gödel's incompleteness theorem

*Natural Computing is a promising research avenue that may lead to new models of computation overcoming current limitations due to the discrete and sequential nature of computing*

# Linking Physicality and Computation – Cyberphysical Systems

electrek

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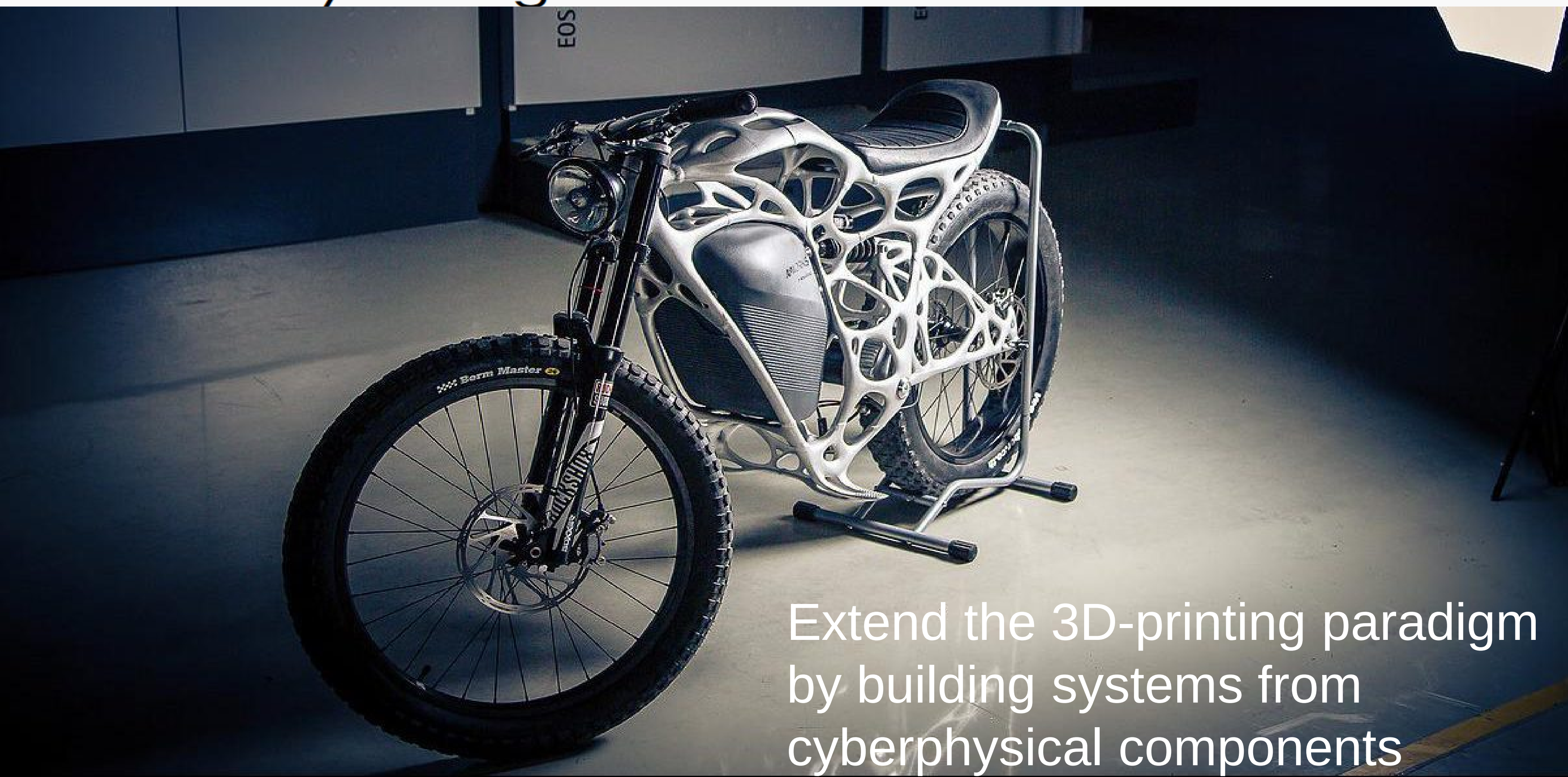
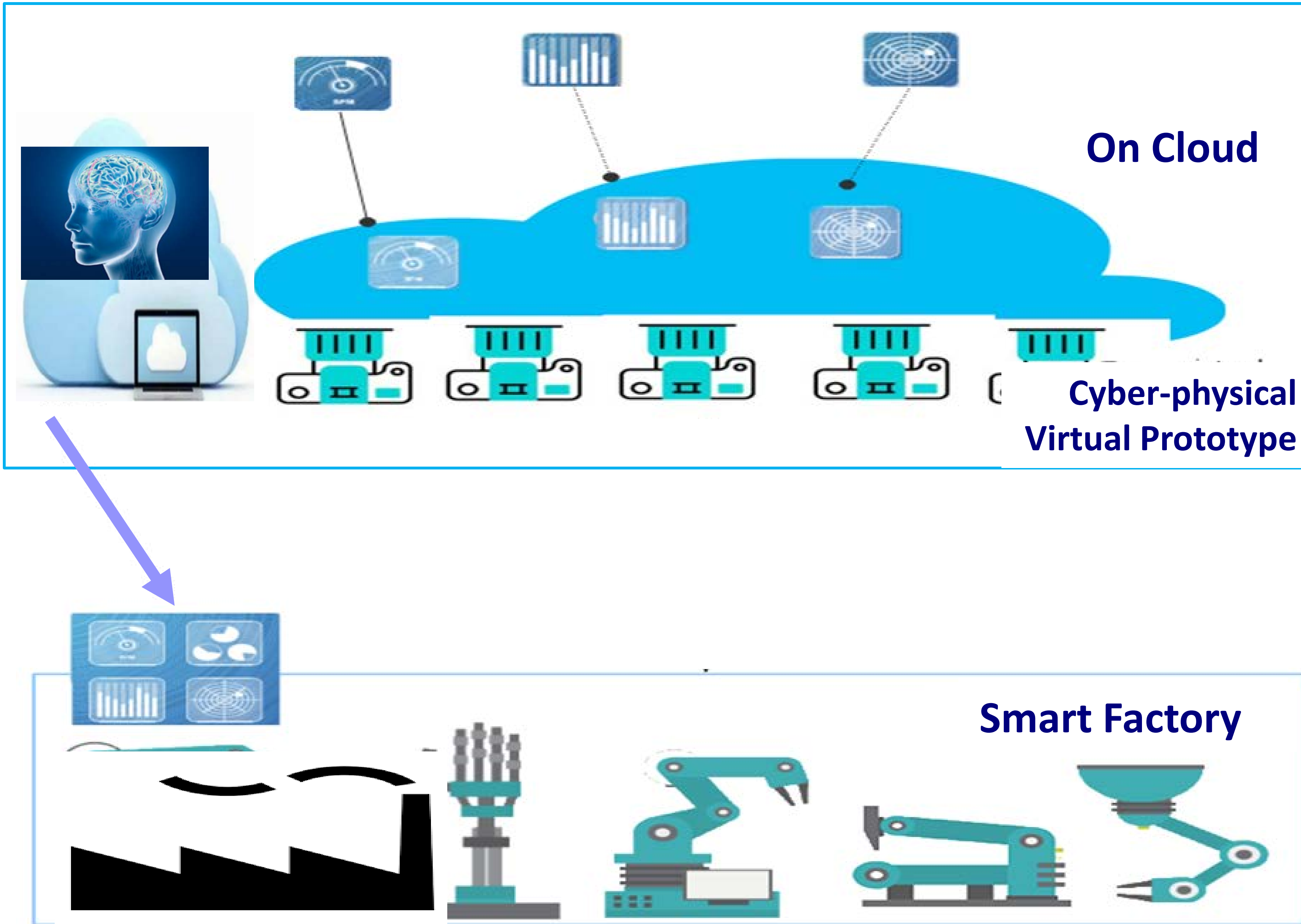
## Airbus unveils the world's first 3D printed electric motorcycle: Light Rider



