



VIRGINIA TECH<sup>®</sup>

AI4SE & SE4AI WORKSHOP

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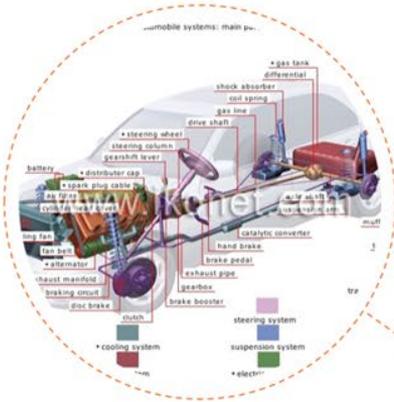
# Closed System Precepts in Systems Engineering for Artificial Intelligence - SE4AI

Niloofer Shadab, Tyler Cody, Alejandro Salado, Peter Beling

# OBJECTIVES

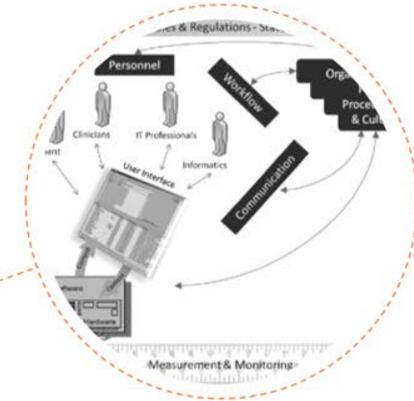
- PROVIDE AN OVERVIEW OF MOTIVATION
- CLEARLY SPECIFY THE GAPS IN SE4AI
- DISCUSS THE PROPOSED SOLUTION
- DISCUSS IMPLICATIONS IN REAL-WORLD

# INTRODUCTION



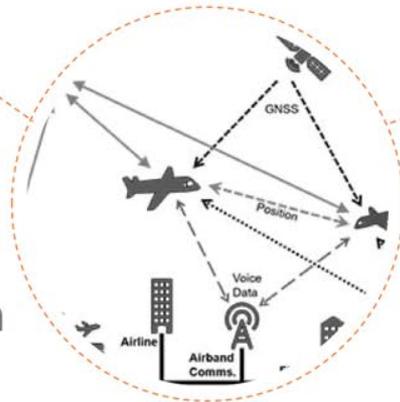
## Traditional Systems

They are integrated traditionally separated engineering systems



## System of Systems

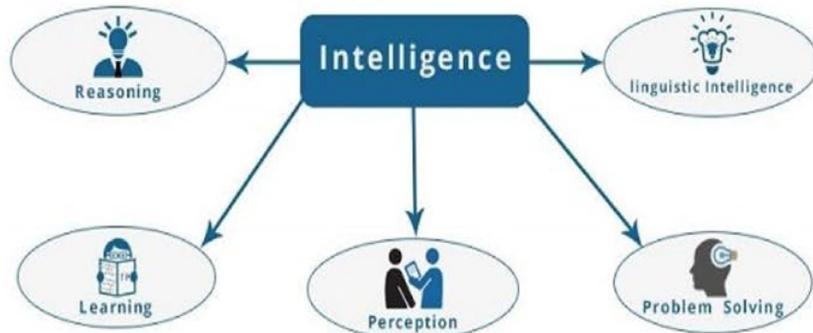
They are defined as a collection of systems that interoperate to achieve a common goal.



## Socio-Tech Systems

These systems recognize the interactions between humans and technology.

## Intelligent Systems As A 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.
- The relation between learning and intelligence is not consistent.
- This category of Systems require a revisit of SE practices

