2023 Annual INCOSE international workshop
HYBRID EVENT
Torrance, CA, USA
January 28 - 31, 2023

Systems Science Working Group

Scientific Foundations on SE

What is the Systems Science WG Purpose?

- Systems science provides a more rigorous, underlying basis to the empirically derived practices to systems engineering that have evolved over time.
  - The application of systems thinking and systems science concepts and principles in engineering is the basis for the practice of systems engineering (SE).
  - Applying SE, and reflecting on the results, helps us improve systems science and systems thinking, further enhancing our ability to design and intervene in complex systems - a virtuous cycle.
  - The success of SE applications reinforces the credibility of the systems worldview.

What are the Systems Science WG Goals?

- Highlight linkages between Systems Science theory and the empirical practice of Systems Engineering. (e.g. short, mid or long-term)
- Promote awareness of Systems Science, its origins, and its possible futures.
- Encourage advancement of Systems Science principles and concepts.

Systems Science as a Foundation for SE

Complexity Science

- ✓ Deals with phenomena difficult to describe but eventually easy to explain
- ✓ Highly scientific and widely used, but can be considered as largely reductionistic

Systems Research

- ✓ Deals with phenomena easy to describe but increasingly difficult to explain
- ✓ Largely holistic but not widely used and mostly grounded in heuristics

Starling murmuration
- Complex to describe
- Simple to explain

Vandalism
- Simple to describe
- Complex to explain

Rousseau, D., Schreinemakers, P., Luman, R., Martin, J., Calvo-Amodio, J. 2020. SF4SE Report to SSWG, INCOSE IW 2020, Redondo Beach CA.

SSWG | Motivation

- We can conclude there is diversity in perceptions regarding:
    1. The maturity of systems science
    2. The nature of its underpinning concepts
    3. What is considered foundational
- We have seen it in our group, it is observed throughout SE

SSWG | Motivation

- In the past 12 years contributions to establishing foundational concepts, include:
  - ***Introduction to Category Theory*** by Larry Lambe, Kent Palmer, Mike Watson, Ken Lloyd, Spencer Breiner (NIST)
  - ***SE definitions*** by INCOSE Fellows
  - ***Systems Engineering Principles***, Mike Watson and team
  - ***Human Agency*** by Sue Gabriele
  - Among many others

SSWG | Motivation

- In the past 12 years contributions to establishing foundational concepts, include:
  - ***Systems Process Theory*** by Len Troncale
  - ***3 General Scientific Systems Principles*** by David Rousseau
  - ***Systemic Semantics*** *(conceptual consistency) and* ***Systemic Virtues*** *for Elegant Design* by David Rousseau, Julie Billingham, and Javier Calvo
  - ***Purposeful Human Activity Systems*** by Javier Calvo

SSWG | Motivation

- The variety of work at the SSWG led to the recognition that we need to be able to map the level of maturity of the theoretical underpinnings of SE
  - advancing the theoretical underpinnings is key if we want to advance our ability to understand, design/engineer for, what works or what matters across disciplinary interests
- We need to begin by bringing clarity to the foundational concepts, purpose, and focus

We have a definition for SE's Purpose
So what? What's next?

Seek conceptual clarity in key systems science components

Transformation of SE

Present paradigm

robust, dependable, mainly-technological, **"deterministic systems"**

implicitly, a **command and control** view of how SE works

Future paradigm

resilient, adaptive, **"evolutionary"** systems and systems-of-systems

- encompassing products, services, people and enterprises
- integrating technological, social and environmental elements

explicitly, a collaborative way that SE facilitates engagement with a variety of stakeholder groups

Need a New Definition of System

A system is an arrangement of parts or elements that together exhibit behavior or meaning that the individual constituents do not

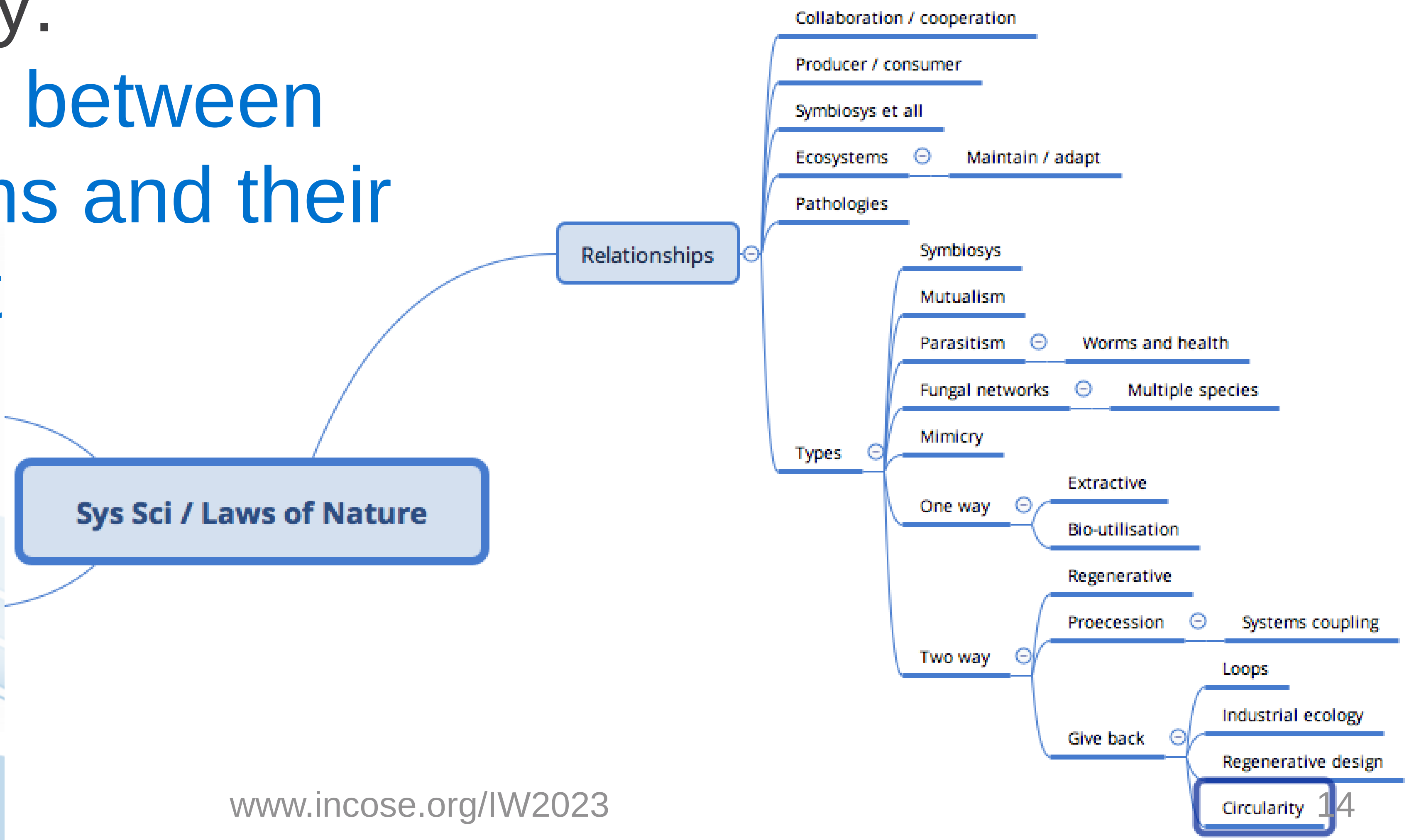
- **Systems can be either physical or conceptual, or a combination of both**
  - Systems in the physical universe are composed of matter and energy, may embody information encoded in matter-energy carriers, and exhibit **observable behavior**
  - Conceptual systems are abstract systems of pure information, and do not directly exhibit behavior, but exhibit "**meaning**"
- **In both cases, the system's properties (as a whole) result, or emerge from:**
  - the parts or elements and their individual properties; AND
  - the relationships and interactions between and among the parts, the system and its environment

New Definition of SE *(changes highlighted)*

Systems Engineering is ~~an interdisciplinary~~ a **transdisciplinary** and **integrative** approach ~~and means~~, to enable the ~~realization of~~ successful realization, use, and retirement of **engineered** systems**,** using systems **principles and concepts**, and scientific, technological, and management methods

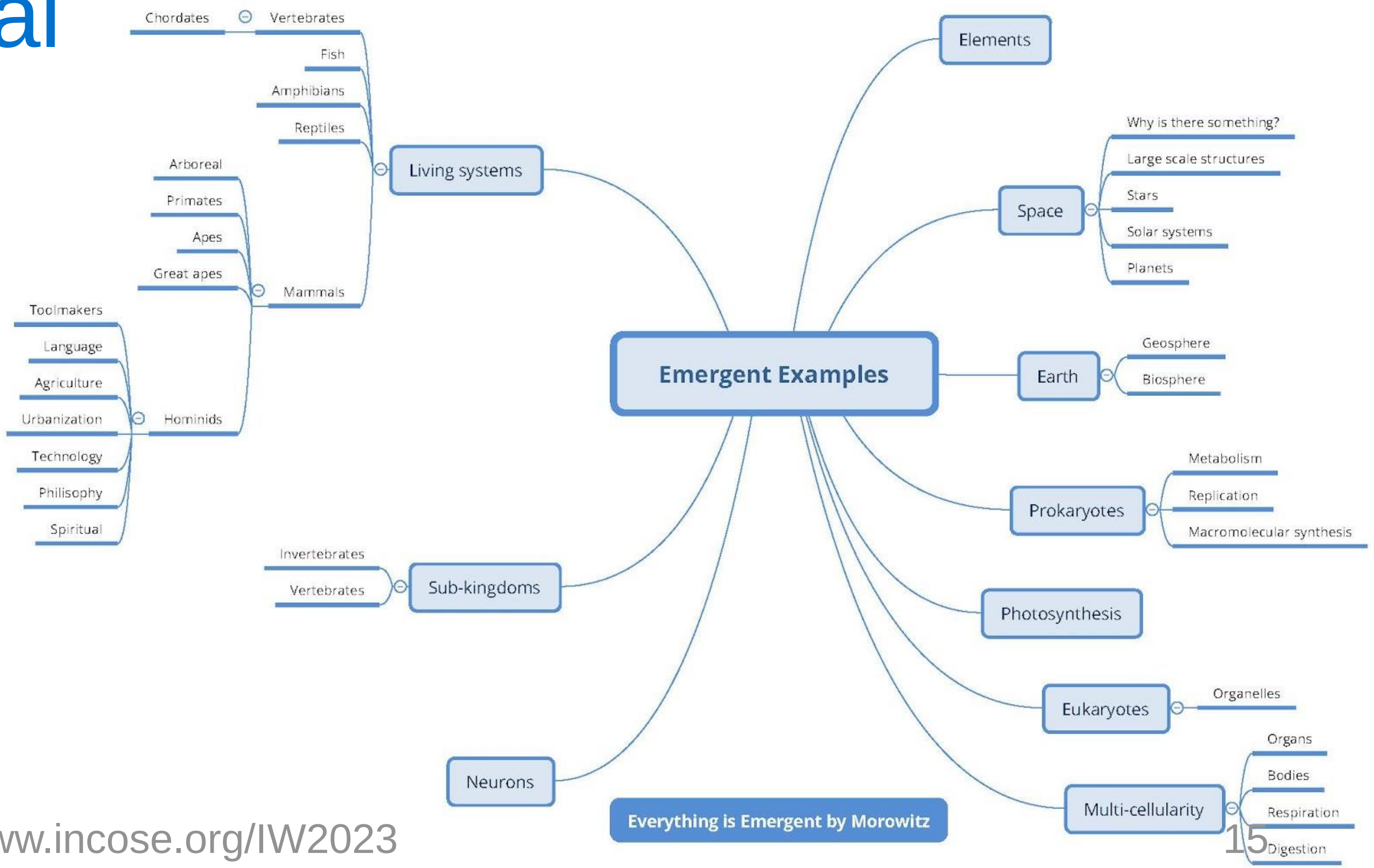
Collaboration with NSWG

- Area of study: Relationship between living systems and their environment



Collaboration with NSWG

- Area of study: Emergence in natural systems



Managing Organizational Complexity

- A VUCA world
  - Volatility: constant change
  - Uncertainty: stochastic nature of change
  - Complexity: interconnectivity and convolution
  - Ambiguity: basic rules of the game might not be understood

