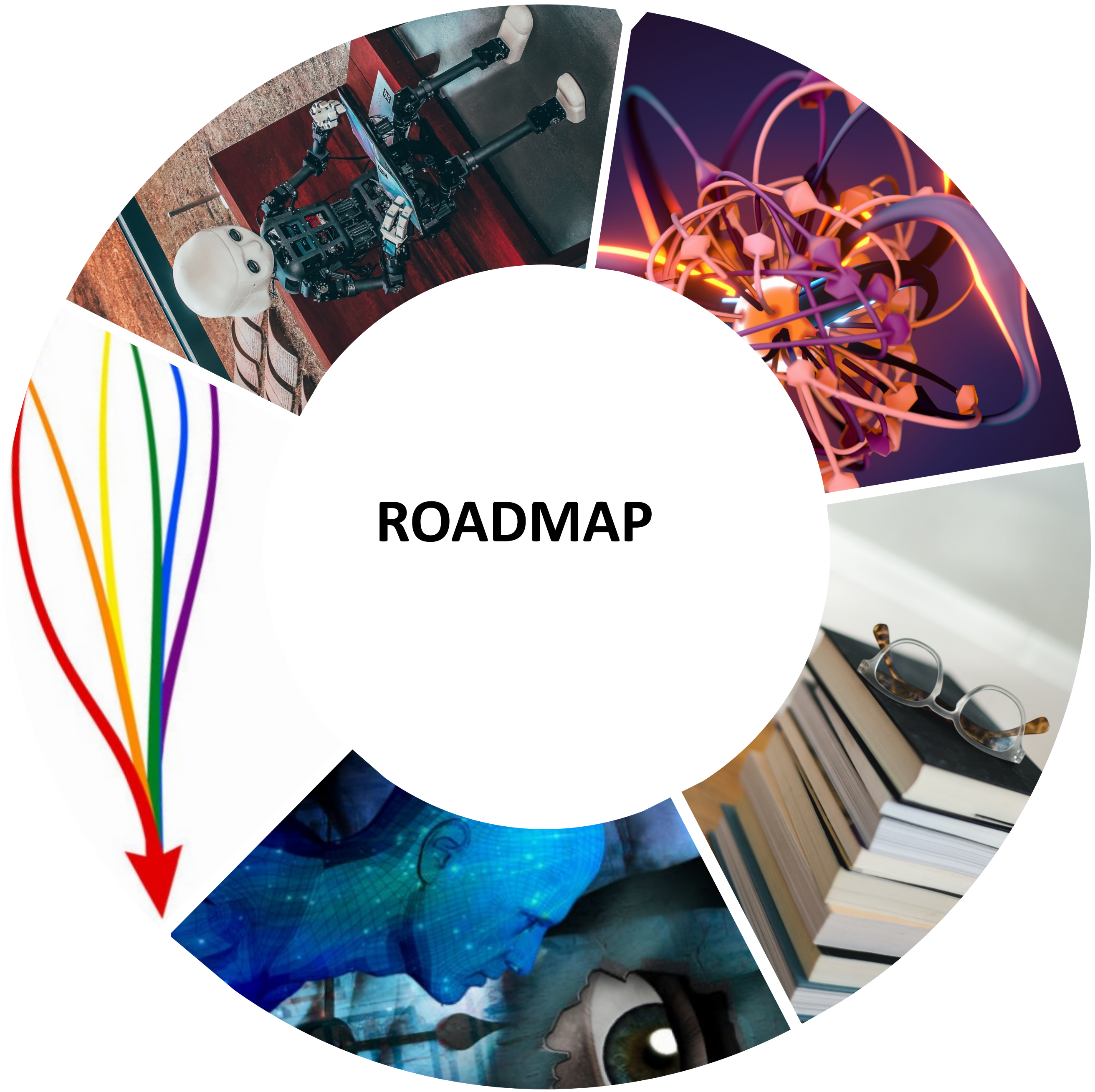
Niloofar Shadab, PhD

03/29/2024

Research Talk

PURDUE UNIVERSITY

VIRGINIA TECH.

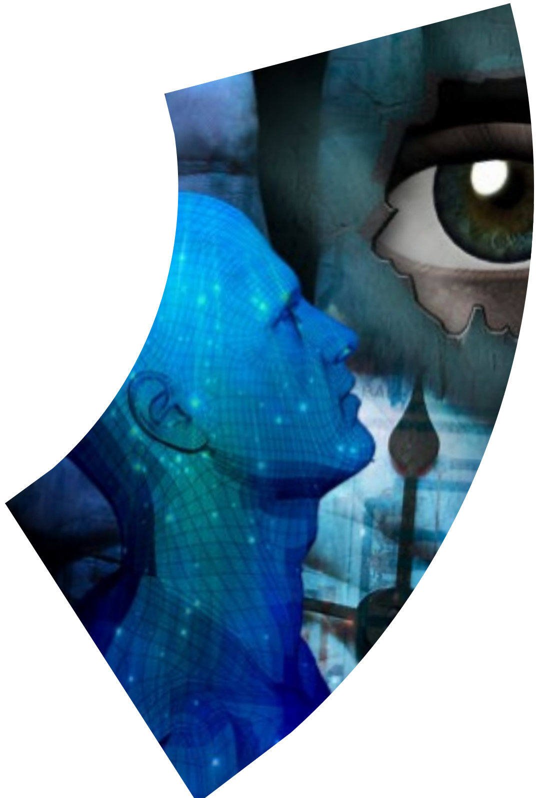

ROADMAP

Closed System Precepts in Systems Engineering for Artificial Intelligence - SE4AI

Niloofar Shadab

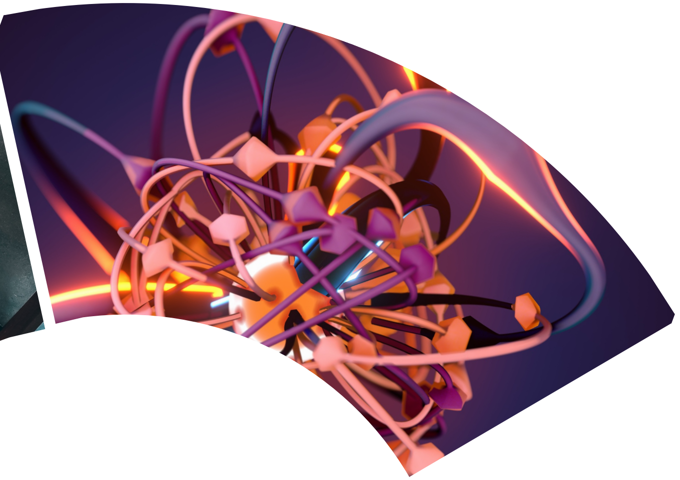
Introduction

ROADMAP



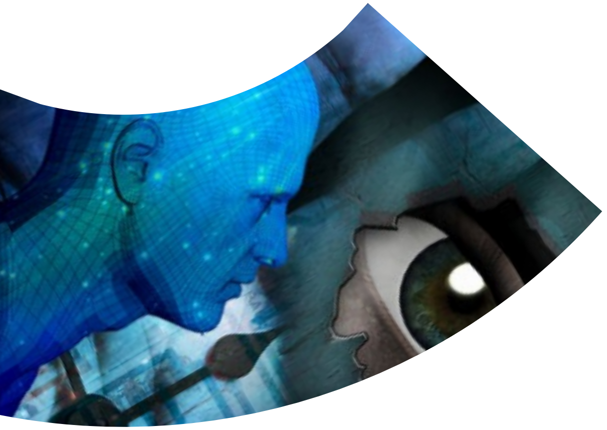
Why we need a new paradigm for SE of Intelligent Systems