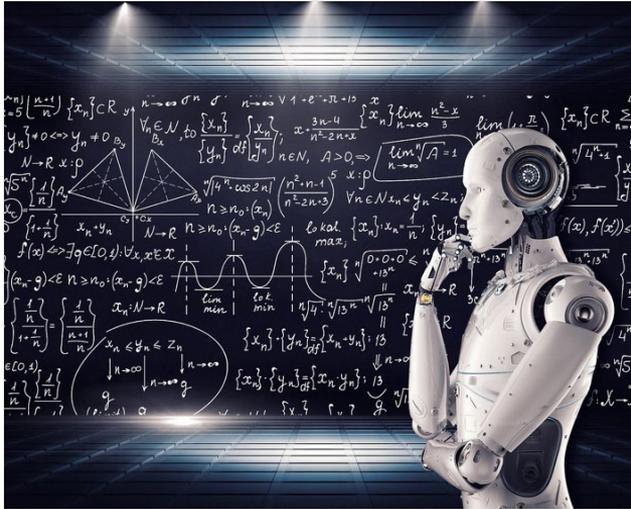
# GAPS IN SE4AI

## Key Findings From The Literature Review.

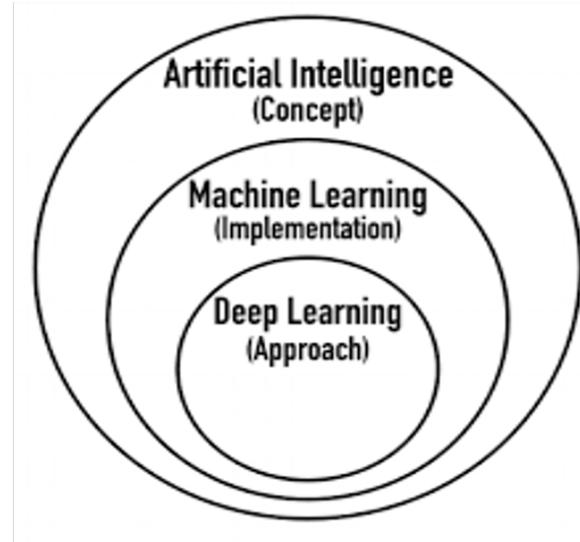


- A gap in defining, characterizing, and engineering intelligence property in both biological and non-biological systems.
- A lack of framework to underpin intelligence characteristics in SE
- Engineering does not focus on scaling and scoping intelligence as a global property
- Research on open vs closed systems are limited and inconsistent.
- Minimal attempts towards formalizing closed systems; inconsistent with systems theoretical framework.

# Defining Intelligence



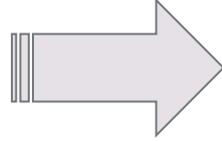
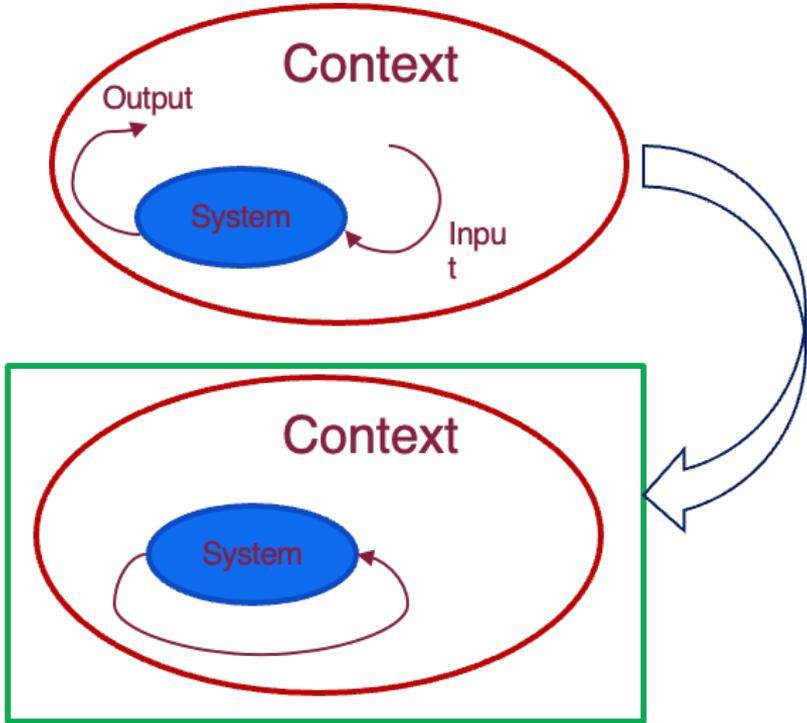
# Engineering Intelligence