Courtesy of Prof. Mike .C. Jackson - 2022

The Nature of Complexity

- Rescher (1998):
  - ‘Ontological complexity’ - the complexity that exists in the real-world
    - Quantity of elements
    - Variety of elements
    - Elaborateness of interrelationships
  - ‘Cognitive complexity’ - different ways the world is viewed
    - Cognitive limitations
    - ‘Spreadthink’ (Warfield)
    - Conflict

Courtesy of Prof. Mike .C. Jackson - 2022

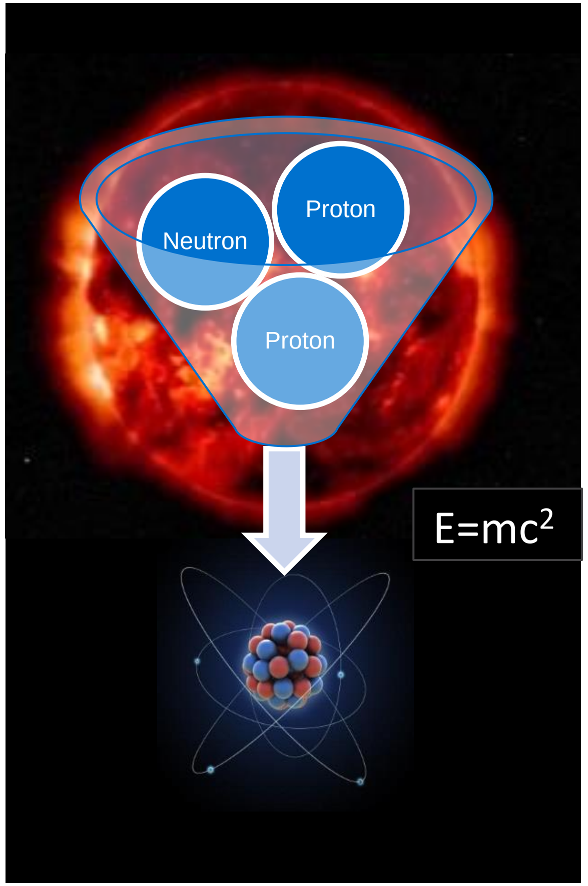
Systemic Perspectives on Complexity

- Morin
  - ***restricted complexity***
    - computational modelling techniques
    - remain "*within the epistemology of classical science*"
  - ***general complexity***
    - resists universal truths;
    - fundamental problem "*is epistemological*, *cognitive, paradigmatic*"

Courtesy of Prof. Mike .C. Jackson - 2022

A First General Scientific Systems Principle

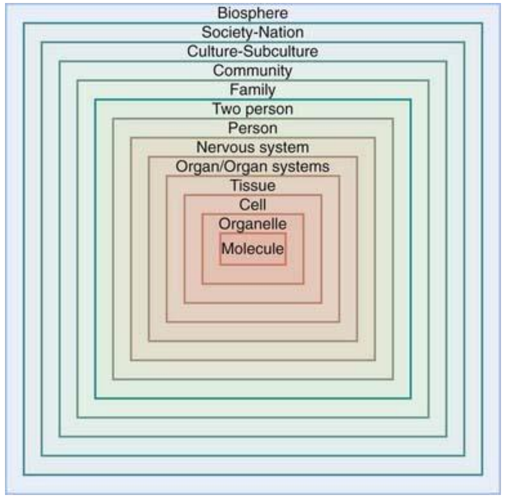
- **Systems Principle 1**: *Conservation of Properties* : emergent properties are exactly paid for by submerged ones
- Value:
  - Research: To prove emergence, show the interplay with submergence
    - Lack of demonstrable interplay ⇒ wrong boundaries drawn or parts misunderstood
  - Design/Intervention: System disruption entails both degradation of systemic functionality and re-emergence of inhibited part behaviours
    - Lack of demonstrable control ⇒ wrong boundaries managed or parts mismanaged

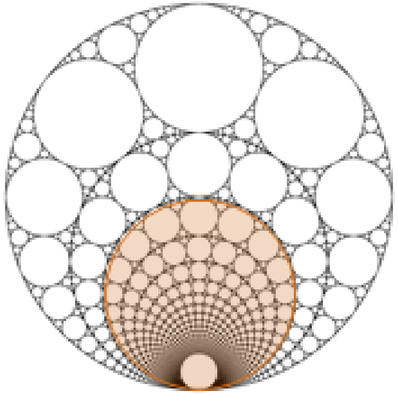


Rousseau, D. 2018 "Three Scientific Systems Principles. INCOSE IW, Jacksonville, FL.

A second systems principle: SP1 plus the idea of open boundaries

- Systems are subsystems in meta-systems, so…
- **Systems Principle 2**: ***Universal Interdependence*** : system properties represent an exact balance between bottom-up emergence and outside-in submergence
- Value:
  - Philosophy: The explanatory arrows point both ways, Scientific Holism replaces Classical Reductionism
  - Research: The explanatory burden tracks in two directions
  - ISE Practice: There are two interconnected kinds of leverage points for changing system capacity (outside-in and bottom-up)





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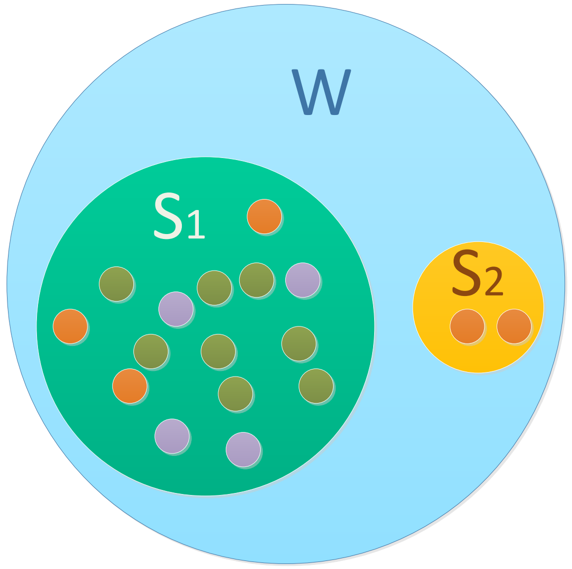
The Difference Complexity Makes

- When a complex system interacts with a simpler one, the simpler one’s properties change more, even thought the mutual force (and hence amount of energy exchanged) is the same
  - Kind of complexity vs. degree of complexity
    - A bull is overall a more complex system than a fence
    - However, when the bull tries to get out of the field, the relevant interaction is between the physical-system-level properties of each party,
      - Here, the fencing system outperforms the bovine system, entraining more mass and leverage into a more enduring structure.
      - The bull has to stay inside or risk suffering more damage than the fence would in a forceful interaction between them.

Rousseau, D. 2018 “Three Scientific Systems Principles. INCOSE IW, Jacksonville, FL.

The Difference Complexity Makes

- **Systems Principle 3:** ***Complexity Dominance*** : the impact of submergence on a part is proportional to the complexity differential between the part and the whole
- Value:
  - Research: The two explanatory arrows differ in size proportionally to relative complexity
  - Management
    - The two interconnected leverage points for modulating system behaviour are unequally weighted
    - To effectively control a system you need a more complex one (→ *Ashby's Law*)



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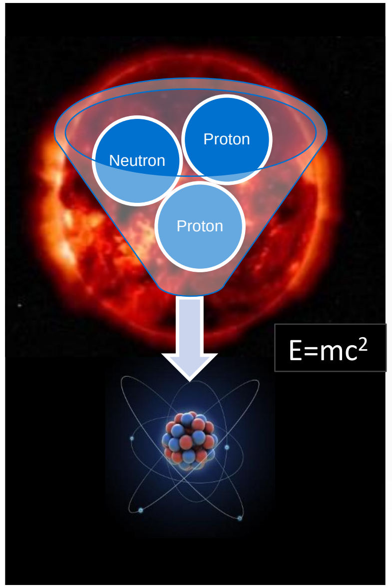
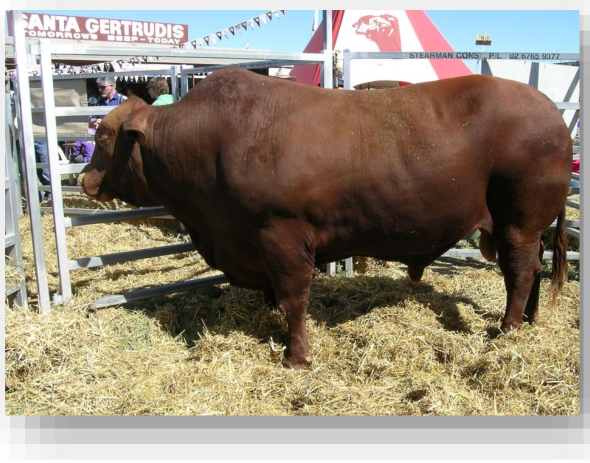
Ontological vs Cognitive? Restrictive vs General?

SYSTEMS ENGINEERING
PRINCIPLES

Proposed Law: Conservation of Complexity

$$C = C_1 + C_2 C_3$$



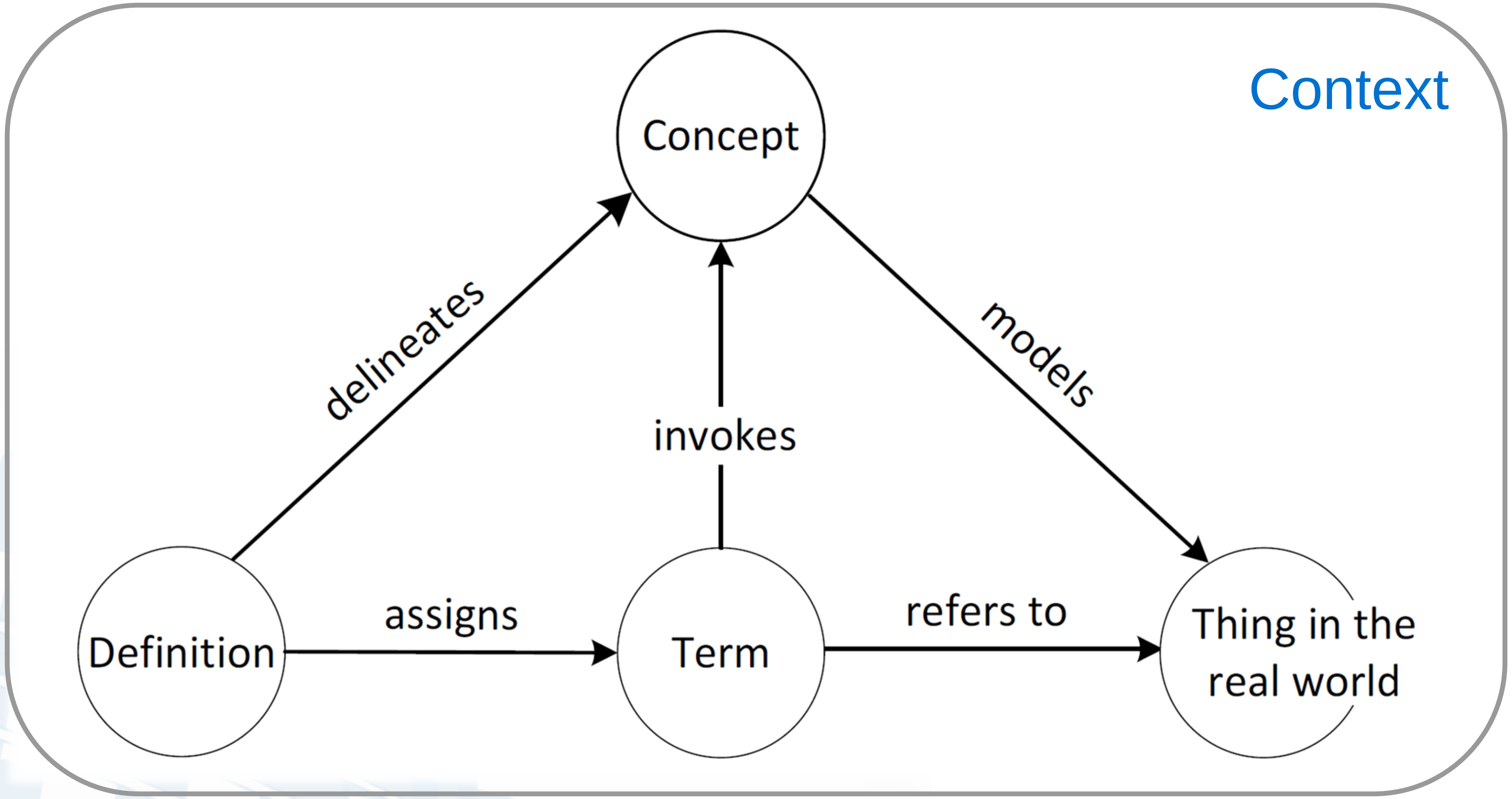


Systemic Semantics

- When talking about systems and their properties,
  - how do we know what kind of complexity we are dealing with?
  - What concepts are relevant to describe the system and its relationship with its context (environment)
- Rousseau, Billingham, and Calvo-Amodio presented a conceptual framework (ontological framework) for selecting and organizing the terminology of systemology
  - The process can be replicated for any systems or non-systems related discipline

Rousseau, D., Billingham, J., & Calvo-Amodio, J. (2018). Systemic semantics: A systems approach to building ontologies and concept maps. *Systems*, *6*(3), 32.