Limitations of current SE practices



Theoretical Framework

ROADMAP



What is the theoretical approach to shift the paradigm

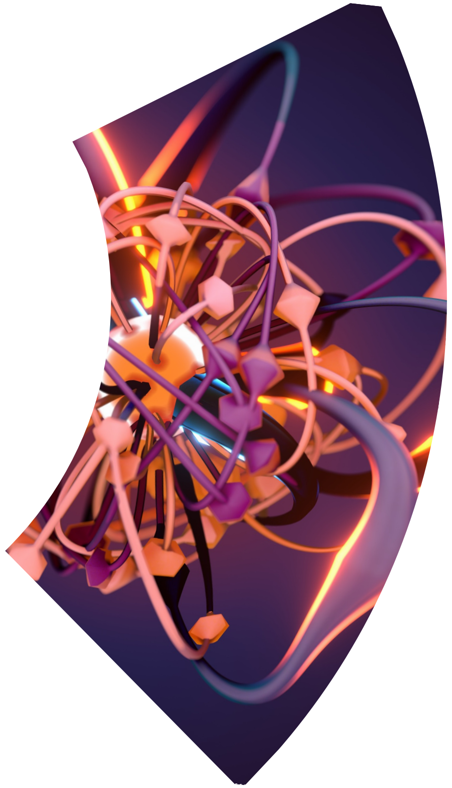
Closed System Paradigm

Functional Closure

Informational Closure

Explaining Real World Application

ROADMAP



How theoretical framework explains real-world

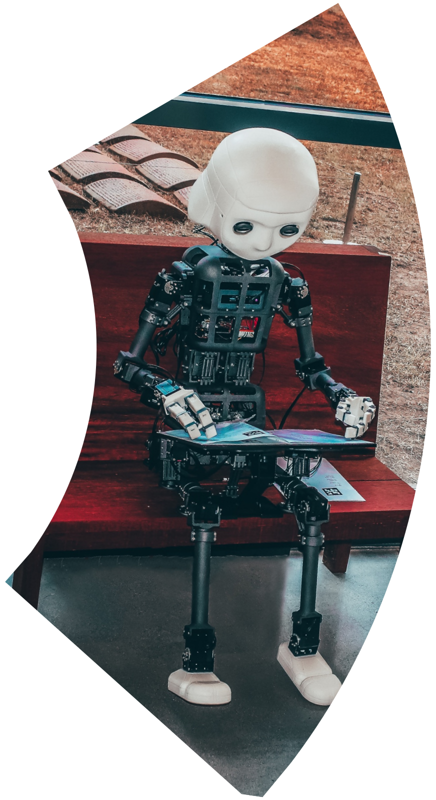
Evidence of Core and Periphery

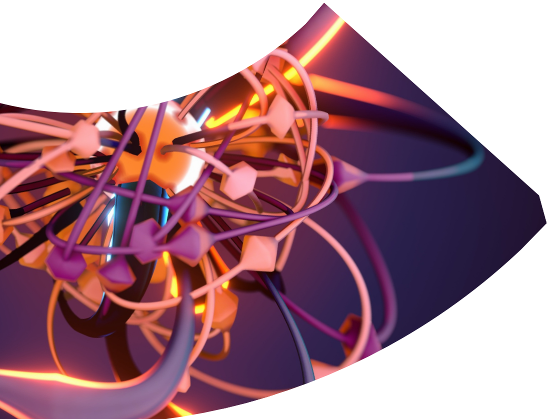
Biological Systems

AI Systems

Informing Engineering Practices

ROADMAP





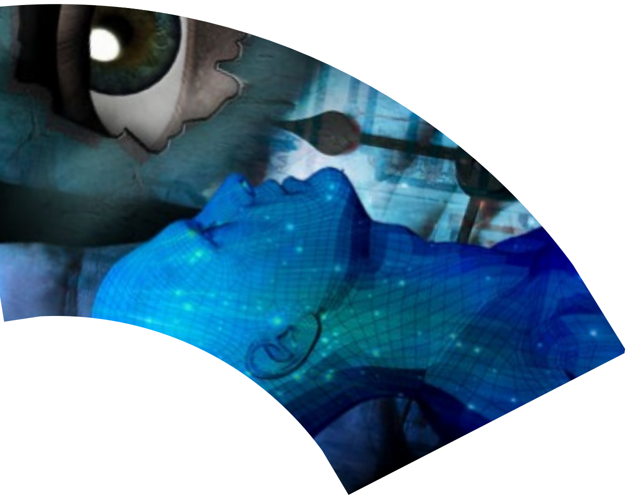
How theoretical framework informs engineering practices

Closed Systems View on Scale and Scope

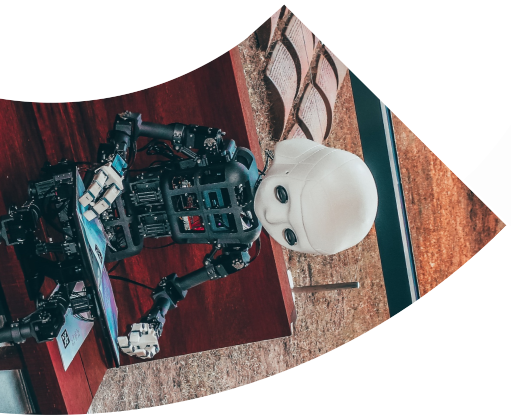
Functional Closure in SE4AI

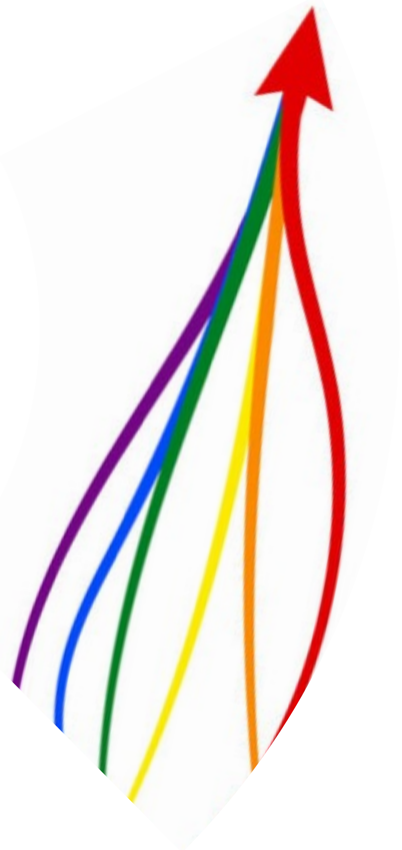
Informational Closure in SE4AI

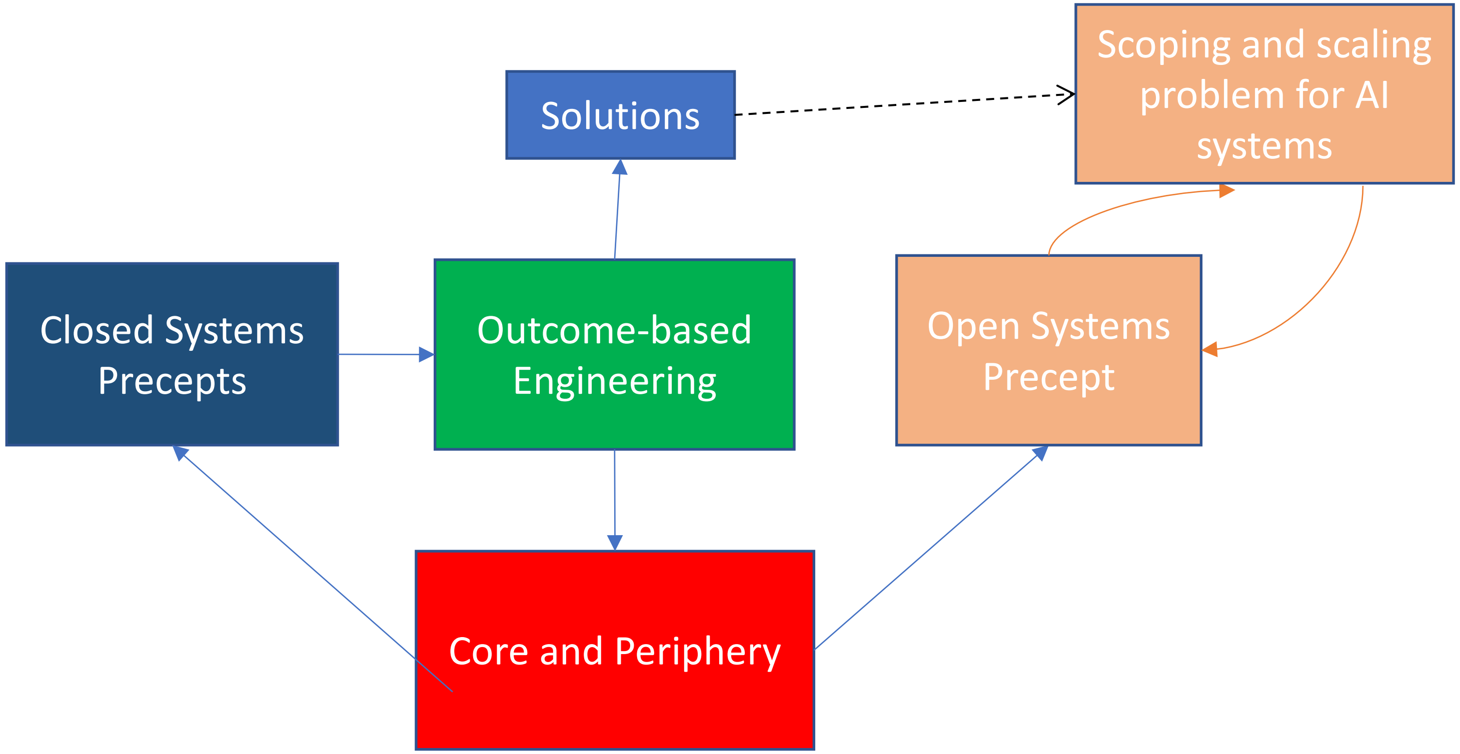
Conclusion



ROADMAP



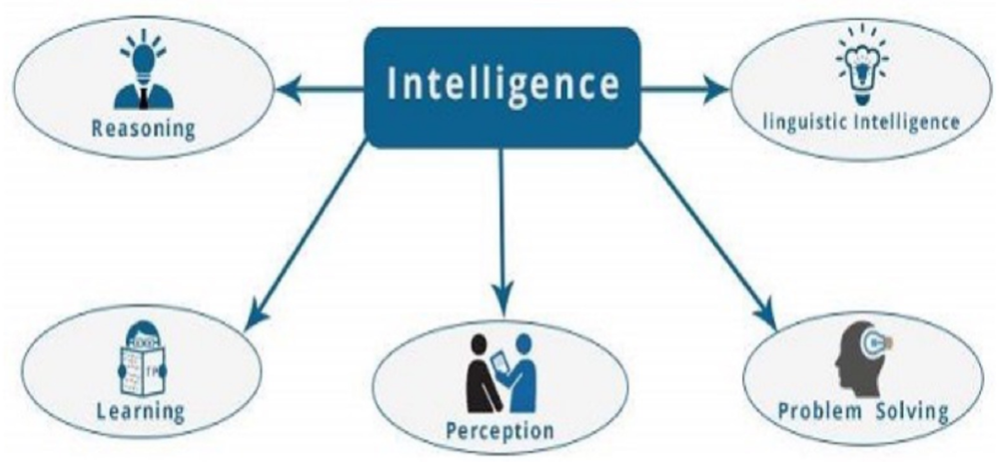




Introduction

Intelligent Systems- New Category of Systems

- Have endogenous evolution of behavior, and/or function over their life-cycle.
- Have intelligence as a new property of a whole; not relegated to a specific components