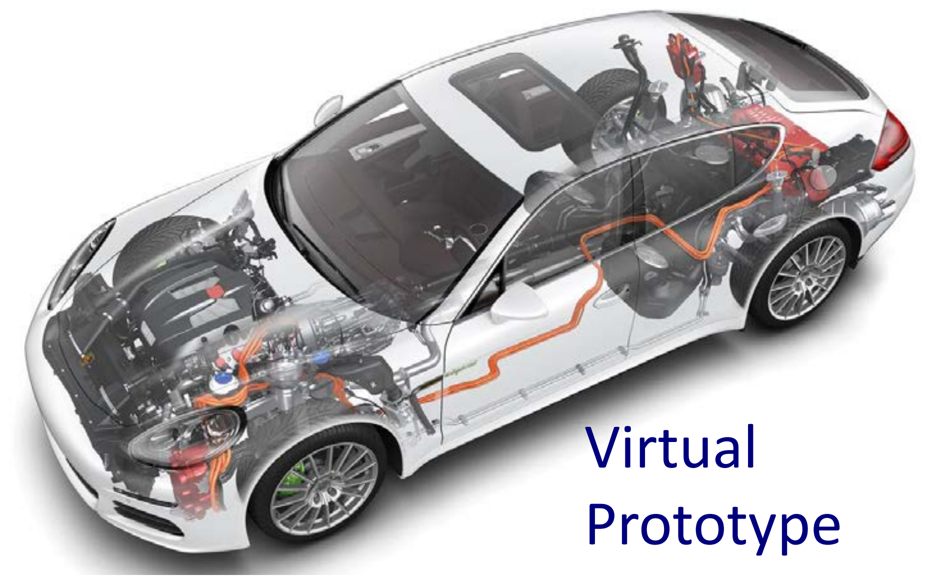

Extend the 3D-printing paradigm by building systems from cyberphysical components