Systemic Semantics



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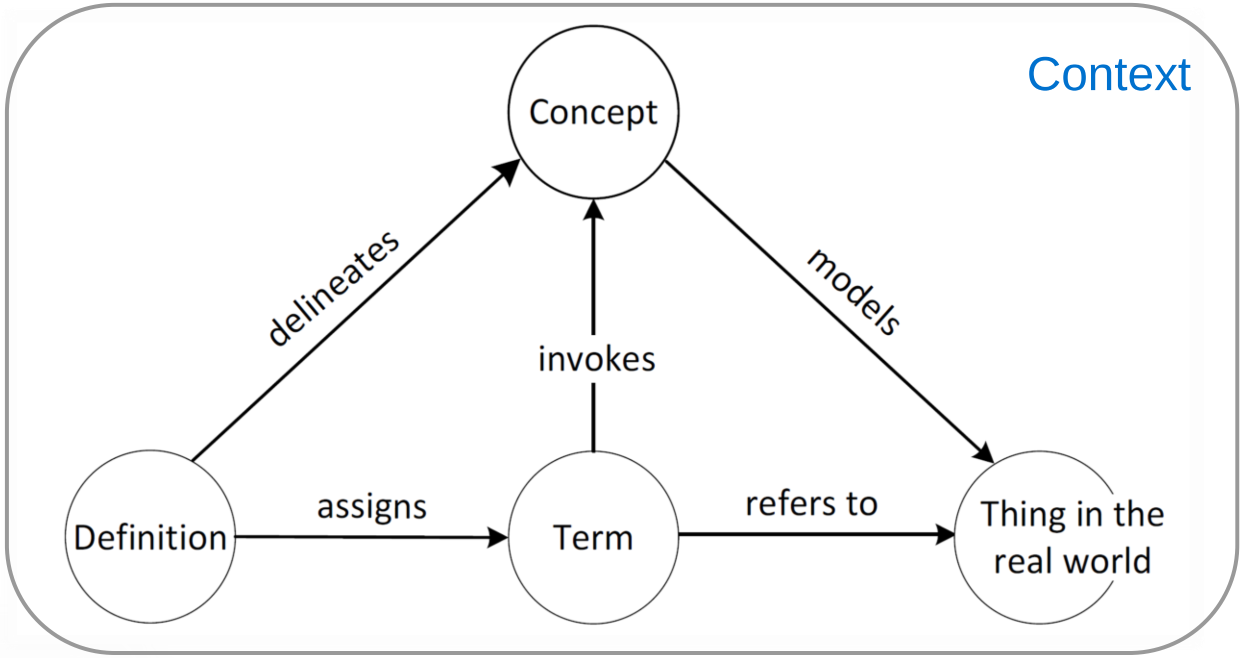
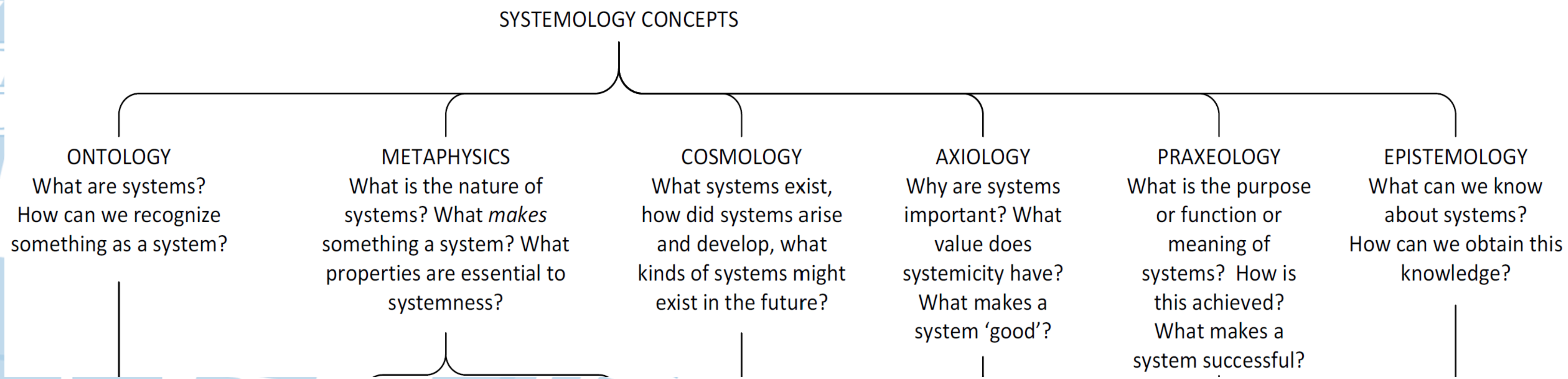
Systemic Semantics





Systems Science Working Group

Collaboration with FuSE

Bridge Team

- What is the objective of SE?

“We have lost sight of the fact that engineering is an art, not a technique; a technique is a tool. From time to time, I am briefed on the results of a systems analysis or systems engineering job in a way that prompts me to ask the questions: ‘That's fine, but is it a good system? Do you like it? Is it harmonious? Is it an elegant solution to a real problem?’”

Robert Frosch, 1969

R. A. Frosch, ‘A classic look at systems engineering - NASA SP-6102’, in *Readings in Systems Engineering*, T. Hoban and W. M. Lawbaugh, Eds. Washington DC: NASA, 1969, pp. 1–7.

Bridge Team

- What is the objective of SE?

“The purpose of systems engineering, is “not the satisfaction of requirements and processes” but rather, “attaining elegant designs””

Mike Griffin, 2010

M. D. Griffin, ‘How do we fix system engineering?’, in 61st International Astronautical Congress, Prague, Czech Republic, 27 September – 1 October 2010, 2010, vol. 27.

Bridge Team

- What is the objective of SE?

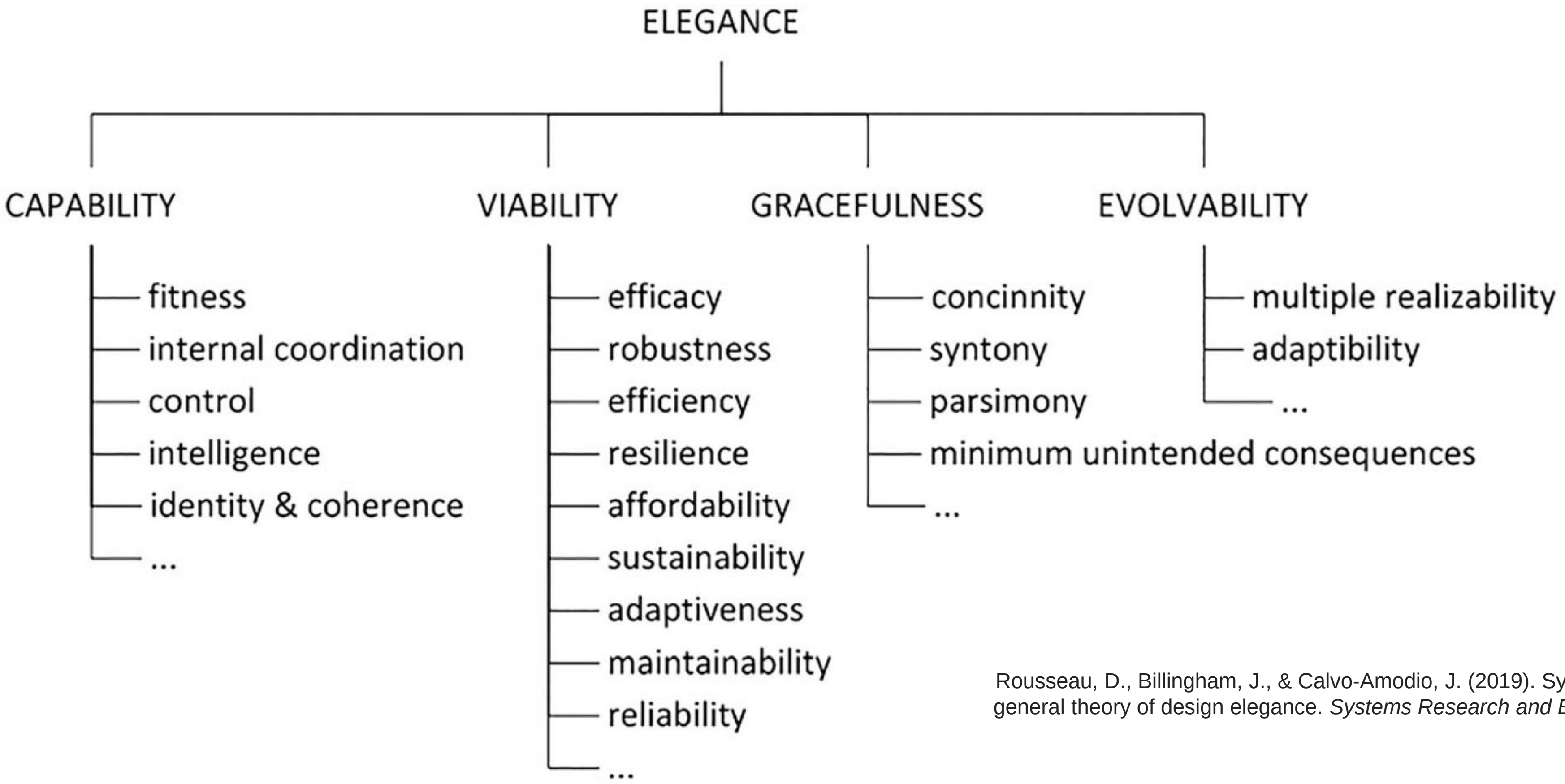
"Elegant systems not only meet their intended outcomes with a reasonable degree of simplicity, they must possess other attributes as well. Elegant designs are also generally thought to be robust in the face of changing circumstances, or adaptable to collateral but originally unanticipated uses."

Mike Watson and Mike Griffin, 2014

Watson, M., & Griffin, M. (2014). System engineering: The discipline of engineering elegance. in Submitted to the American Institute of Aeronautics and Astronautics (AIAA) Complex Aerospace Systems Exchange (CASE) 2014. San Diego: CA.

Systemic Virtues

- Elegance is an emerging property



Rousseau, D., Billingham, J., & Calvo-Amodio, J. (2019). Systemic virtues as a foundation for a general theory of design elegance. *Systems Research and Behavioral Science*, *36*(5), 656-667.

Bridge Team

- Going from objective to purpose
  - How does SE create value?