Implications of Intelligence in SE

INPUT-OUTPUT BASED PROBLEMS:

- Learn a new function
- Learn to handle a larger set of inputs for existing functions
- Learn to perform a function better

OUTCOME-BASED PROBLEMS:

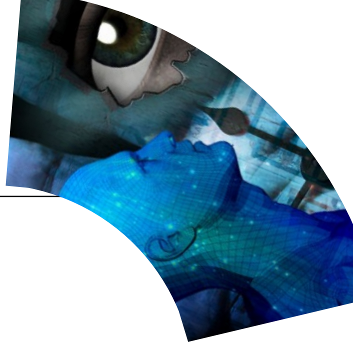
- Learn to achieve an outcome
- Deciding to pursue a new outcome
- Learning to achieve an existing outcome in a new context
- Learning to achieve an outcome better

Current Gaps in SE4AI

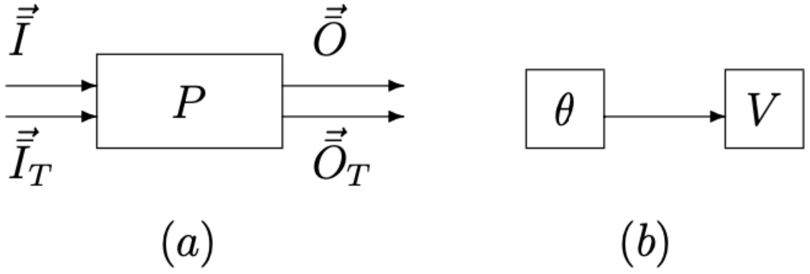
- AI Fragility to Environmental Changes

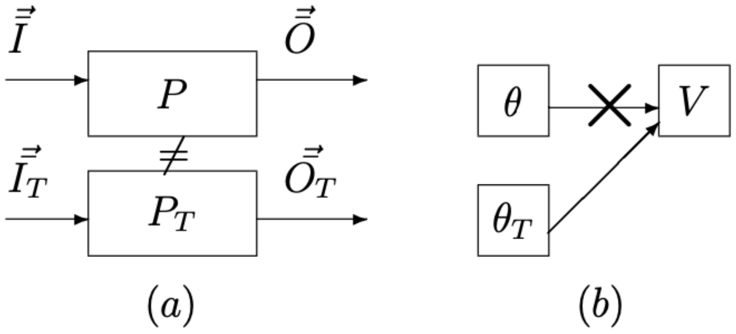
- Small changes in inputs set would have unpredicted consequences
- No direct relation between the changes in inputs and outputs.

Current Gaps in SE4AI

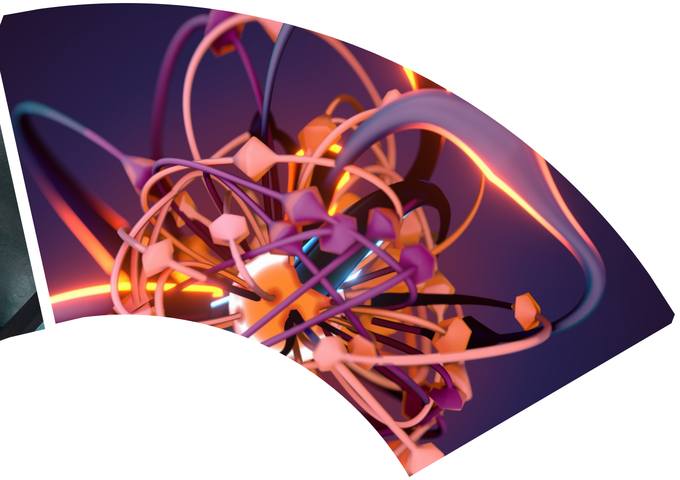


- Continuous Learning Aspects

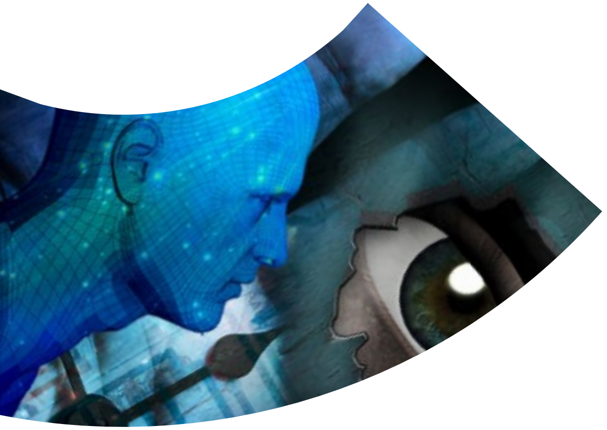




- Similar problems can appear in other SE activities such as manufacturing, design, and requirements engineering



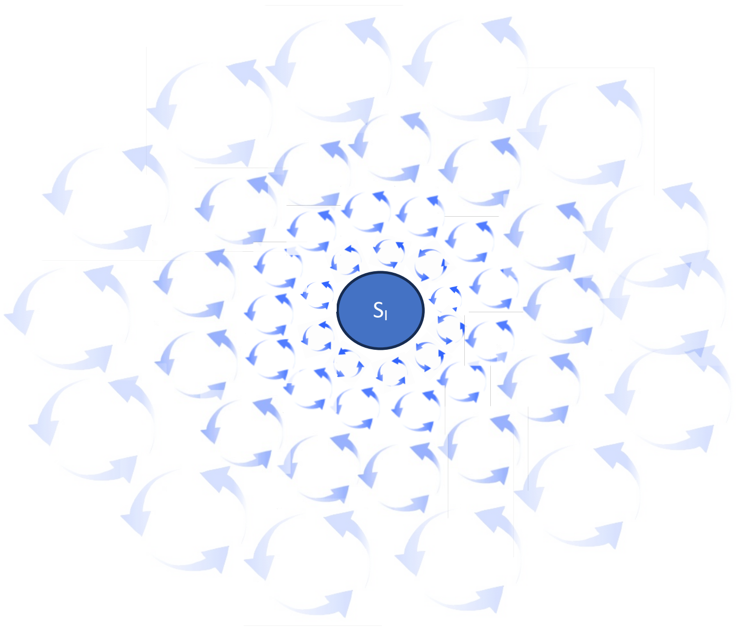
ROADMAP



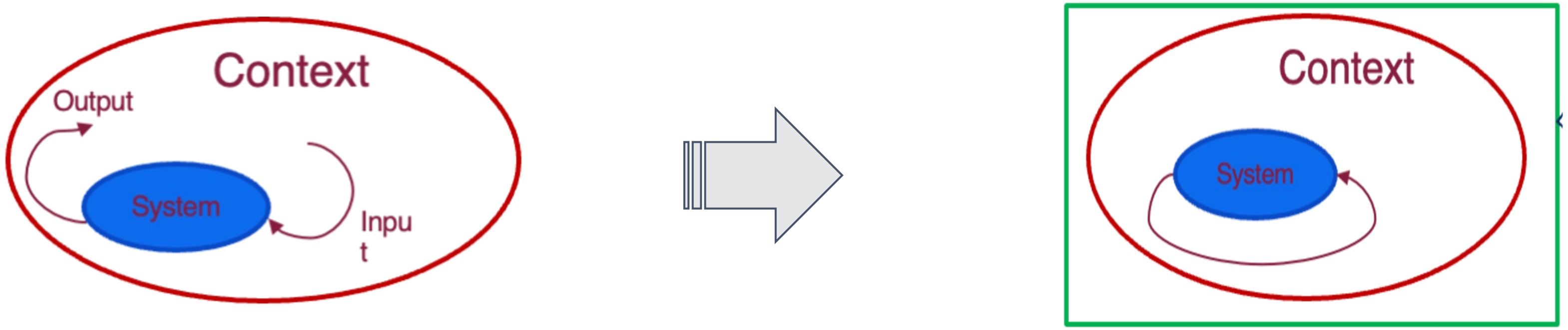
Theoretical Framework

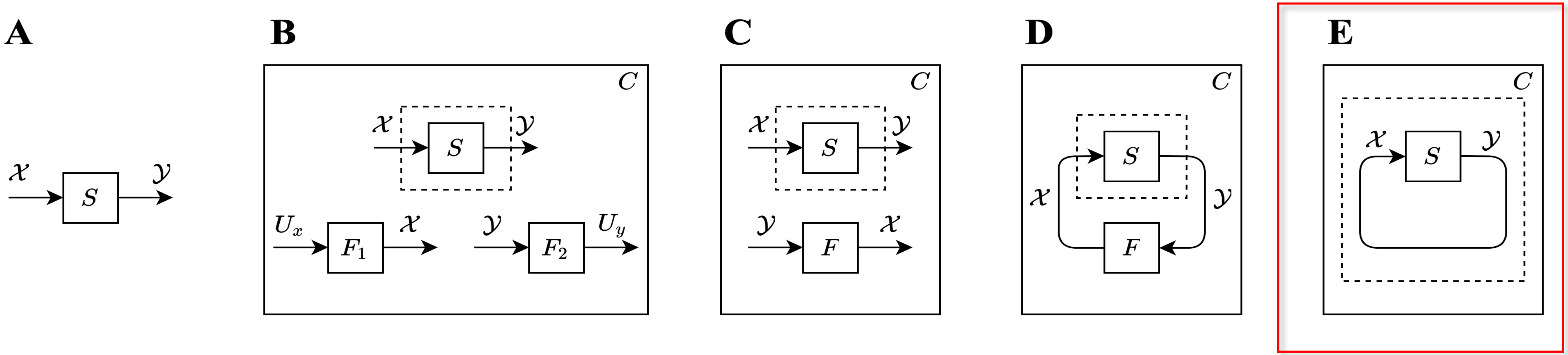
Unique Nature of Intelligence Property

- Closed Relations between the system and its environment
- Dissolution of boundary of intelligence
- Intelligence as a system-level relational property to its environment