# Linking Physicality and Computation – Cyberphysical Systems

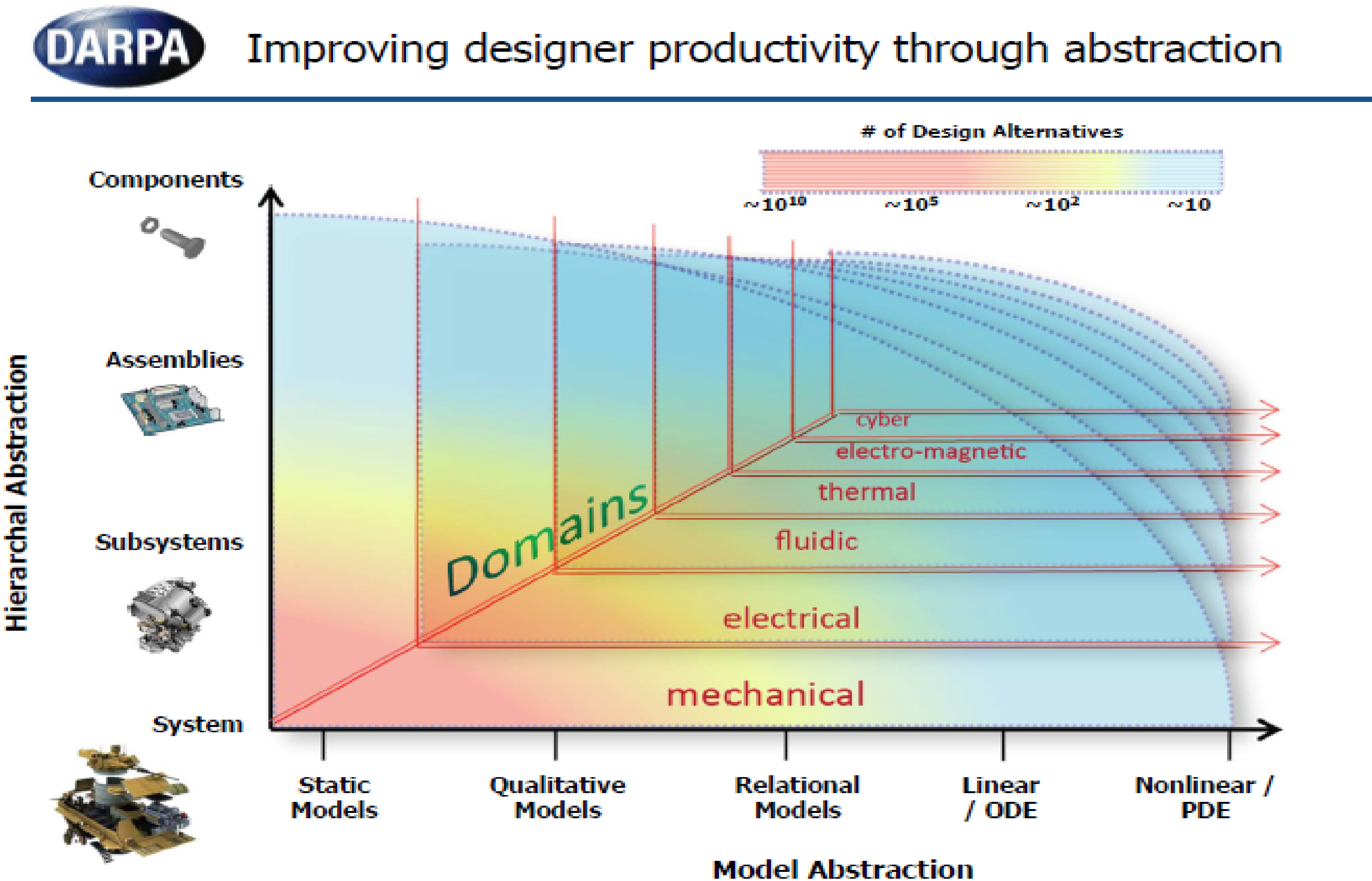


# Linking Physicality and Computation – Cyberphysical Systems



# Linking Physicality and Computation – Cyberphysical Systems




Multiscale multidomain integration of theories!

OVERVIEW

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# Artificial vs. Natural Intelligence – The Myth of AI

29 January 2015 Last updated at 18:05 GMT

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## Microsoft's Bill Gates insists AI is a threat

By Kevin Rawlinson
BBC News


Bill Gates said he could not understand why people were not concerned by AI

**Humans should be worried about the threat posed by artificial Intelligence, Bill Gates has said.**

The Microsoft founder said he didn't understand people who were not troubled by the possibility that AI could grow too strong for people to control.

Mr Gates **contradicted one of Microsoft Research's chiefs, Eric Horvitz**, who has said he "fundamentally" did not see AI as a threat.

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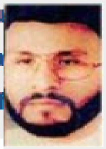

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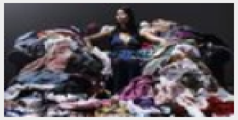

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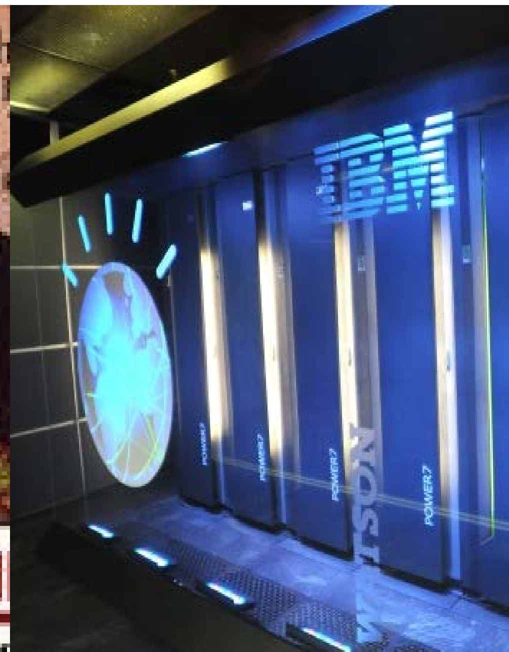
# Artificial vs. Natural Intelligence – Commonalities

- Computers surpass conscious human thinking in that they compute extremely much faster and with extremely much higher precision.
- This confers them the ability to successfully compete with humans in solving problems that involve the exploration of large spaces of solutions or the combination of predefined knowledge.