"The purpose of Systems Engineering is to achieve Elegant Solutions that resolve Complex Problems"

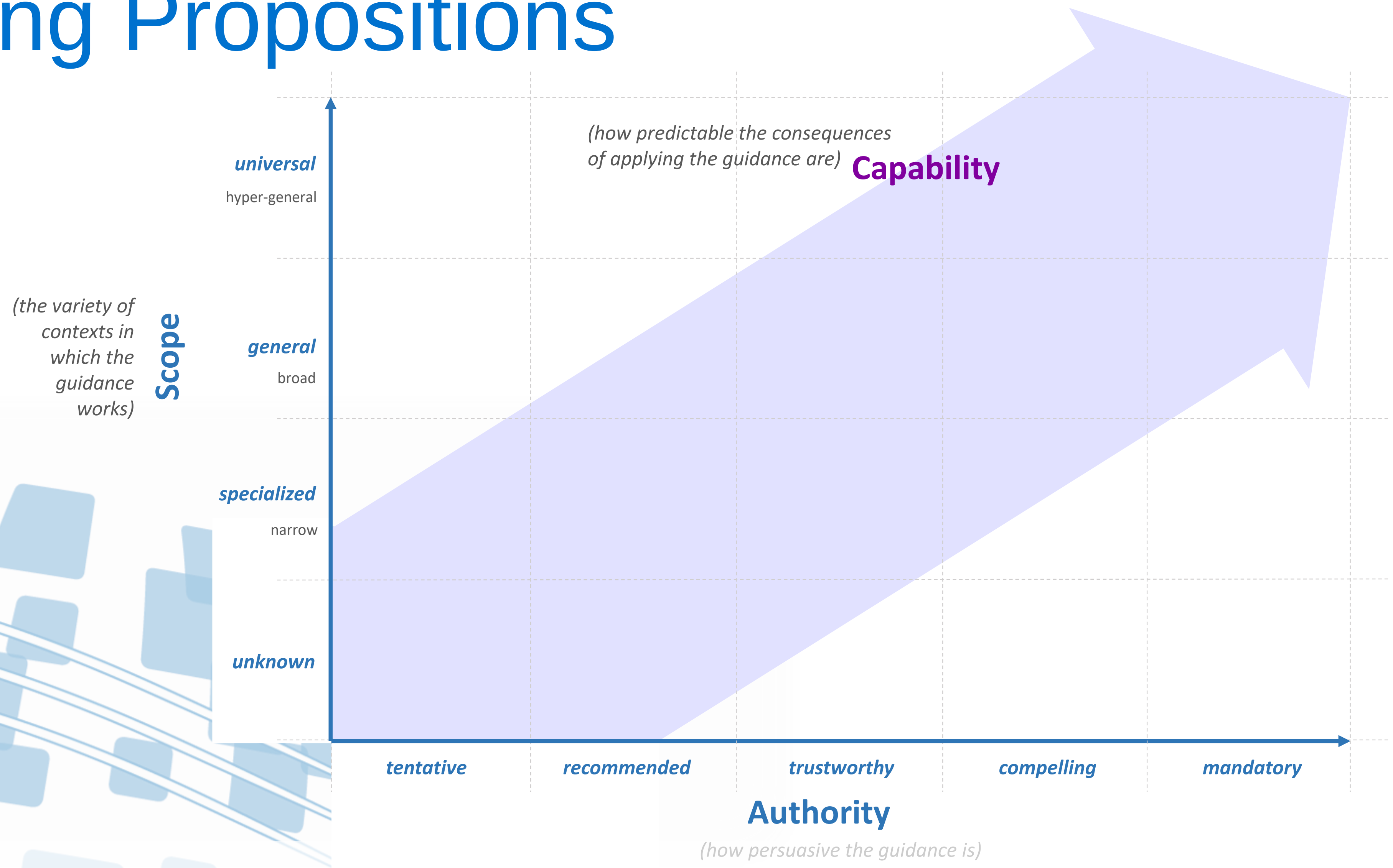
Bridge Team

- The bridge team began by seeking clarity onto what constitutes a principle and what constitutes a heuristic – FuSE Projects: SE Principles vs. SE Heuristics .
  - The concept of guiding propositions provides a wider perspective that exposes common processes by which they principles and heuristics evolve
    - In other words, it exposes a way to map how we evolve our knowledge in a systematic way

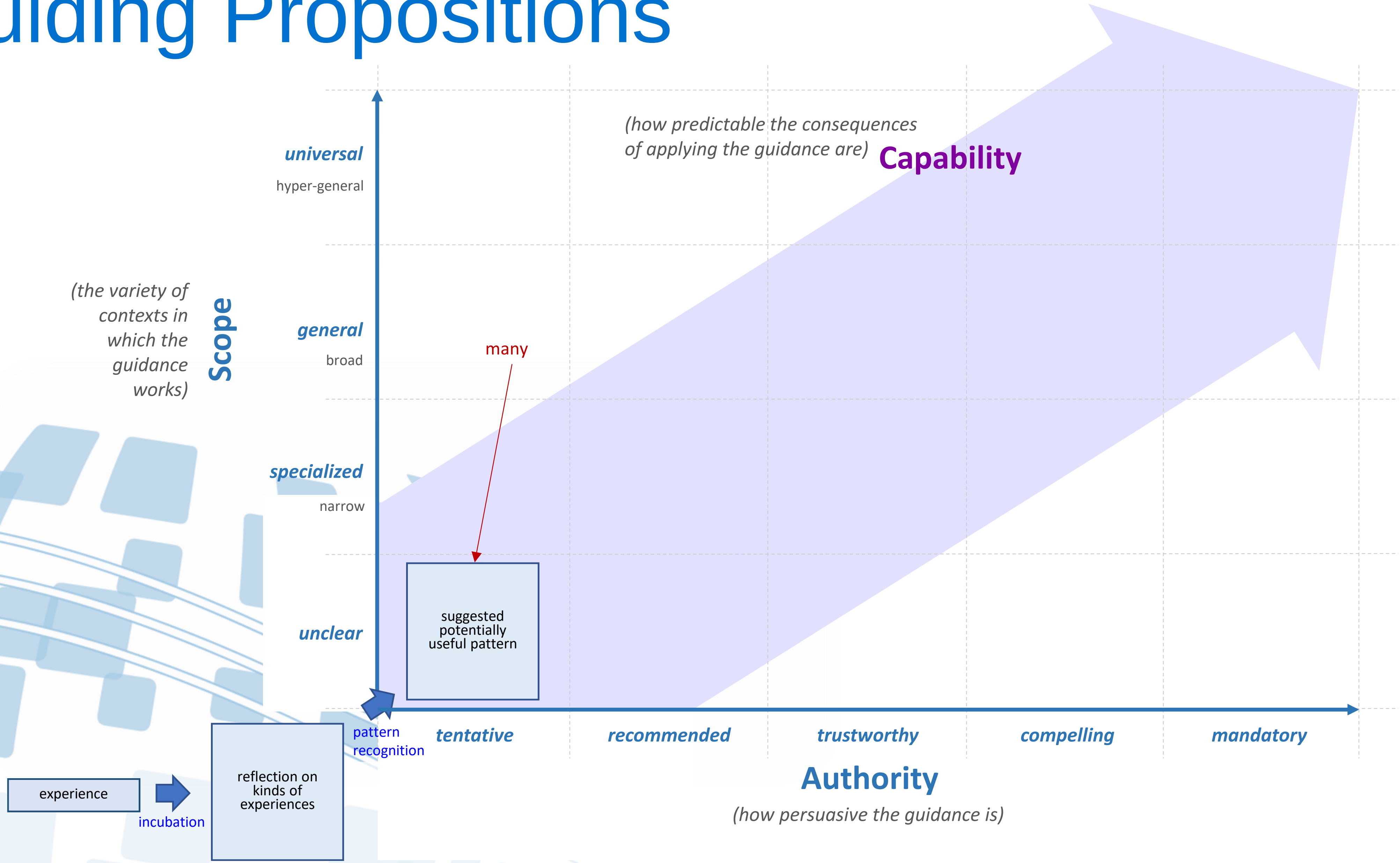
Bridge Team

- All the kinds of *guiding propositions* can be called *principles* once there is some insight into why they work
  - for example via scientific theory or simulation and modelling.
  - On this basis they propose we can refer to *principles* as designating any kind of guiding proposition that has a reasonable level of rational support

Guiding Propositions



Guiding Propositions



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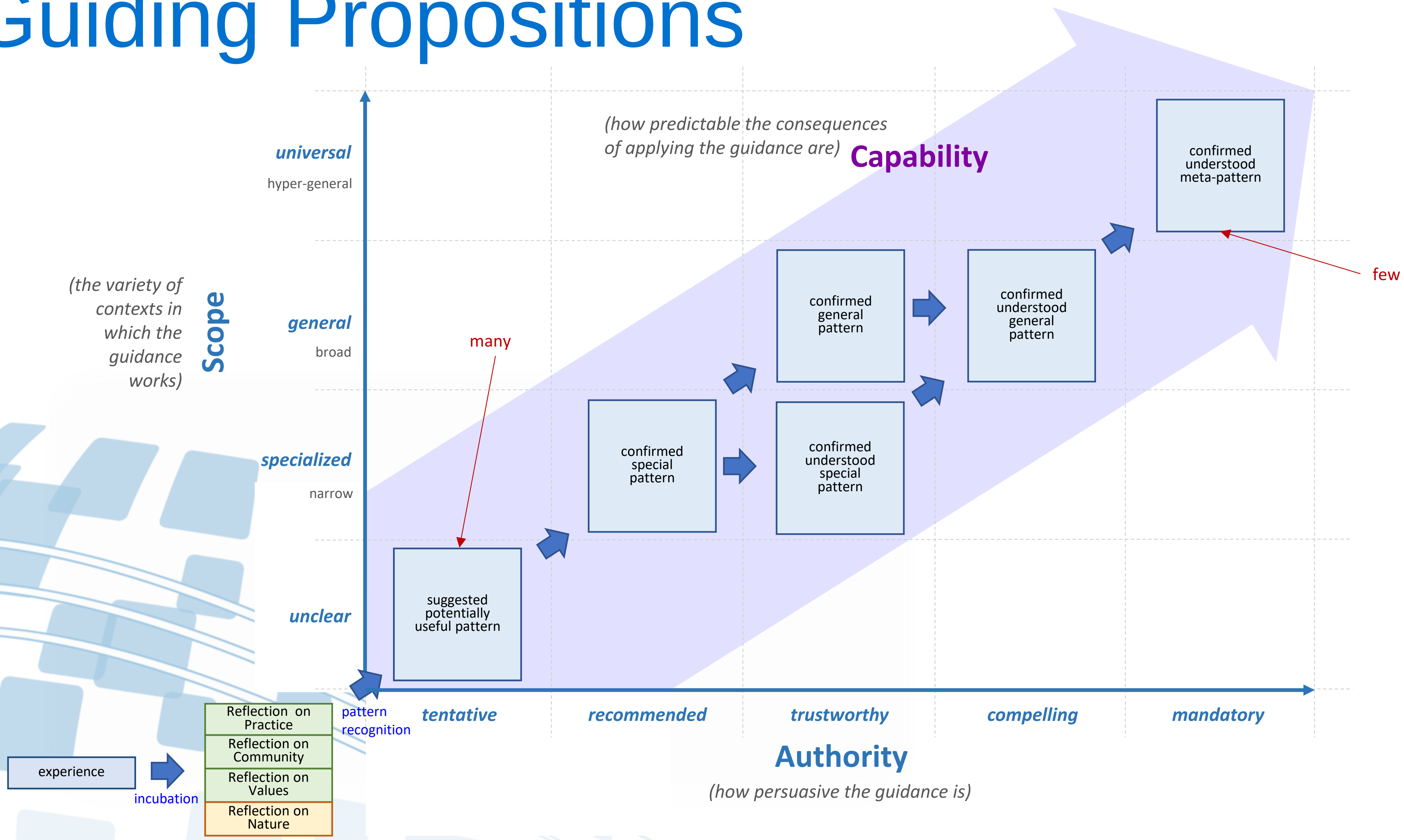