Closed Systems Precepts





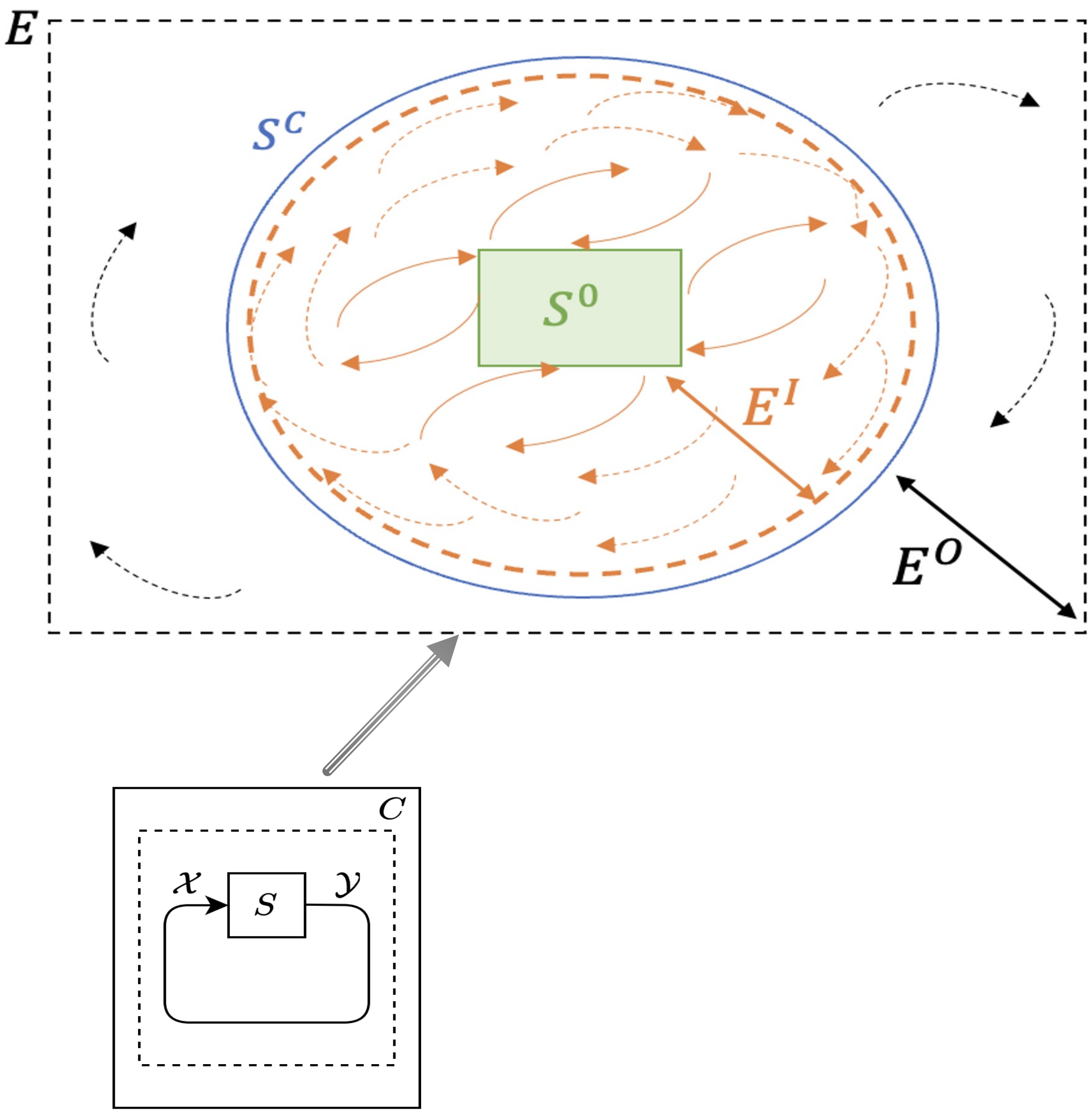
$$S \subset \times\{\mathcal{X}, \mathcal{Y}\}$$

$$\mathcal{X} \cap \mathcal{Y} = \emptyset$$

$$S \subset \times\{\mathcal{X}, \mathcal{Y}\}$$

$$\exists f : \mathcal{Y} \to \mathcal{X}.$$

Terminology Framework



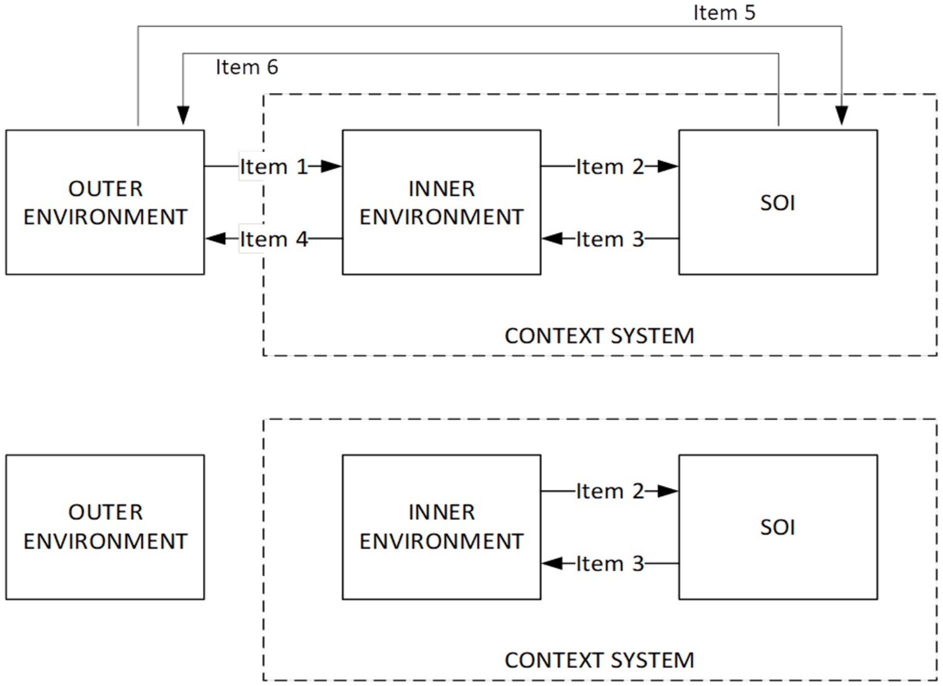
$$S^0 : S^0 \subseteq \times\{\mathcal{X}^0, \mathcal{Y}^0\}$$
$$U : \mathcal{X}^u = \mathcal{Y}^u = \emptyset$$
$$S^C : S^C \subseteq \times\{\mathcal{X}, \mathcal{Y}\}$$

$$E : E \subseteq \times\{\mathcal{X}^E, \mathcal{Y}^E\}$$
$$\text{Where, } \bar{E} = \bar{U} \setminus \bar{S}^0$$

$$E^I : E^I \subseteq \times\{\bar{E} \cap \bar{S}^C\}$$
$$E^0 : E^0 \subseteq \times\{\bar{E} \setminus \bar{S}^C\}$$

Functionally Closed System

Definition 1 (Functionally Closed Context System): A functional context system, S^C, is functionally closed from its outer environment, E^O, if and only if,
1) There exists a minimal set of inputs and outputs, , M, such that S^C is functionally dependent on M. This condition can be shown as: $S^C \subseteq \times\{\mathcal{X}_M, \mathcal{Y}_M\}$, and
2) There are no additional inputs from E^O beyond M that can influence the behavior of S^C. and
3) There are no additional outputs from S^C beyond M that can affect the behavior of E^O.



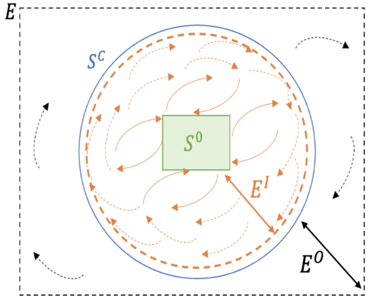
Given: $S^C : \mathcal{X}_M \to \mathcal{Y}_M$ & $E^O : \mathcal{X}^O \to \mathcal{Y}^O$

Where: $y \in \mathcal{Y}_M$ & $x \in \mathcal{X}_M$

we know: $\mathcal{Y}^O \to \mathcal{Y}_M \wedge \mathcal{X}_M \subseteq \mathcal{Y}^O$

If: $x' : x' \in \mathcal{Y}^O \wedge x' \notin \mathcal{X}_M$

$$\forall y \in \mathcal{Y}_M, \ \nexists x' \in Y^O, \quad \text{s.t.} \quad S^C(x') = y$$



Informationally Closed System

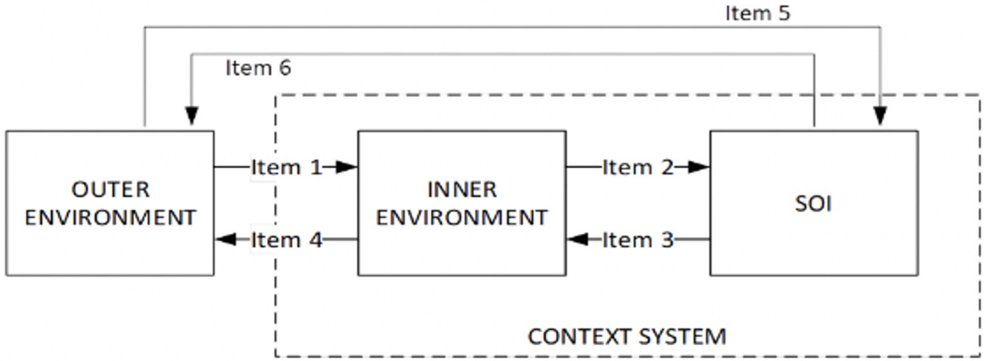
Definition 2 (Interpretation of An Informationally Closed Systems Using Information): A Context System that transitions through states $1, 2, \ldots, n, n+1$; is informationally closed at state n if there is no joint information between S^C_{n+1} and $E^O_n | S^C_n$.