IBM Deep Blue (1997)



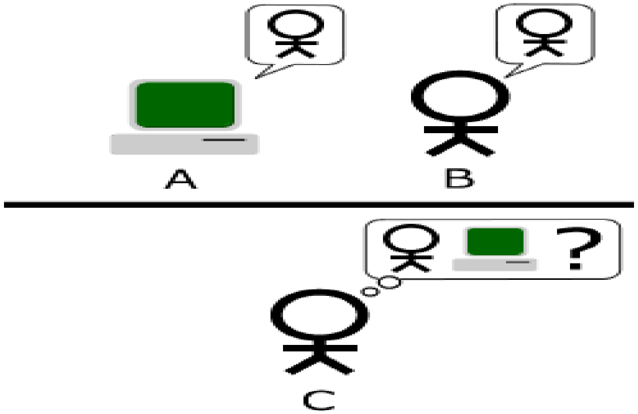

IBM “WATSON” (2011)
The Jeopardy!


AlphaGo (2016)
Google DeepMind

Defeating so human intelligence make people believe that computers exhibit intelligence and are even superior to humans in that respect.

# Artificial vs. Natural Intelligence – The Turing Test

*"If you were talking online with a Computer A and a Person B, could you distinguish which was the computer?"*




Behavioral tests may be criticized for several reasons:

- John Searle's Chinese Room Argument (1980) is a thought experiment which shows that understanding the meanings of symbols or words – what we will call semantic understanding – cannot simply amount to the processing of information.
- The Test may be diverted from its original purpose if the experimenter asks questions such as "*compute a digital expansion of length 100 for $\pi$*" - Computers are faster than humans in performing any well-defined computation!
- Even if the Computer passes the Turing test, all I can conclude is that it was programmed by a *genius programmer*

# Artificial vs. Natural Intelligence – General Intelligence

We need systems that exhibit general intelligence - The route may start with a better understanding of human intelligence (perception and reasoning)

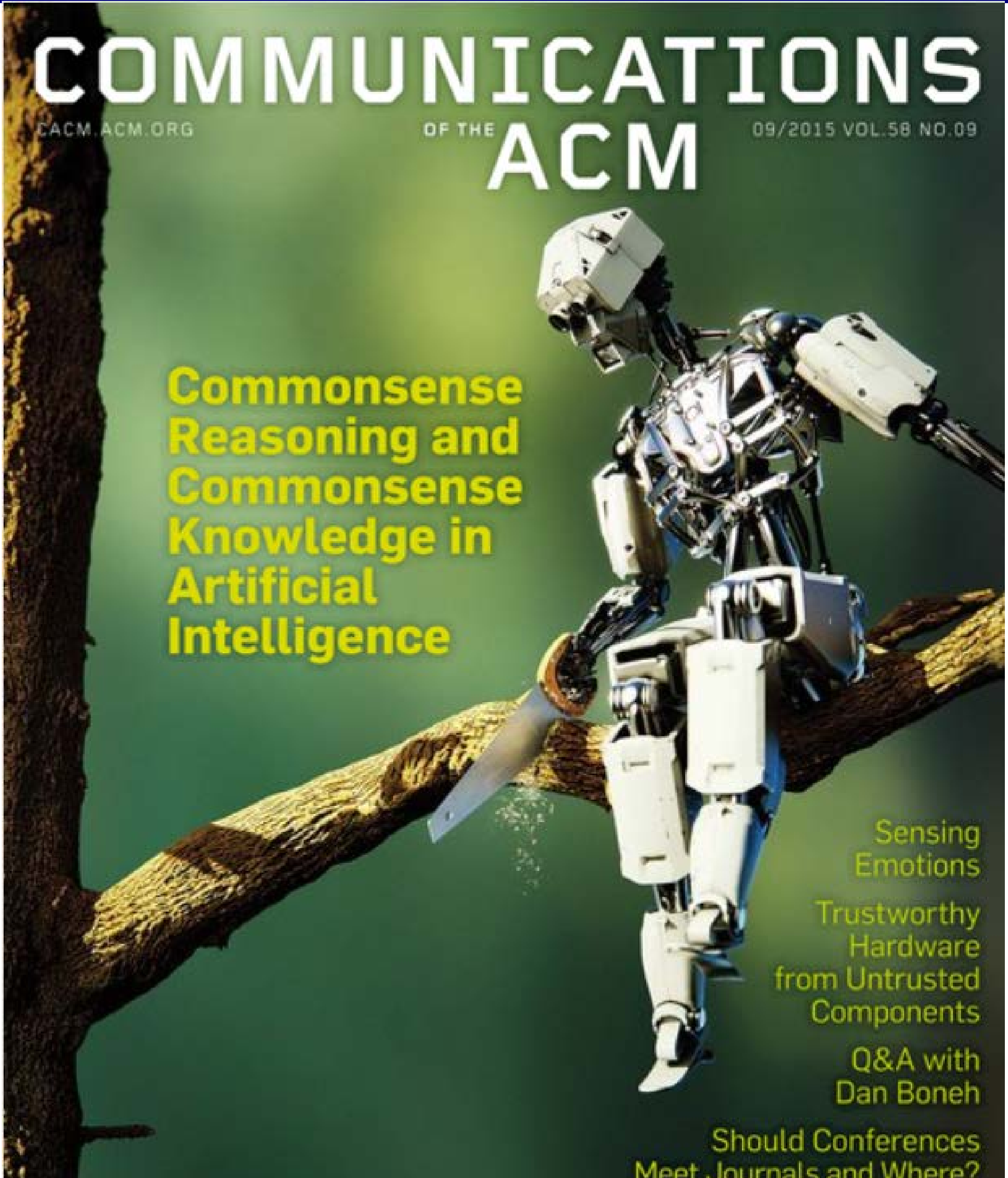
- Human reasoning uses a semantic model of the external world that has been progressively built in the mind though learning and by consistently integrating knowledge acquired along lifespan.
- Consciousness is the ability to "see" the Self interact with the semantic model contemplating possible choices and evaluating the consequences of actions.