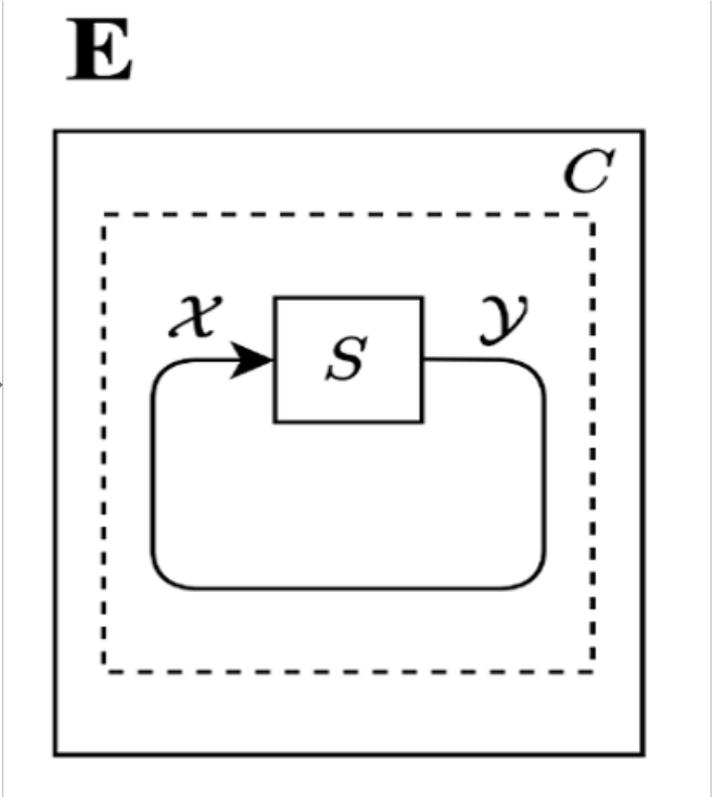
There should be a systems theoretic foundation that can provide a general framework while abstracting the concept of intelligence from specific definitions.