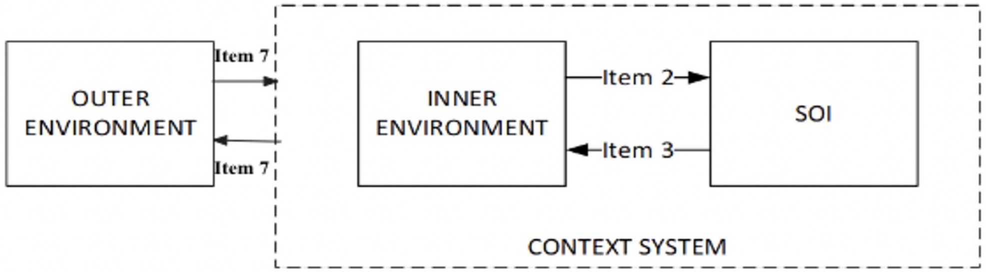
$$I(S^C_{n+1}; E^O_n | S^C_n) = 0$$

Theorem 1 (Inequality for mutual information in closure):

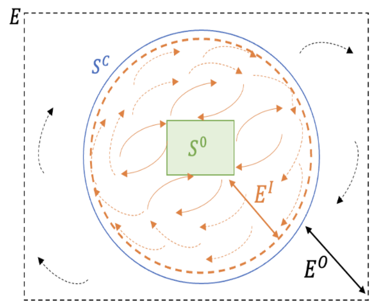
$$I(S^C_n; E^O_n) \geq H(S^C_{n+1}, S^C_n) - H(S^C_{n+1}, S^C_n | E^O_n)$$

Theorem 1 provides the relation for the level of mutual information being presented in the boundary of an informationally closed system. To maintain closure at state $n+1$,

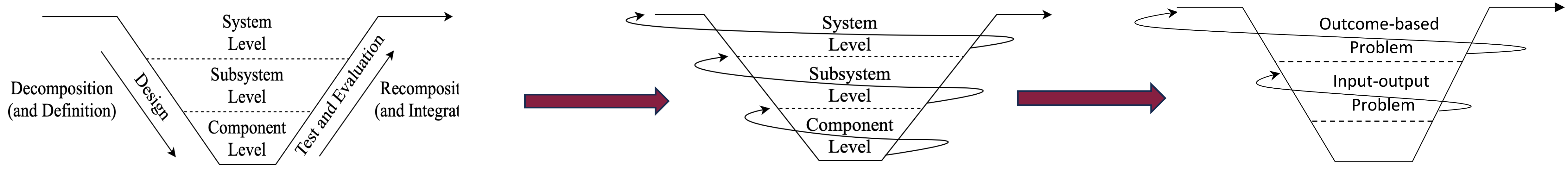




Item 7 $\subseteq \times$ (Item 1, Item 4, Item 6, Item 5)



Different Level of Abstraction in SE



Ashby's Law of Requisite Variety:

$$S \text{ is stable } \rightarrow Variety(S) > Variety\ (C)$$

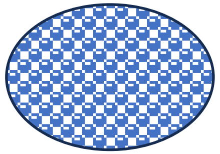
$$Variety(O) \geq Variety(C) - Variety(S)$$

Variety is a measurement of complexity in systems.

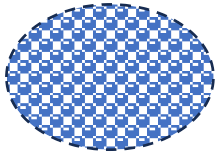
$$V_A = -\sum_{i}^{|A|} p_i \log_2 p_i;$$

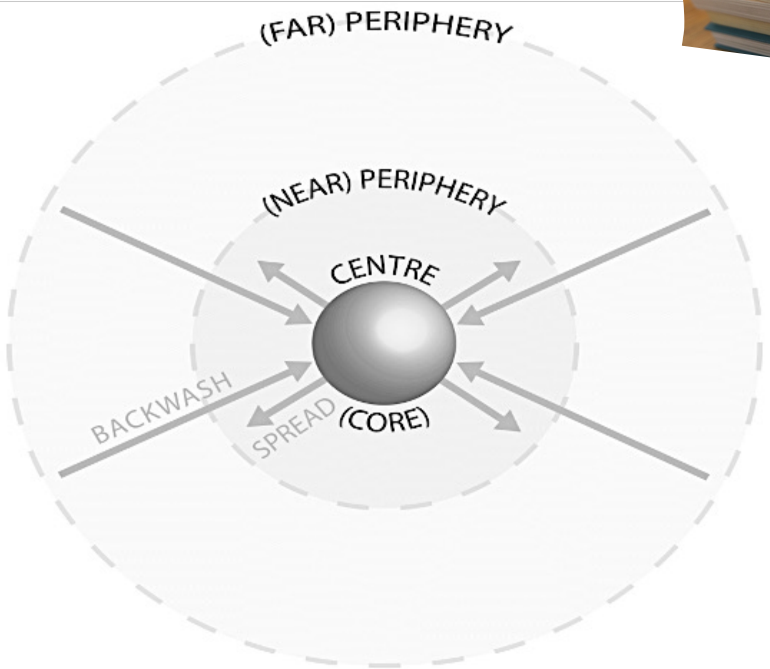
Core And Periphery Precepts

Bounded Variety:



Unbounded Variety:





Residual Change: $R_{\bar{S}}^{t,t\prime} = \{X^{t'} \setminus \mathrm{X}^{t}, Y^{t'} \setminus \mathrm{Y}^{t}\}$

Consider a system S at time t and at a later time t’, The **core** of S from t to t' is

$$C_{\bar{S}}^{t,t\prime} = \bar{S} \setminus R_{\bar{S}}^{t,t\prime}$$

The **Periphery** of S from t to t’:

$$\mathcal{P}_{\bar{S}}^{t,t\prime} = R_{\bar{S}}^{t,t\prime}$$

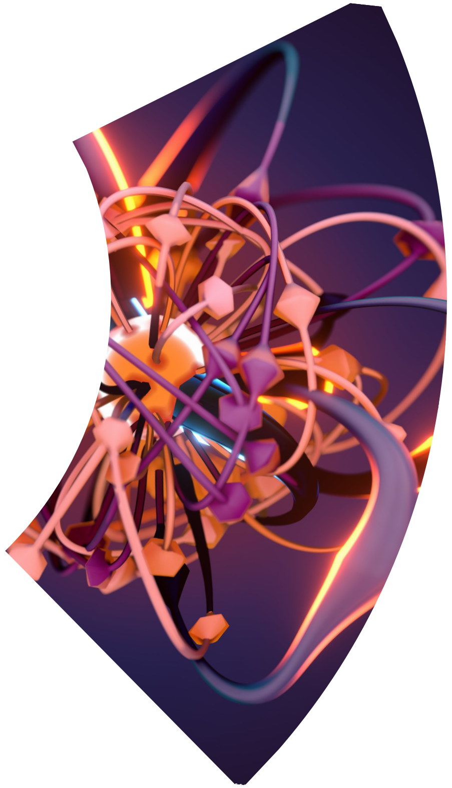
Use of Core And Periphery as Precepts

- **Blocking:** Outcome-based value judgement on the distribution of variety. What aspects of an intelligent system are being used to block environmental variety to regulate outcome
  - **Core-dominant**
  - **Periphery-dominant**

- **Outcome-based Engineering:** By avoiding restrictive assumption of decomposition and recomposition, subsystems can be abstracted to lower level of core and periphery distribution at subsystem level independent to the system-level abstraction.

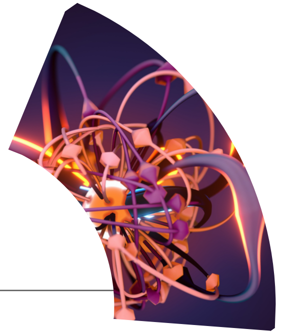
- **Modeling Dynamics of Variety:** Modeling of core and periphery elements over time. Trace adaptation in a system as elements move between core and periphery.

ROADMAP



Explaining Real World Application

Biological Intelligence through Core and Periphery



- **Homeostasis and Homeodynamics**
  - Homeostasis: It refers to the body’s ability to maintain a stable and balanced internal environment, despite external changes and fluctuations.
  - Homeodynamics: It describe a state of dynamic equilibrium or balance within a biological system.