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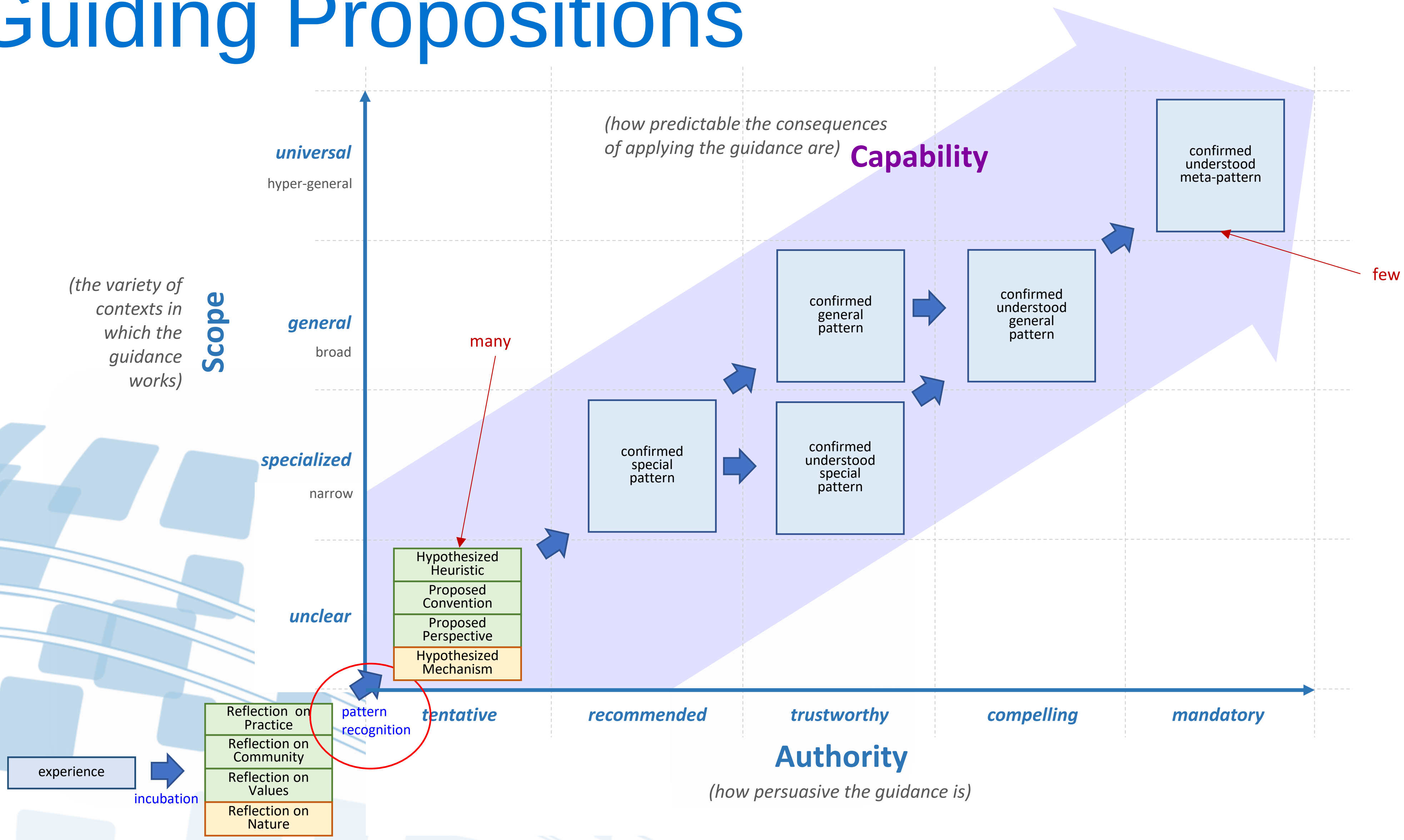

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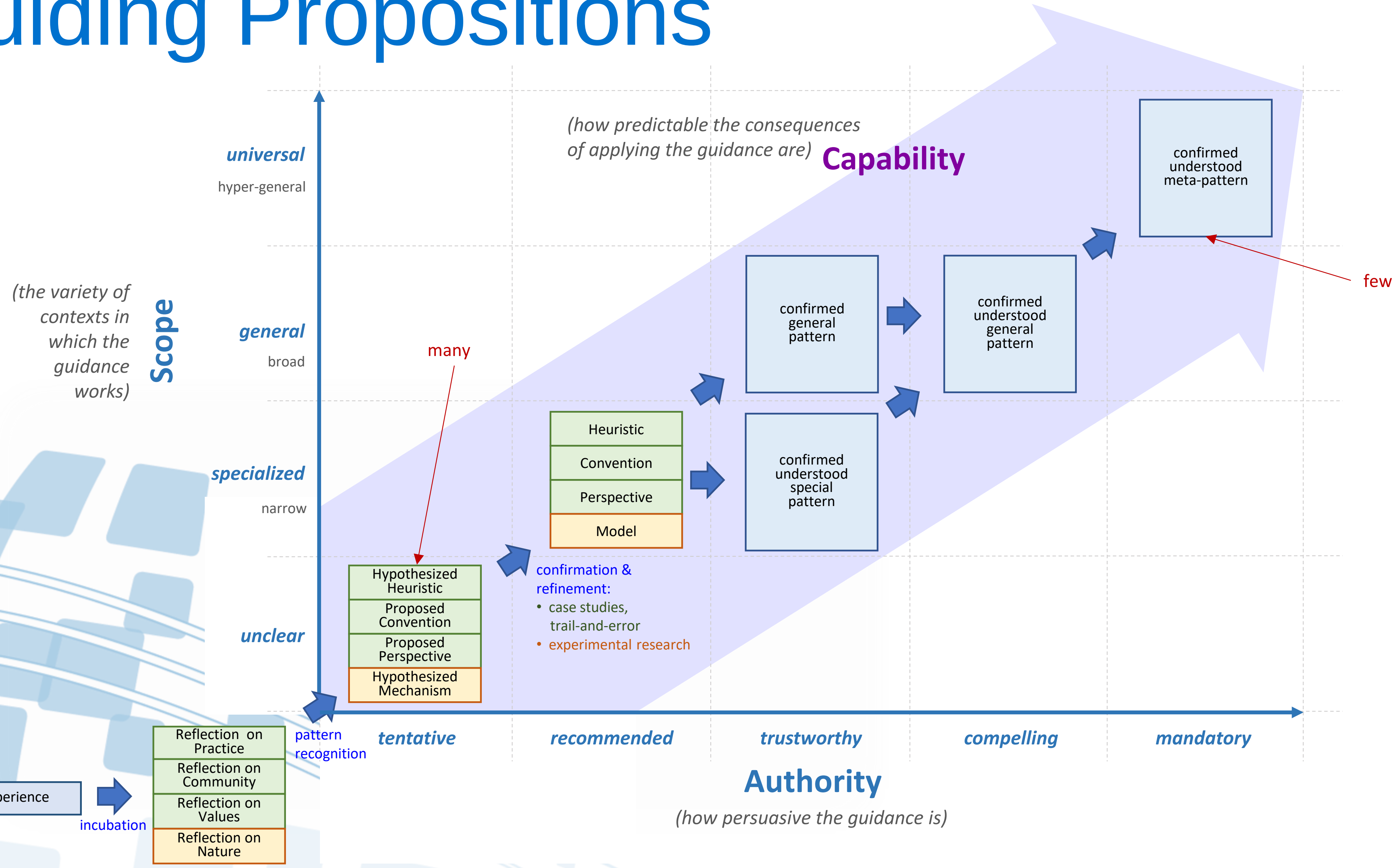

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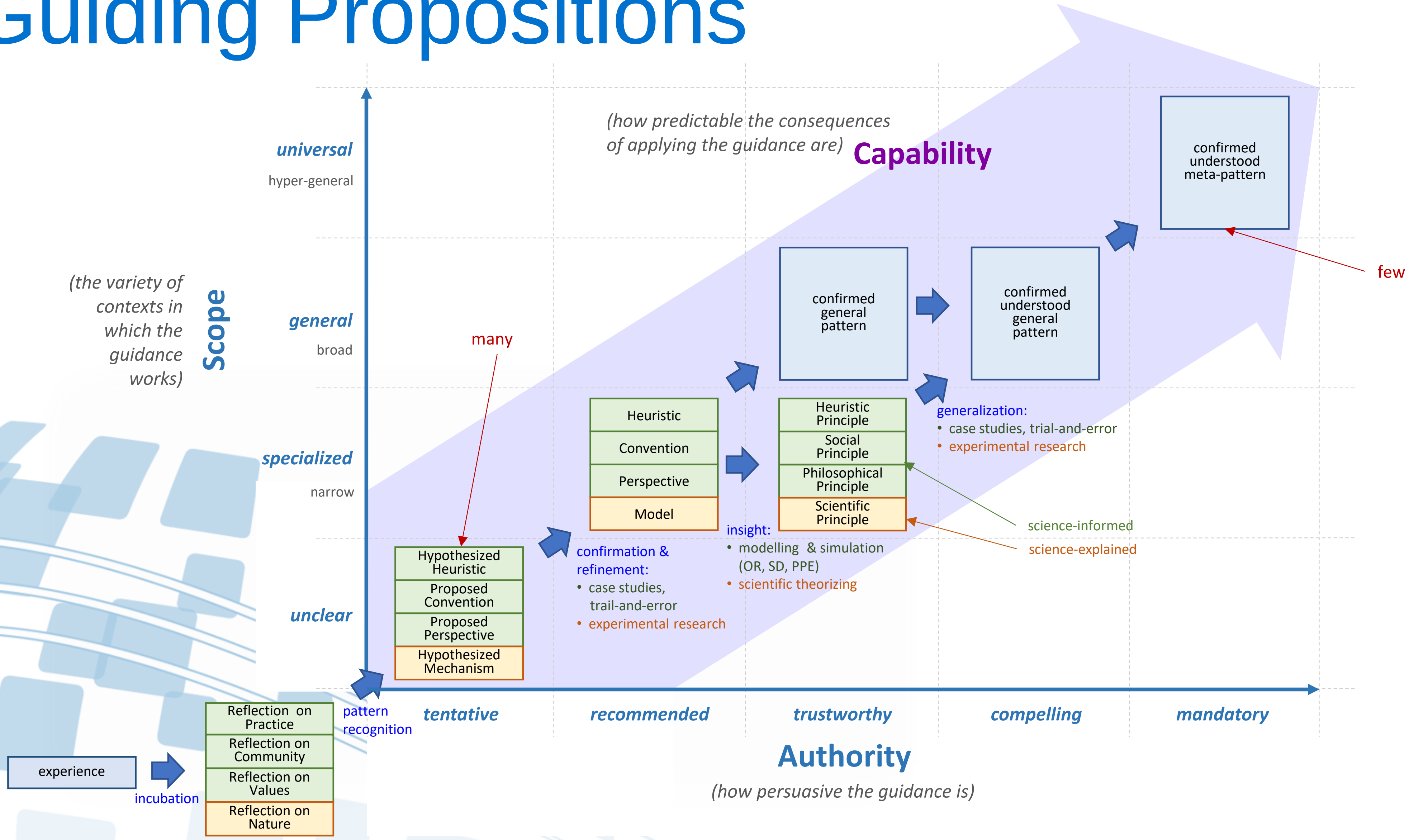