# PROPOSED SOLUTION

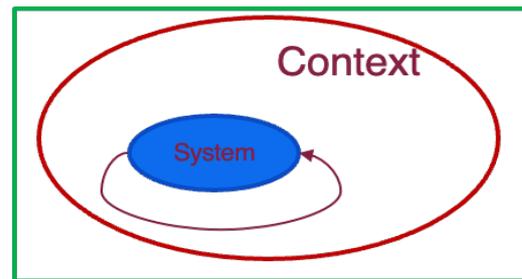
# Closed Nature of Intelligence



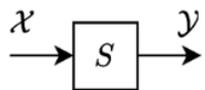
# Closed Systems Precepts



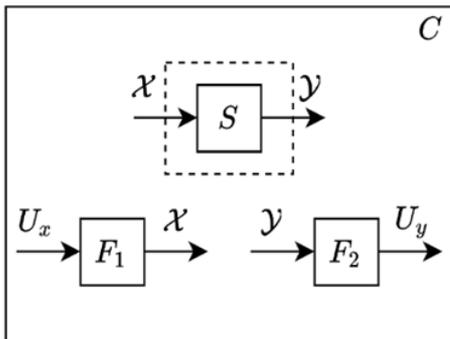
# Closed Systems Spectrum



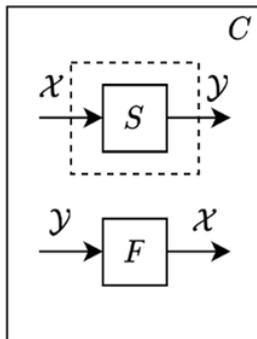
**A**



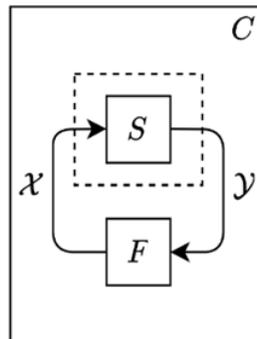
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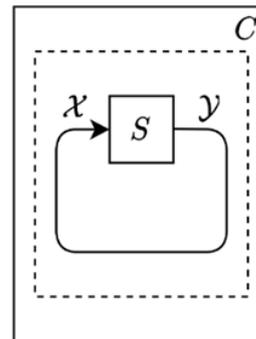
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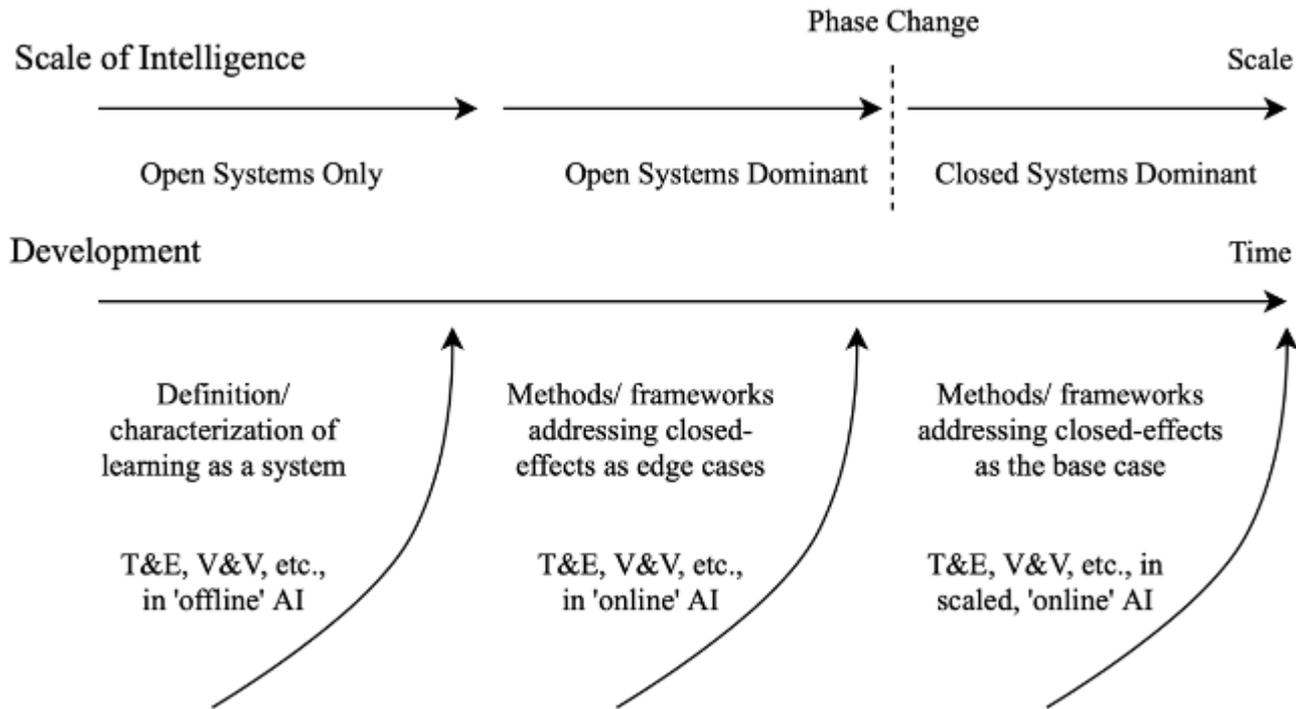
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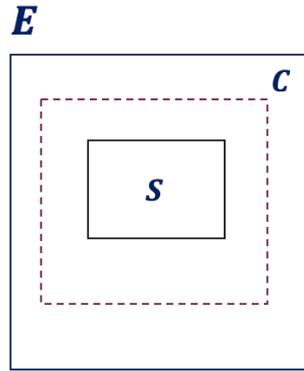
**E**