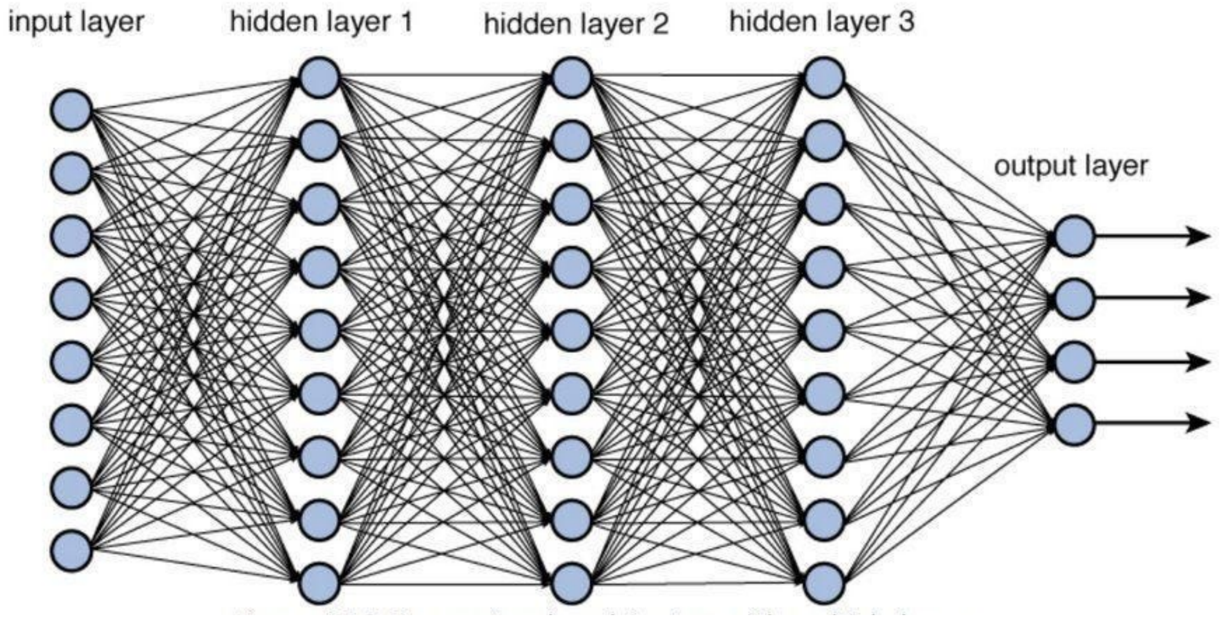
  - Homeostatis variables → **core** homeodynamic variables → **periphery**

- **Belief and Interrogative Attitude**
  - Interrogative attitude can transfer to belief and vice versa through the conduct of inquiry due to suspension of judgment.

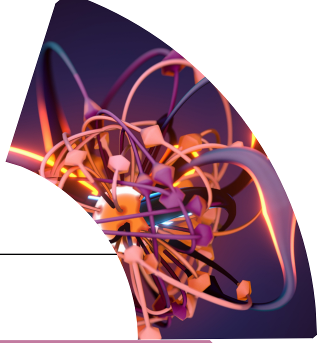
  - Belief → **core** Interrogative Attitude → **periphery**

Artificial Intelligence Through Core and Periphery

- Motivation: Observe how environmental variety is absorbed by the System through its internal variety
- CNN Structure: Fully-connected layer has a fixed structure, feature set, activation, and loss function.
- Where is the variety absorbed? **Weights of the layers.**
- How to capture environmental variety? **Through inputs set** (both in terms of structural complexity, size)

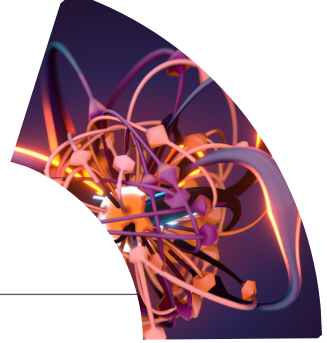


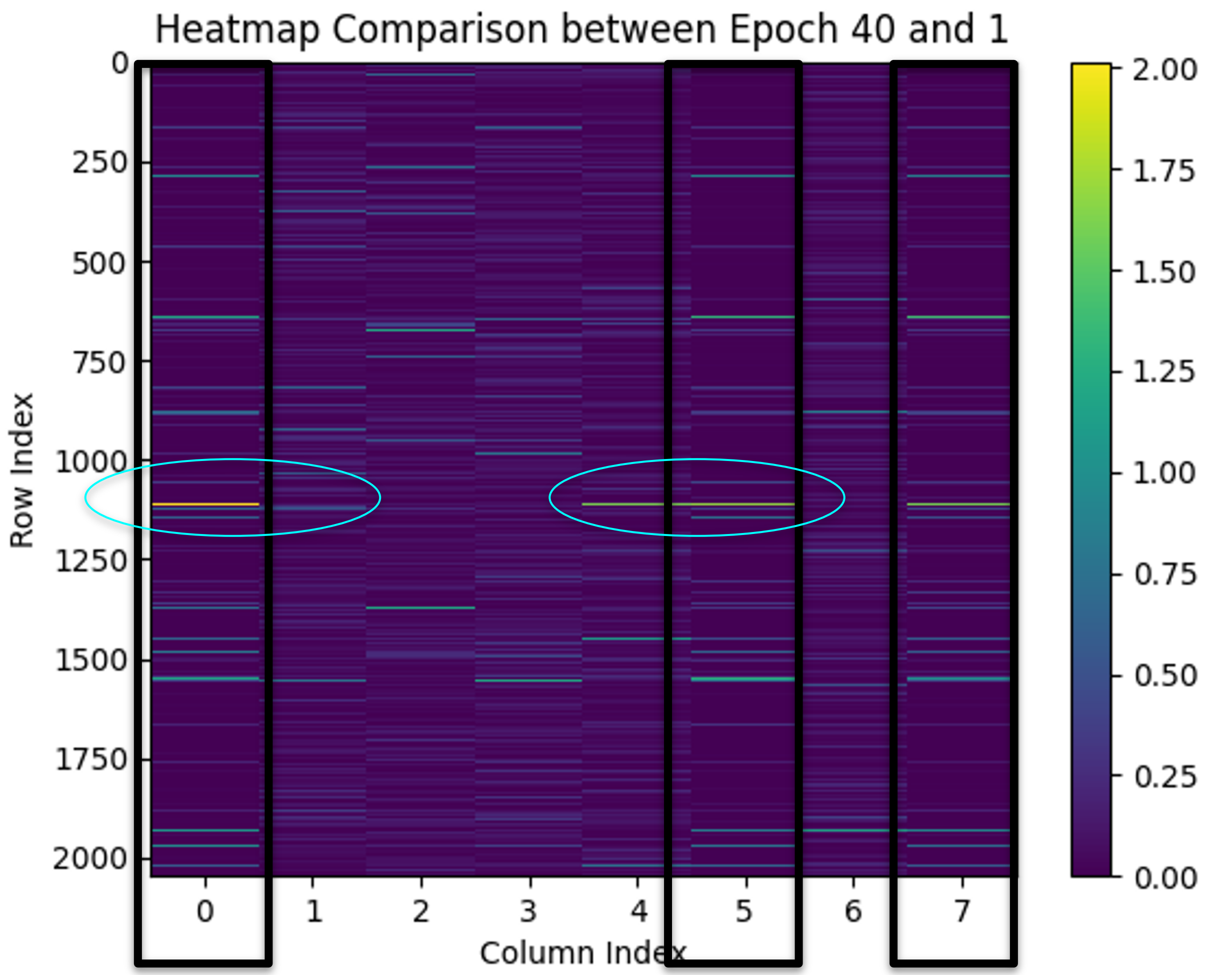
Artificial Intelligence Through Core and Periphery