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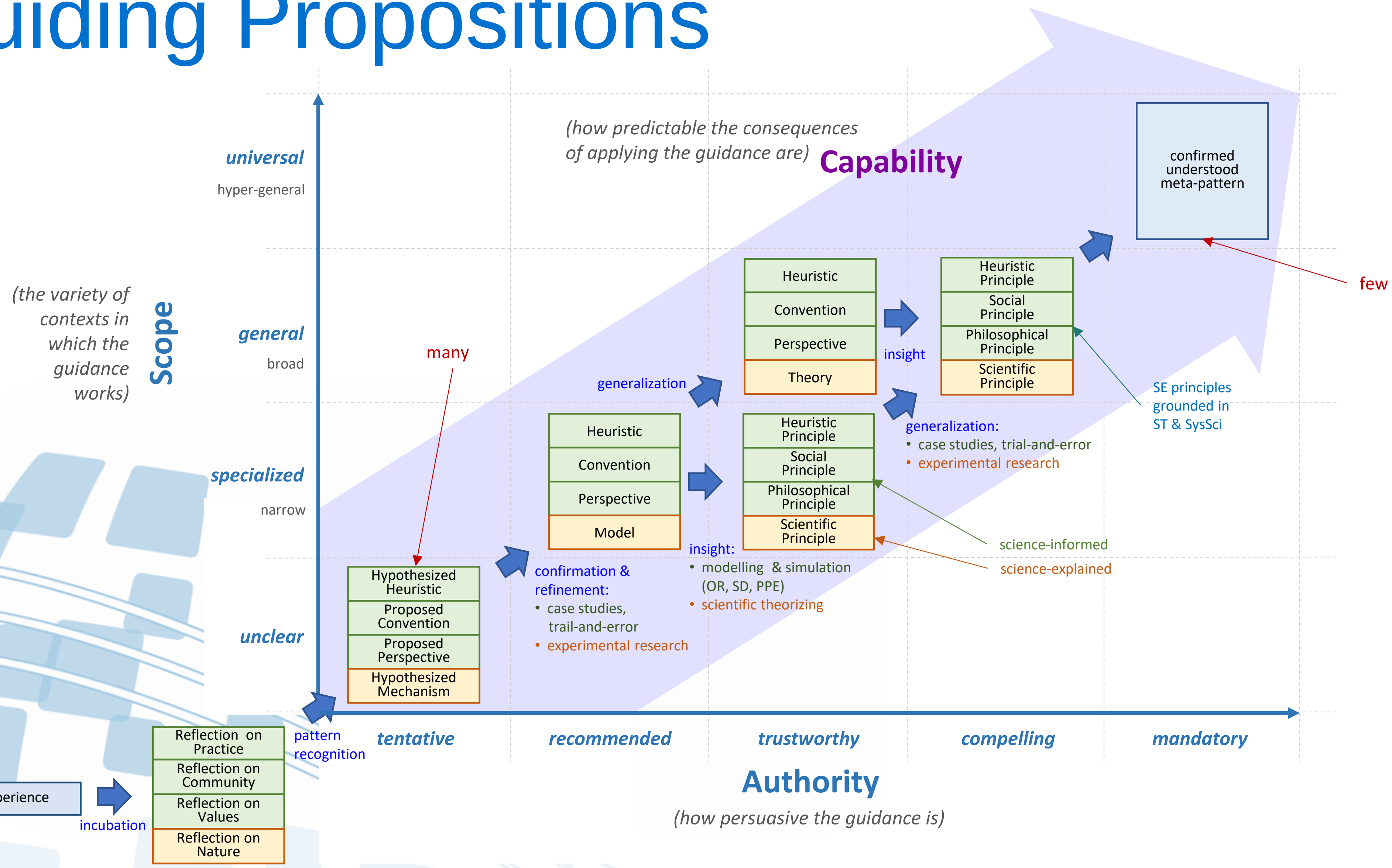
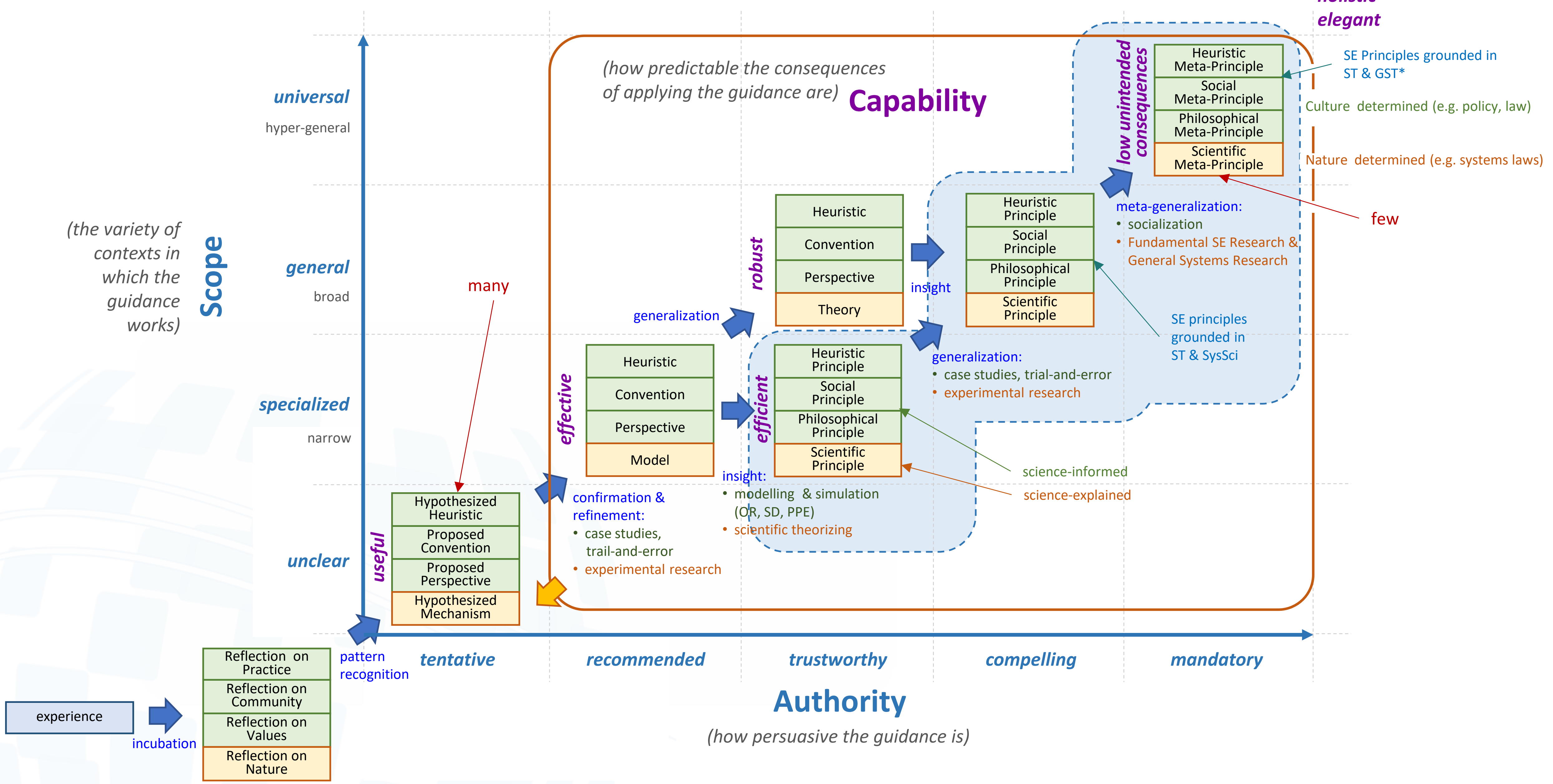
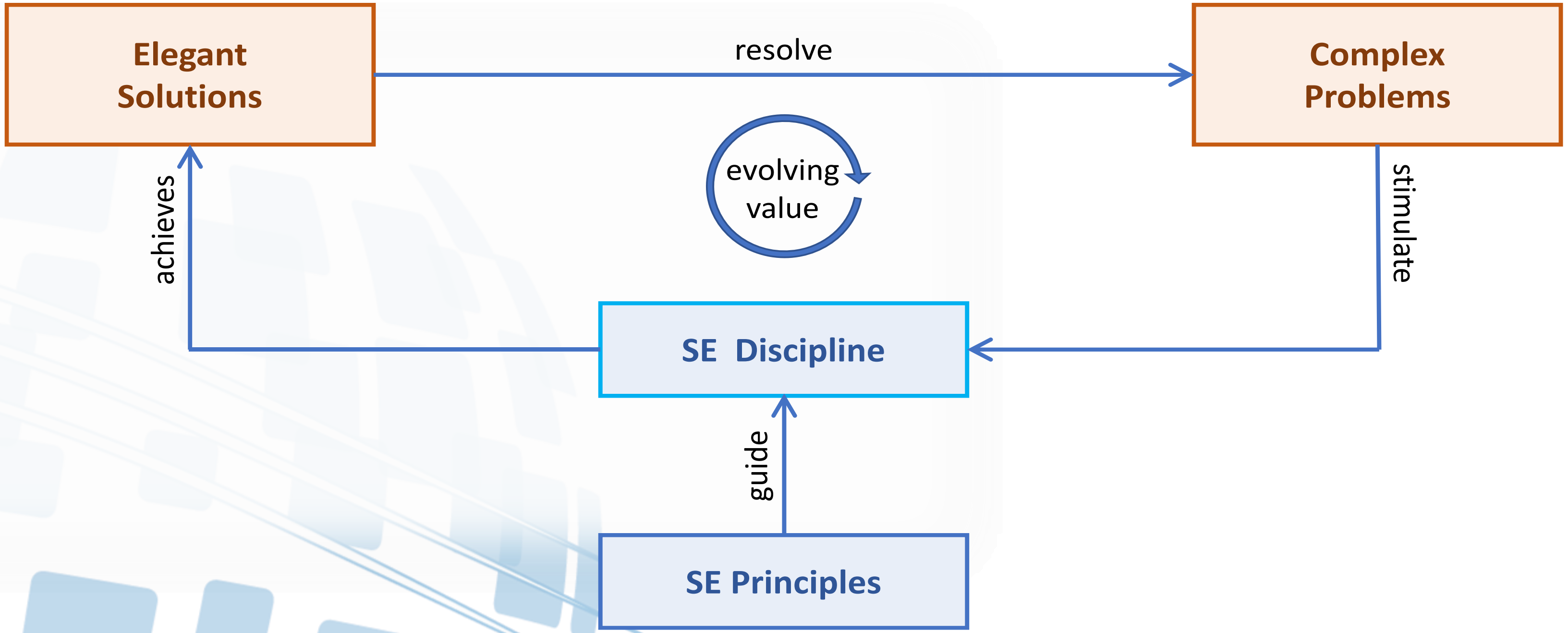


The spectrum and evolution of SE's "guiding propositions"



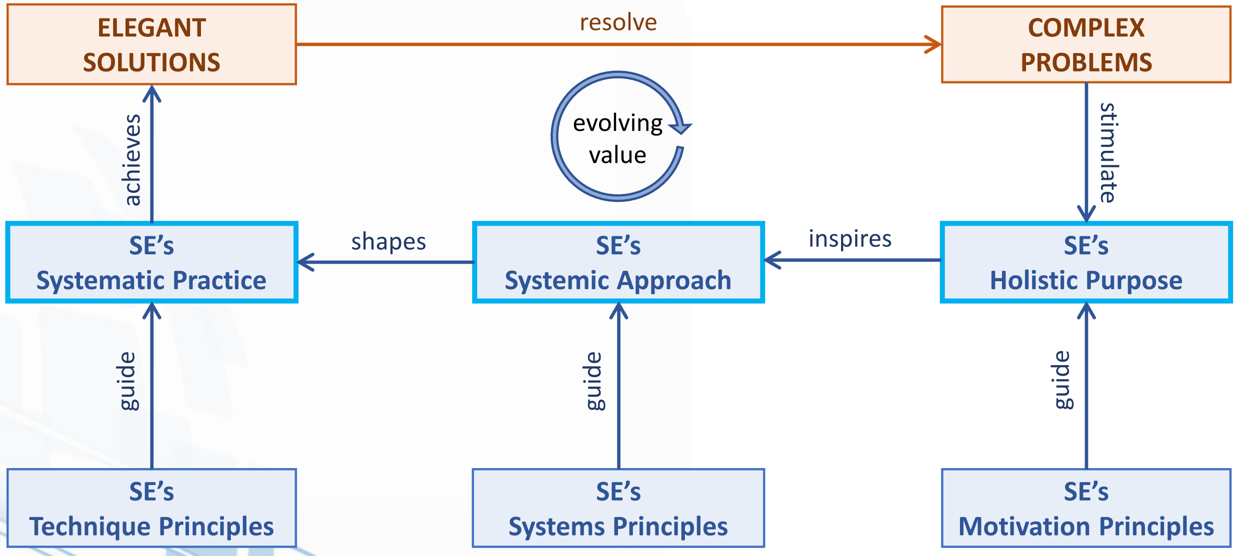
Systemic relationships in the evolution of SE's approach – *The Bridge*

- Systems Engineering creates value by achieving elegant solutions to complex problems.
  - The SE discipline's relationship to purpose and principles



Systemic relationships in the evolution of SE's approach – *The Bridge*

- Systems Engineering creates value by achieving elegant solutions to complex problems.
  - The systemic relationships between SE's value, facets and principles



***How** we do it*
- *Execute systematically*
- *Leverage methods, tools, processes*

***What** we do*
- *Think systemically*
- *Apply systems thinking to engineering*

***Why** we do it*
- *Build a better world (sustainable, equitable, …)*
- *Achieve elegant solutions to complex problems*