# Closed Systems Engineering for Intelligent Systems

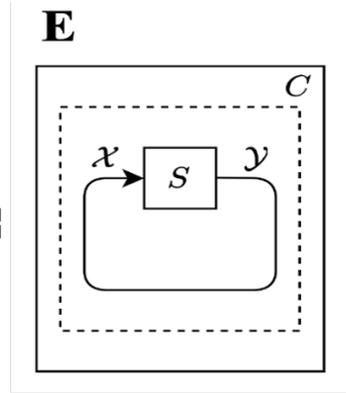


# Systems-Theoretical Closure

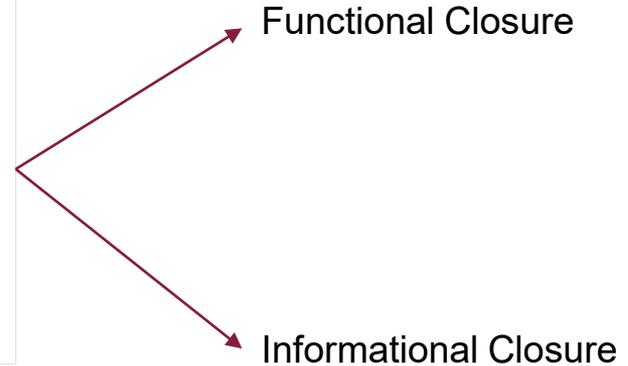


$$x = y = \phi$$

Infeasible Condition



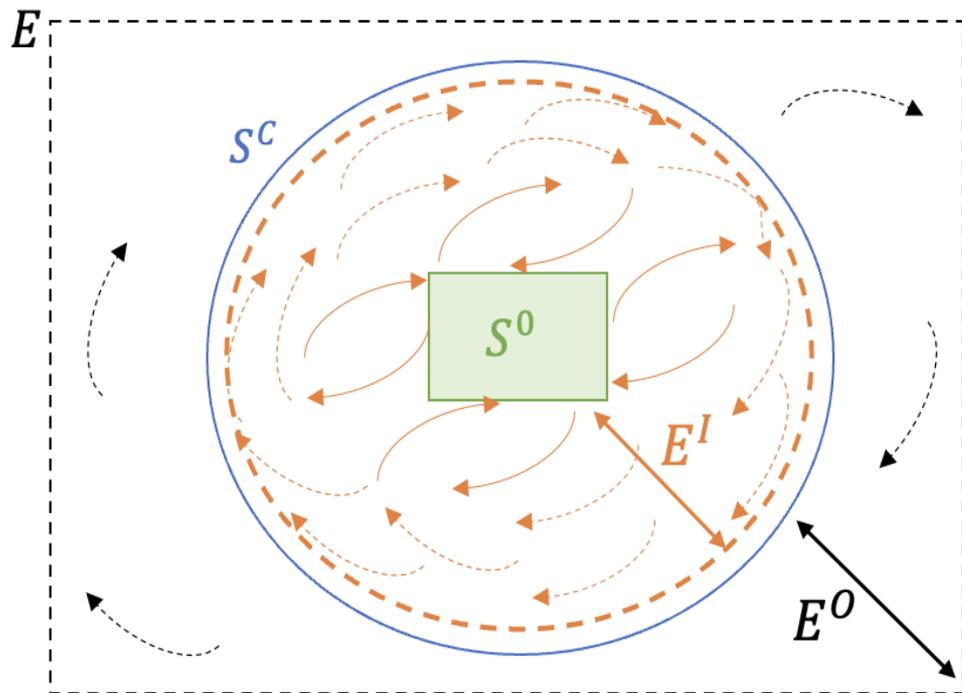
Approximation  
of Systems  
Theoretical  
Closure