- To build semantic models of the perceived reality we need
  - to analyze natural language and create semantic networks involving hierarchies of disjoint categories (concepts) representing knowledge about the world.
  - to define rules for updating and enriching the knowledge used by the model.

Very little progress has been accomplished so far !

# Intelligence – Common Sense Reasoning

Humans are much superior to computers in using common sense knowledge and reasoning.



# Intelligence – Common Sense Reasoning

The instantaneous interpretation of this sequence by a human as an aircraft crash requires the combination of implicit knowledge and of rules of reasoning which is hard to make explicit and formalize.

# Artificial vs. Natural Intelligence – Thinking Fast and Slow

Human mind combines two types of thinking (Thinking Fast and Slow by Daniel Kahneman):

- Slow conscious thinking that is procedural and applies rules of logic
- Fast automated thinking that is used to solve computationally hard problems e.g. speaking, walking, playing the piano etc.

Computers are well-suited for modeling slow, deliberate, analytical and consciously effortful human reasoning but not for fast, automatic, intuitive and largely unconscious thinking.

- Mathematics and Logic as the creation of conscious procedural thinking capture and reflect its internal laws implemented in computers
- Natural Computing seems to be more adequate for studying fast thinking.
- Unfortunately, as fast thinking is non-conscious it is impossible to understand and analyze the underlying mechanisms and laws, as we did for slow thinking.

# Artificial vs. Natural Intelligence – The Limits of Understanding

- Understanding means that we can connect a perceived relation between objects to our mental representations in some meaningful manner
- We cannot determine the behavior of a complex system not because it is not subject to laws but because its complexity exceeds our cognitive capabilities

The limits of understanding

- The cognitive complexity of a model can be measured as the time needed by a subject.
- There is a limit in the size of the relations that human mind can deal with: relations of rank five (one predicate + four arguments)
- To break complexity human mind uses abstraction (layering), modularity and if possible segmentation (temporal, procedural decomposition).

Extending the limits of understanding

- Computers can be used to significantly improve/extend our capabilities of understanding complex phenomena and create knowledge

# Artificial vs. Natural Intelligence – Predicting w/o Understanding

For many domains of knowledge e.g. earth sciences, epidemiology, economics phenomena are irreducibly complex and depend on a large number of parameters.