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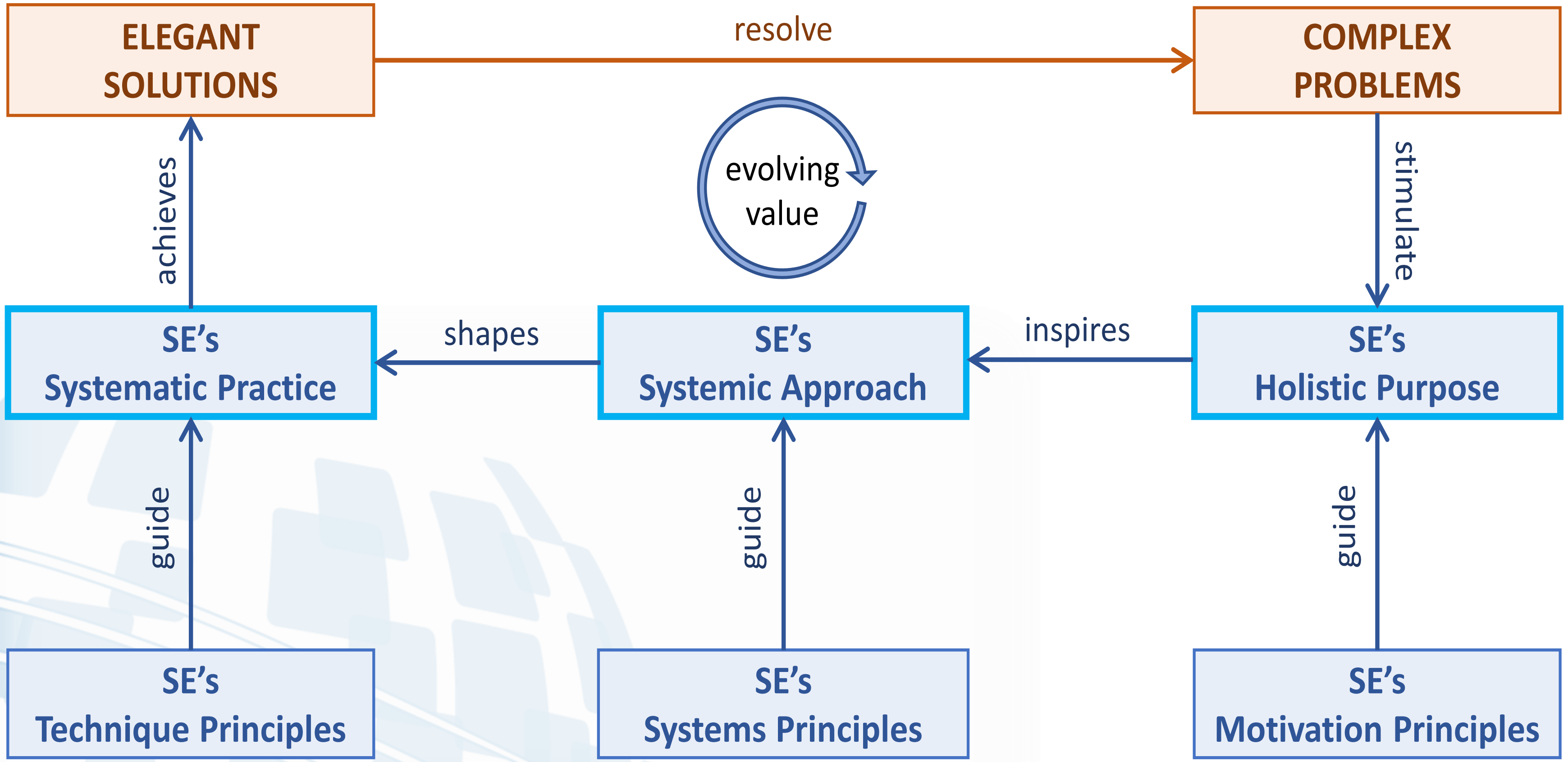

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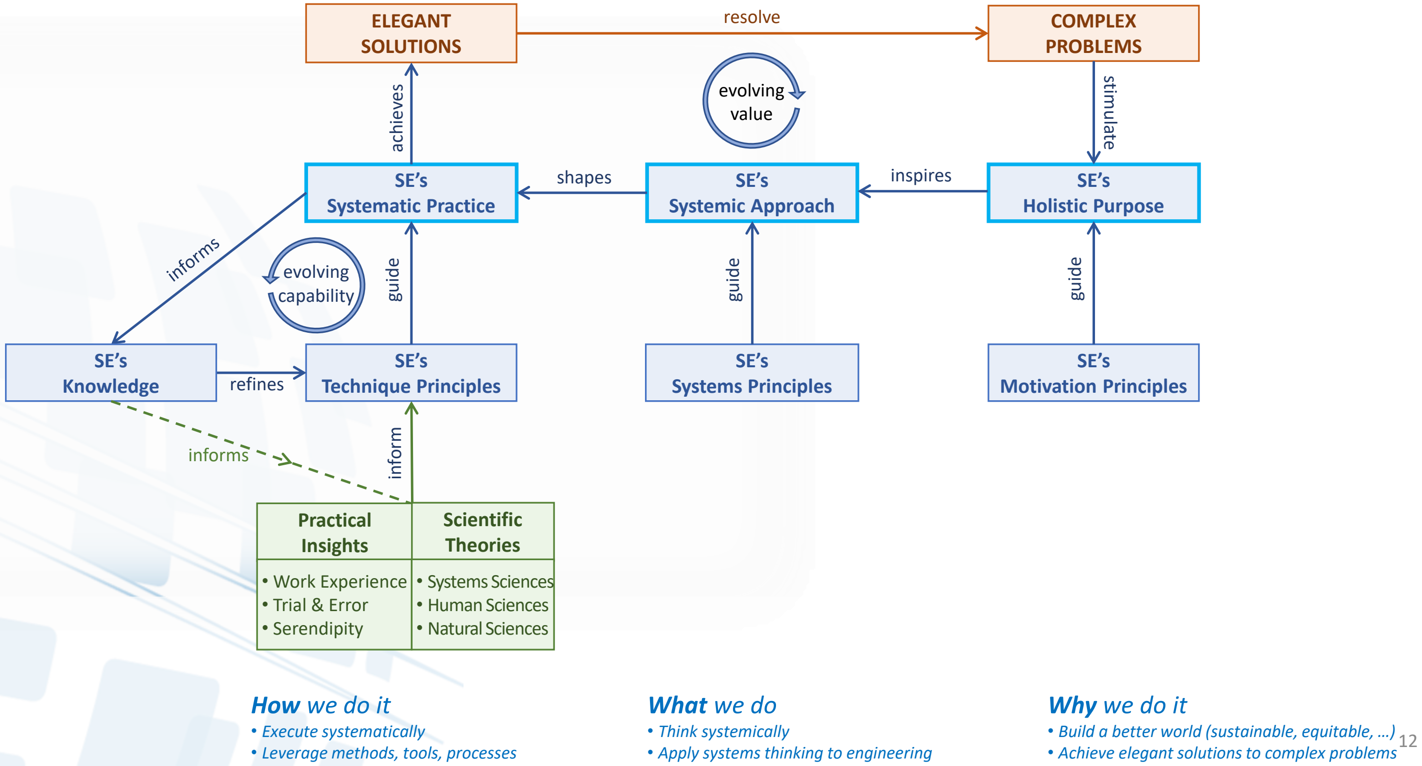

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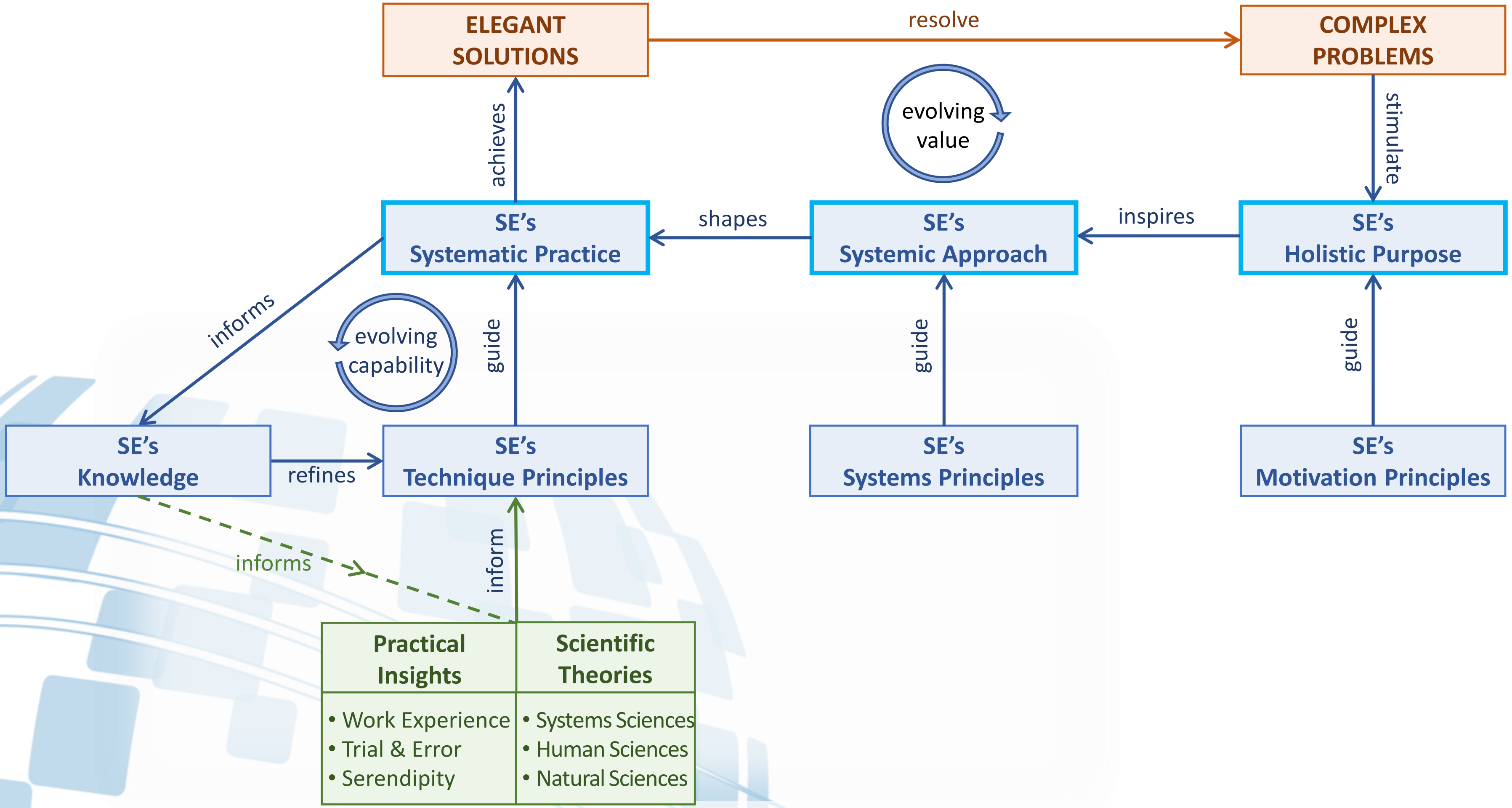

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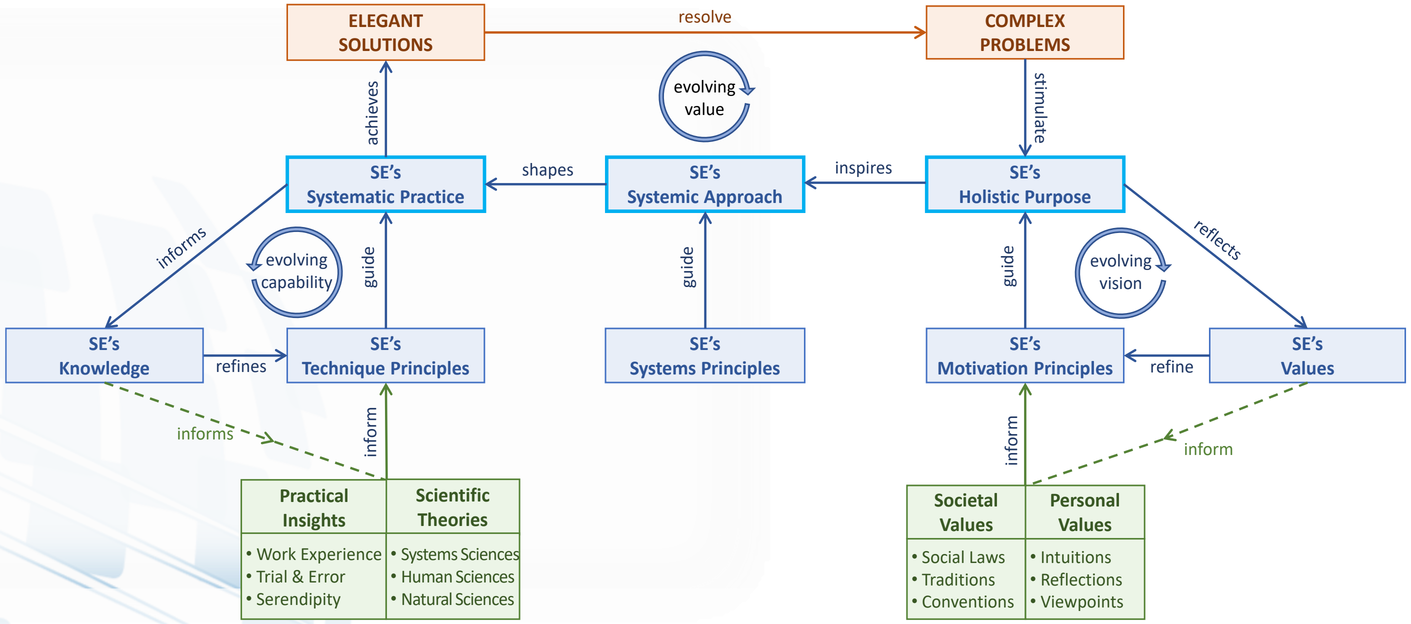
- Systems Engineering creates value by achieving elegant solutions to complex problems.
  - Systemic relationships in the evolution of SE's vision