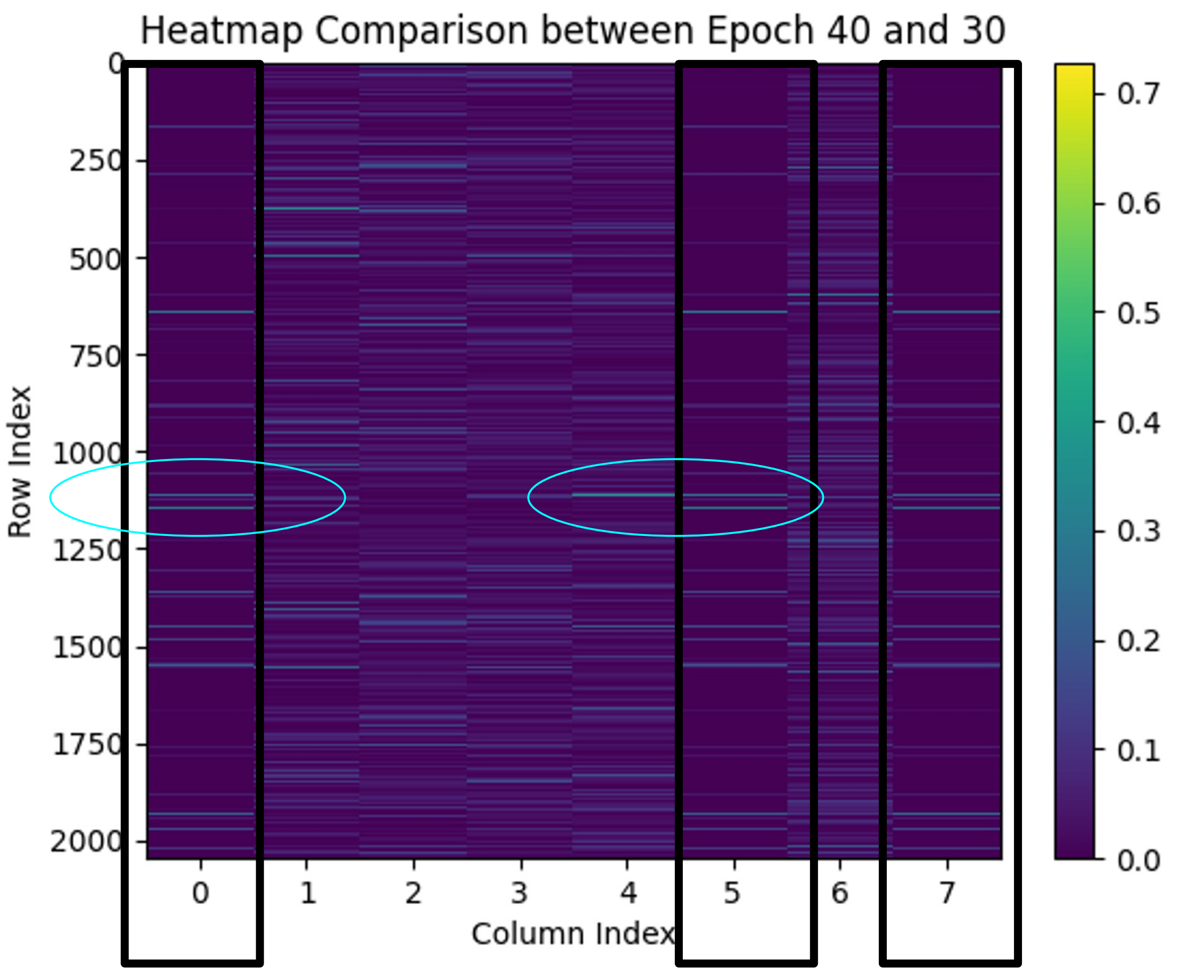


Step 1	Step 2	Step 3
Used ResNet-50 model. Trained it with CFAR-10. Stored weights of the fully connected layer. Captured the weights on heatmaps. Compared the weights change at each epoch for a total of 40 epochs.	Used the trained model in step 1 to retrain with CFAR-100, a more complex dataset with more classes. Saved the weights for each epoch for a total of 40 epochs. Compared the weights of each epoch with one from previous training epochs.	Picked epoch 1, epoch 10, epoch 20, and epoch 30 from step 2. Found the difference between weights of epoch 40 from step 1 with the above-mentioned epochs. Then we compare the four heatmaps of weight differences to find evidence of core and periphery.

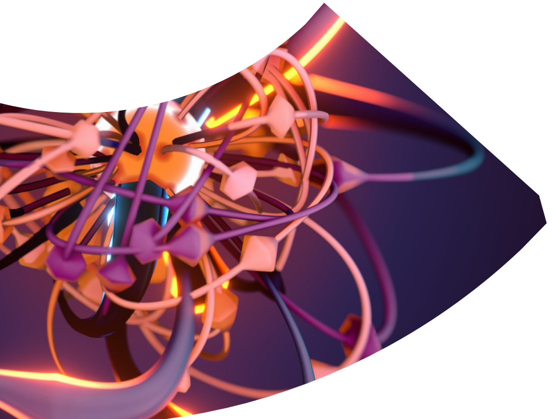
Artificial Intelligence Through Core and Periphery

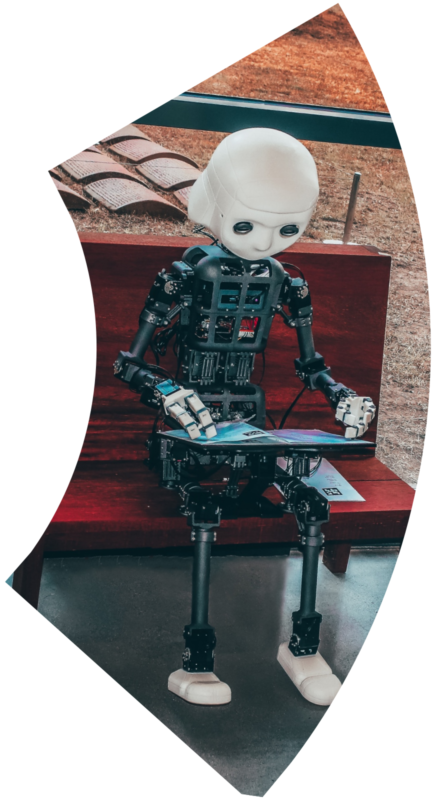






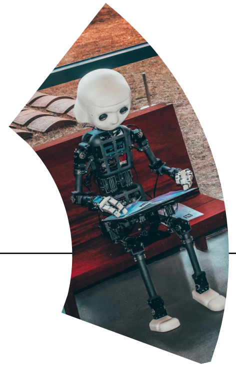
ROADMAP





Informing
Engineering Practices

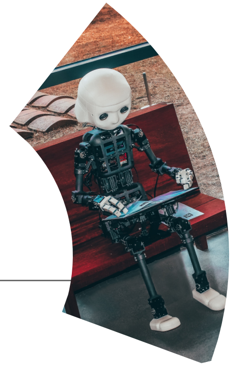
Scalability and Scope Problem in SE4AI

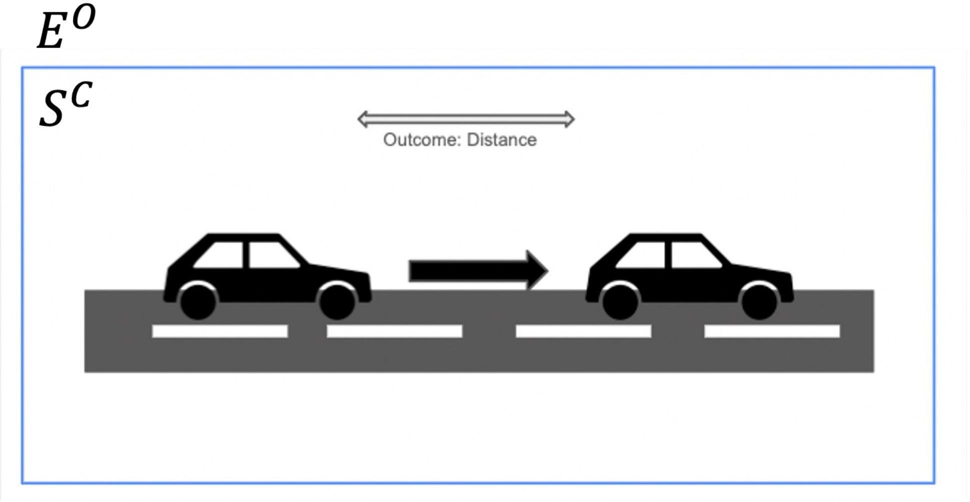


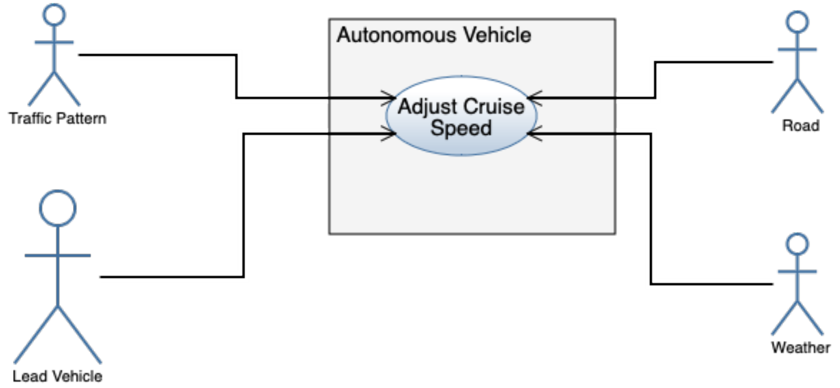
- The set of states continuously evolves.
- Exceptionally sensitive to changes in their environment
- The need to capture many boundary conditions.
- Situations of having defined use case models dissolve boundaries.

We suggest that, to attain scalable well-scoped intelligent capabilities, transitioning from scenario-based engineering to outcome-based engineering is worth exploring.

Example of Functional Closure in SE







$O_{FCS} =$ Outcome of The Functionally Closed System

$F_{FCS} \subseteq \times\{F_{Following}, F_{Lead}\}$

$S^C \subseteq F_{FCS}$

$F_{FCS} : \mathcal{X}_M \rightarrow \mathcal{Y}_M$

Where: $\mathcal{X}_M \subseteq M \quad \mathcal{Y}_M \subseteq M$

$X_M \subseteq \{V_L, a_L, J_L, F_{fric}\}$

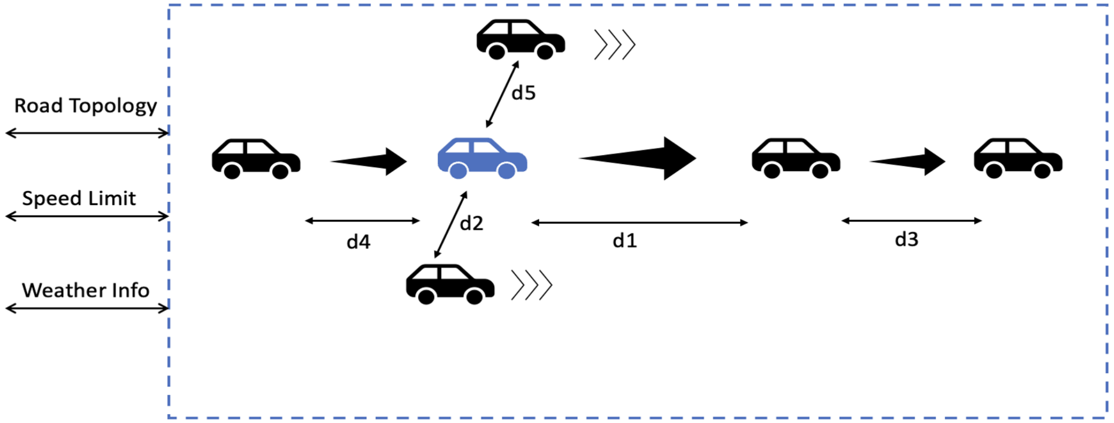
$Y_M \subseteq \{V_F, a_F, J_F\}$

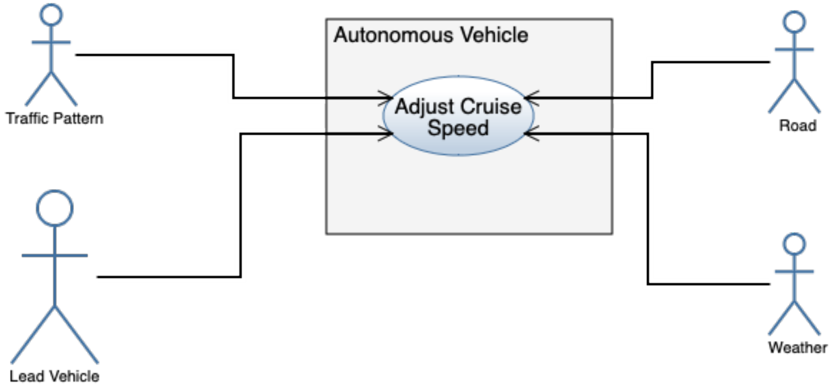
$X = X_E \setminus M$ and $Y = Y_E \setminus M$