- The development of all encompassing theoretical models seems practically impossible.
- Theories are necessarily partial - consider drastic abstractions.
- Computers allow the validation of <u>empirical models</u> e.g. combining theoretical and ad hoc models

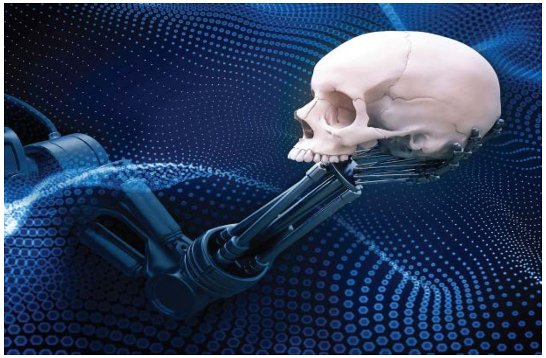
<u>Big data analytics</u>

The process of examining large and varied data sets to discover correlations between parameters e.g. market trends, customer preference, disease propagation

- <u>Prediction without understanding</u> or with 0-theory (lack of any conclusive evidence or even of sufficient evidence).
- <u>Criticism</u>: correlation does not imply causality
- Toward “Web  Science”, a field of investigation of the Cyber-Universe ?

# Artificial vs. Natural Intelligence – Singularity

- The technological singularity (also, simply, the singularity) is the hypothesis that the invention of artificial superintelligence will abruptly trigger runaway technological growth, resulting in unfathomable changes to human civilization (Wikipedia)



- Ray Kurzweil has "predicted" that the singularity will occur around 2045 — a prediction based on Moore's Law as the time when machine speed and memory capacity will rival human capacity.

Exponential increase of hardware does not imply any "increase of intelligence" (!!!!)

- I.J. Good has "predicted" that such super-intelligent machines will then build even more intelligent machines in an accelerating 'intelligence explosion.' Super-intelligent machines will pose an existential threat to humanity, for example, keep humans as pets or kill us all.

<u>It is sad that all these purely speculative ideas are taken seriously</u>

# Artificial vs. Natural Intelligence – The Real Threats

- The rise of AI-driven automation will lead to unemployment and greatly exacerbate the already acute wealth inequality
- Worrying about machines that are too smart distracts us from the real and present threat from machines that are too dumb!

*Asimov's Laws of Robotics*

1. *A robot may not injure a human being or, through inaction, allow a human being to come to harm.*
2. *A robot must obey the orders given to it by human beings, except where such orders would conflict with the First Law.*
3. *A robot must protect its own existence as long as such protection does not conflict with the First or Second Laws.*

Big Bad Robots vs. Complex Mindless Systems

- Systems although mindless and devoid of intention, can violate any of these laws with humongous consequences!
- Increasing system integration changes social relations and concentrates decisional power in the hands of a small minority.

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- What is Information
- What is Computing
- Domains of Knowledge
- Linking Physicality and Computation
- Artificial vs. Natural Intelligence
- Discussion

# Discussion

- Computing is a distinct domain of knowledge, a broad field that studies information processes, natural and artificial as well as methods for building computing artefacts.

- Computing should be enriched and extended to encompass physicality –
  - resources such as memory, time, and energy to become first class concepts.
  - Integrate natural processes that seem like computation but do not fit the traditional algorithmic definitions.

- Computing has a deep impact on the development of science and technology <u>similar to the discovery of mechanical tools and machines</u>.
  - Computers <u>multiply our mental faculties</u> by extending our ability for fast and precise computation.
  - Nonetheless, <u>as an aircraft is not a bird, a computer is not a mind</u>!<br>To make computers more intelligent we should better understand how our mind works and cope with linguistic complexity of natural languages.

# Discussion

- Computing has revealed the importance of <u>design</u> as a “problem-solving process” leading from requirements expressing needs to <u>correct</u> artefacts.
  - Design formalization raises a multitude of deep theoretical problems related to the formalization of needs and their functional and extra-functional implementation.
  - Endowing design with a rigorous foundations *is both an intellectually challenging and culturally enlightening endeavor – it nicely complements the quest for scientific discovery in natural sciences*

- Computing has revealed the importance of <u>knowledge</u> and its cross-fertilization to achieve enhanced predictability and designability.

- Computing complements and enriches our understanding of the world with a <u>constructive and computational view</u> different from the declarative and analytic adopted by Physical Science.

# Thank You