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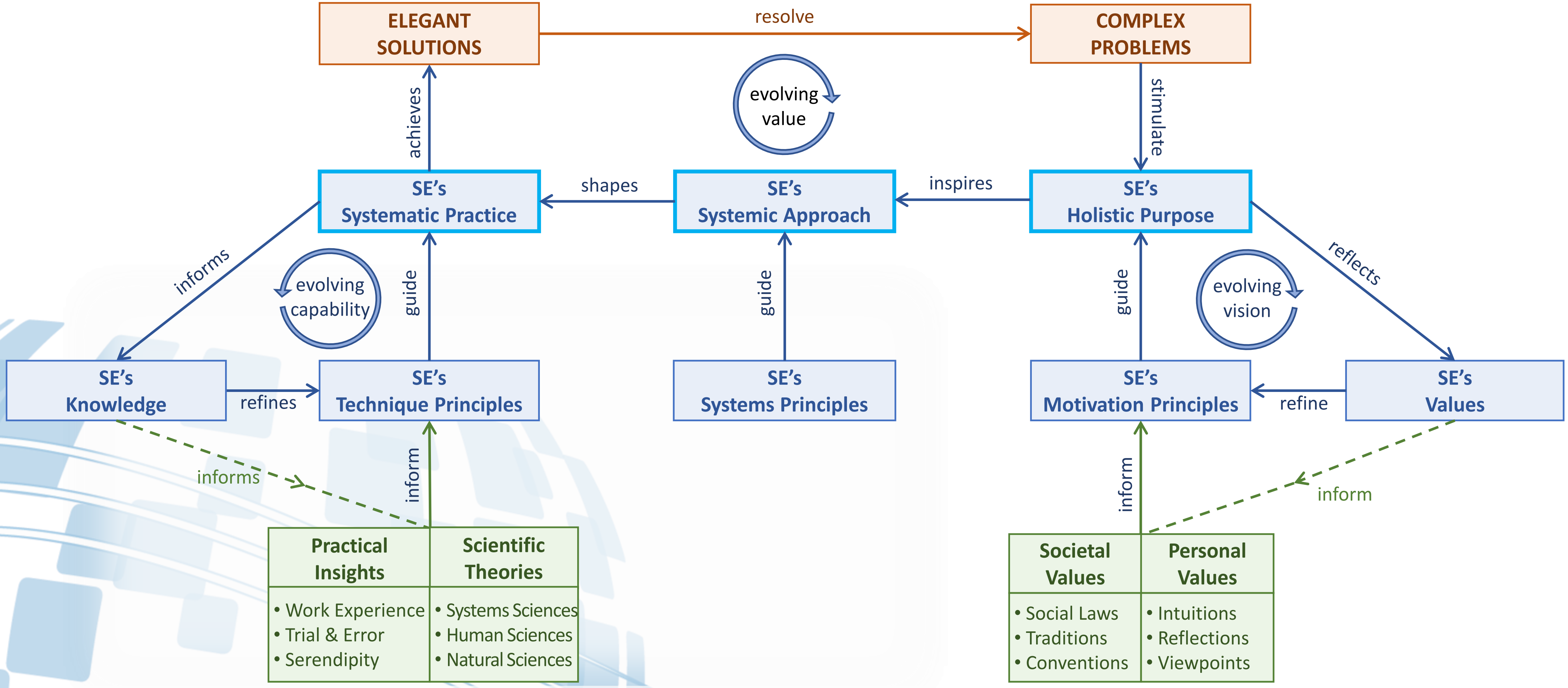

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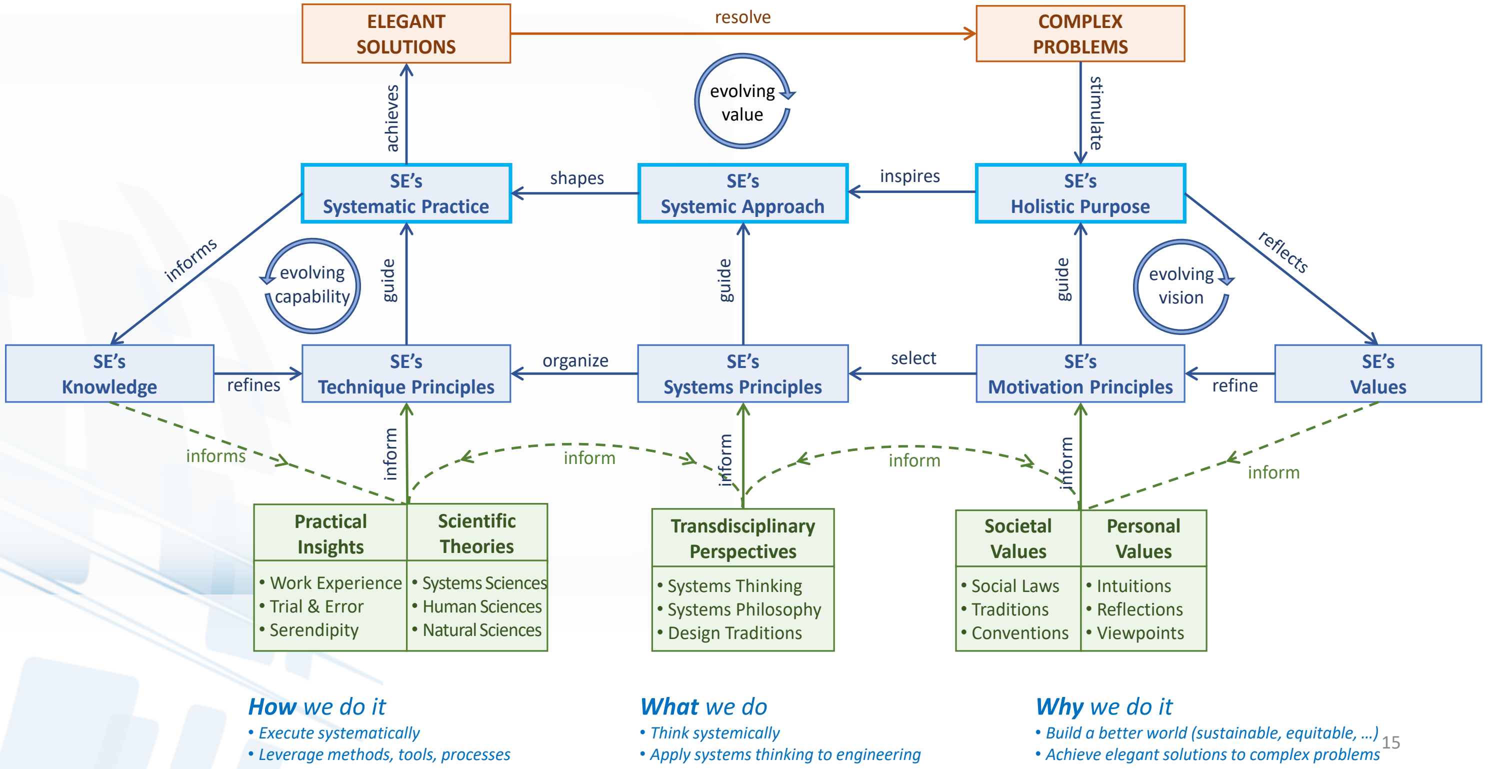

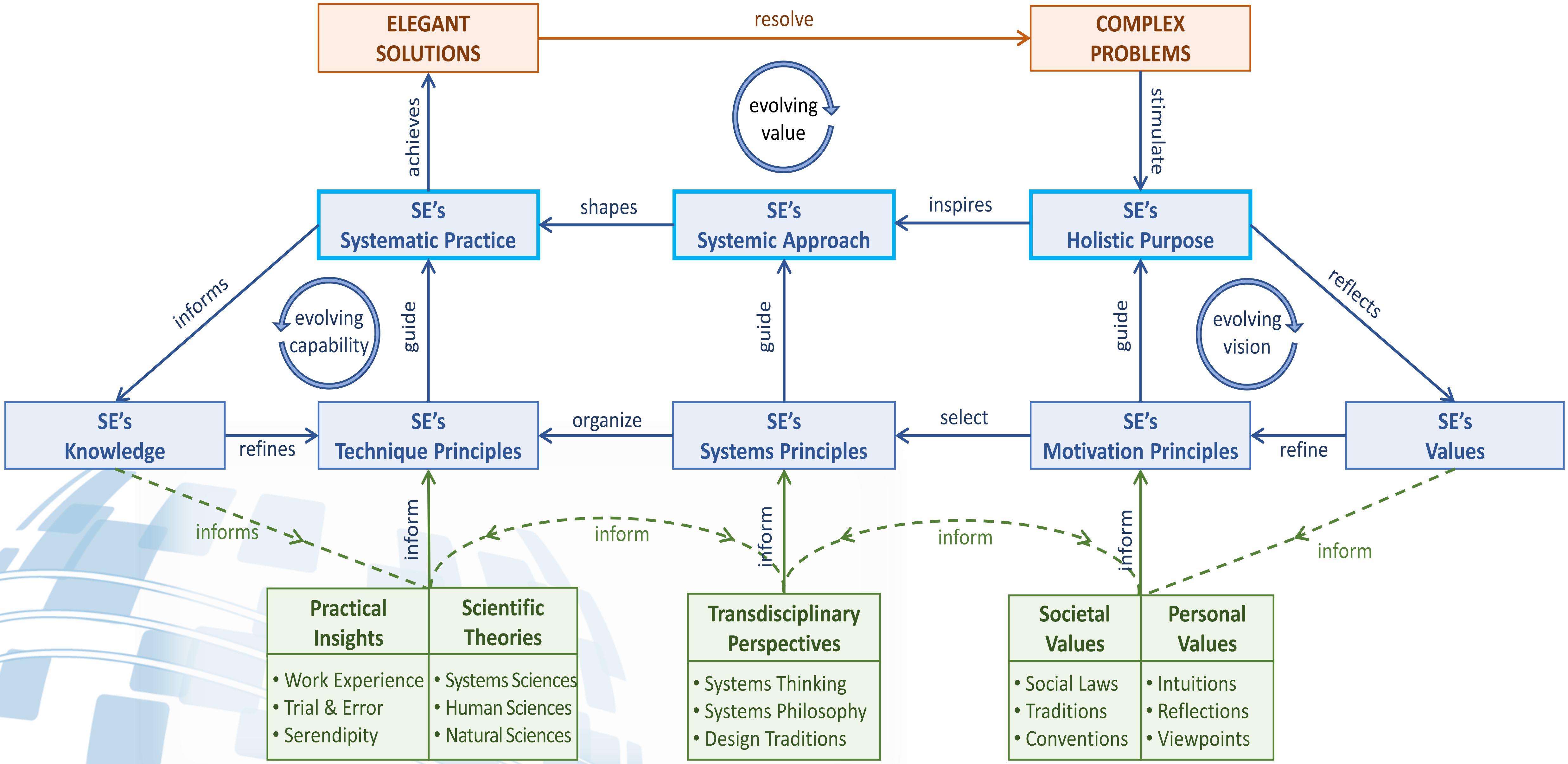

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Advance Conceptual Clarity

Categorical Systems Theory

- Composition is a process that does not provide point solutions, but rather:
  - assembles general pieces in a way that addresses the features and then specify (contextualize) problems inside the tools.
  - If problem changes, most of the work of constructing the solution is almost done.
    - Partial general solutions can be assembled into specialized solutions, and parameterized

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