We have: $S^C \not\subset \times\{\mathcal{X}, \mathcal{Y}\}$

$\Rightarrow O_{FCS} : M \times F_{FCS} \rightarrow \mathcal{D}$

Example of Informational Closure in SE





$$\textit{Theorem 1}: I(S_n^C; E_n^O) \geq H(S_{\{n+1\}}^C, S_n^C) - H(S_{\{n+1\}}^C, S_n^C | E_n^O)$$

Initial Modelling Assumptions:

$$I(S_n^C; E_n^O) = \{V_{limit}, R^0, W^0\}$$

$$I(E_n^O) = \{V_{limit}, R^0, W^0, RU\}$$

Calculation of Entropy in The Proposed Model:

$$H(S_n^C) = -\sum_{x \in S_n^C} P(x) \log P(x) = -\sum_{d_n^1}^{d_n^5} p(d_n^i) \log(d_n^i)$$

where: $p(d_n^i) = p(V_n^i, a_n^i, V_n^0, a_n^0)$

$$H(S_{n+1}^C) = -\sum_{y \in S_{n+1}^C} P(y) \log P(y)$$

$$= -\sum_{d_{n+1}^1}^{d_{n+1}^5} p(d_{n+1}^i) \log(d_{n+1}^i)$$

where:

$$p(d_{n+1}^i) = p((V_{n+1}^i, a_{n+1}^i | V_n^i, a_n^i), (V_{n+1}^0, a_{n+1}^0 | a_n^0, V_n^0))$$

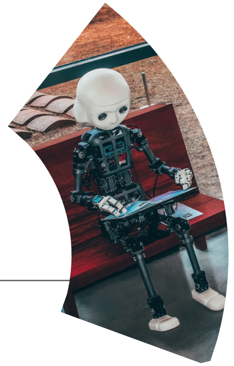
Final Calculation of Inequality:

First: $I(S_n^C, E_n^0) = H(S_n^C) - H(S_n^C | E_n^0)$

Second: $H(S_{n+1}^C, S_n^C | E_n^O) =$

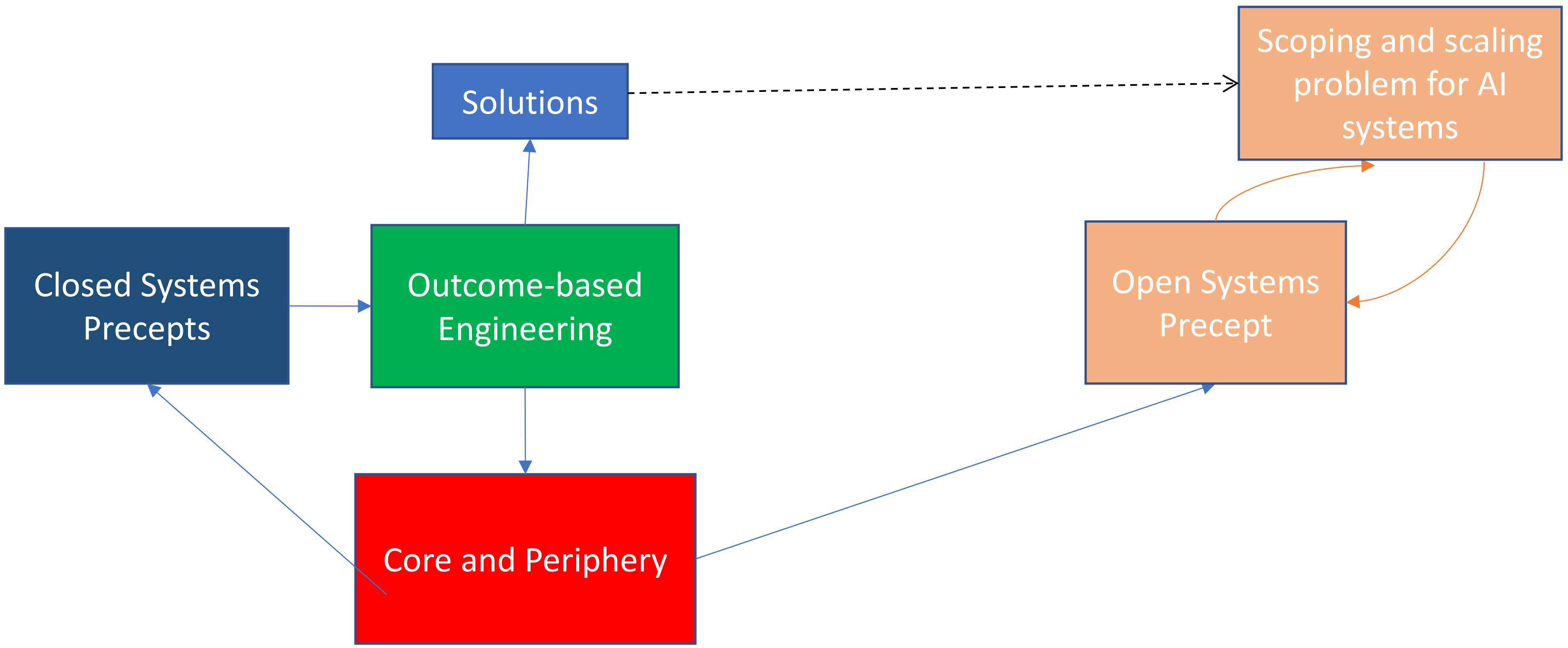
$$H(S_{n+1}^C) + H(S_n^C | E_n^O) - I(S_{n+1}^C; S_n^C | E_n^O)$$

Third: $H(S_n^C, S_{n+1}^C) = H(S_n^C) + H(S_{n+1}^C | S_n^C)$



Conclusion

Conclusion



Solutions
Scoping and scaling problem for AI systems
Closed Systems Precepts
Outcome-based Engineering
Open Systems Precept
Core and Periphery

Contributions of This Research

- This research provides arguments on why intelligent systems require a paradigm shift for SE.
- This research contributes to the theory of SE by providing formal definitions of the closed systems concepts, and variety at different abstraction levels of system.
- This research will help pave the way for systems engineers to build methodologies to explain intelligent outcomes in intelligent systems.
- This research provides an avenue to enable direct engineering of outcome-based problems
- This research proposes a concept that can help scaling and scoping intelligence property as a property of the whole.
- This research will provide a framework that introduces an additional layer of abstraction in SE of intelligent systems that can result in reduction of the number use-case models in the SE process.

Limitation

- The lack of empirical evidence of the application of this framework in a real-world intelligent systems. The need for a new type of measurement techniques. The lack of concrete decision on what should be measured in the empirical evidence.
- Lack of formalism in some of the concepts related to systems theory and systems engineering.
- The abstract level of the formalism is still not suitable for the engineering applications.
- The current AI systems do not express the expected level of intelligence. Therefore, the applicability of this research is yet to be tested and recognized

Future Work

- Empirical studies can shed light on the real-world impact of these introduced precepts potentially by providing test beds for intelligent systems.

- A deeper dive into formalizing additional concepts.

- Exploring the dynamics of boundaries between highly coupled systems, as well as the human-centric aspects of incorporating these precepts in engineering workflows.

- Revisit of different SE practices such as reusability, requirements vs needs, verification and validation processes, product line in manufacturing, system maintenance and management, among others.

Publications

- Shadab N, Cody, T, Salado A, Beling P, A Systems-Theoretical Formalization of Closed Systems, IEEE Open Journal of Systems Engineering **(Published in 2023)**
- Shadab N, Cody T, Salado A, Beling P, From Scenario-based to Outcome-based Engineering in SE4AI, **(submitted to OJSE)**
- Shadab N, Cody T, Salado A, Beling P, Exploring Outcome-Based Biological and Artificial Intelligence Through Core and Periphery Precepts **(Ready to be submitted to System Research and Behavioral Science)**
- Shadab, N., Cody, T., Salado, A., & Beling, P. (2022, April). Closed Systems Paradigm For Intelligent Systems. In *2022 IEEE International Systems Conference (SysCon)* (pp. 1-8). IEEE.
- Cody, T., Shadab, N., Salado, A., & Beling, P. (2022, August). Core and Periphery as Closed-system Precepts For Engineering General Intelligence. In *International Conference on Artificial General Intelligence* (pp. 209-219). Cham: Springer International Publishing.
- Shadab, N., Kulkarni, A. U., & Salado, A. (2021). Shifting Paradigms in Verification And Validation of AI-enabled Systems: A Systems-Theoretic Perspective. *Systems Engineering and Artificial Intelligence*, 363-378.
- Shadab, N., Cody, T., Beling, P., & Salado, A. (CSER 2023). Product Herding for Intelligent Systems.
- Shadab, N., & Salado, A. (2020, October). Towards an Interface Description Template For Reusing AI-enabled Systems. In *2020 IEEE International Conference on Systems, Man, and Cybernetics (SMC)* (pp. 2893-2900). IEEE.

Thank You!

Email:
nshadab@vt.edu