Functional Closure

Informational Closure

# Terminology Framework



$$S^0 : S^0 \subseteq \times\{\mathcal{X}^0, \mathcal{Y}^0\}$$

$$U : \mathcal{X}^u = \mathcal{Y}^u = \emptyset$$

$$S^C : S^C \subseteq \times\{\mathcal{X}, \mathcal{Y}\}$$

$$E : E \subseteq \times\{\mathcal{X}^E, \mathcal{Y}^E\}$$

$$\text{Where, } \bar{E} = \bar{U} \setminus \bar{S}^0$$

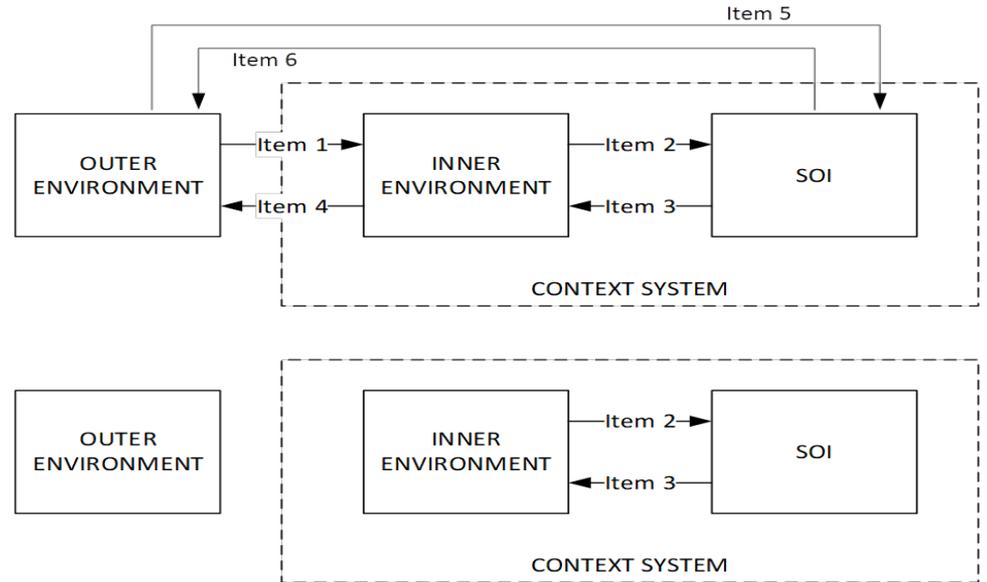
$$E^I : E^I \subseteq \times\{\bar{E} \cap \bar{S}^C\}$$

$$E^O : E^O \subseteq \times\{\bar{E} \setminus \bar{S}^C\}$$

# Functional Closure

**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  $S^C$ .



Where  $F$  is the set of system's functions. When the conditions stated above are present, functional independence of the system from inputs set and outputs set can be relaxed as  $\mathcal{X} = \mathcal{Y} = \emptyset$ , which is the same condition for a systems-theoretic closed system.

# Informational Closure

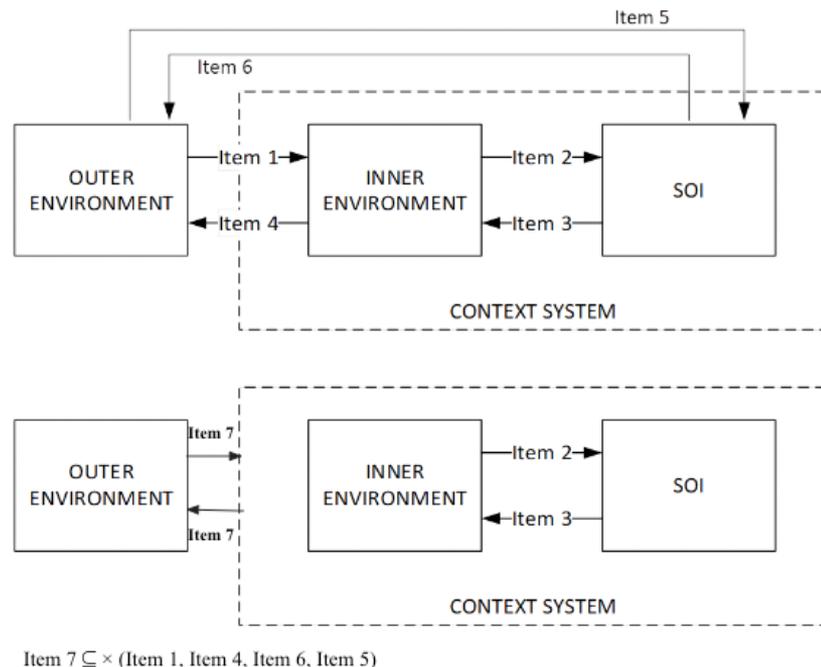
**Definition 2 (Interpretation of An Informationally Closed Systems Using Information):** A Context System that transitions through states  $1, 2, \dots, n, n+1$ ; is informationally closed at state  $n$  if there is no joint information between  $S_{n+1}^C$  and  $E_n^O | S_n^C$ .

$$I(S_{n+1}^C; E_n^O | S_n^C) = 0$$

**Theorem 1 (Inequality for mutual information in closure):**

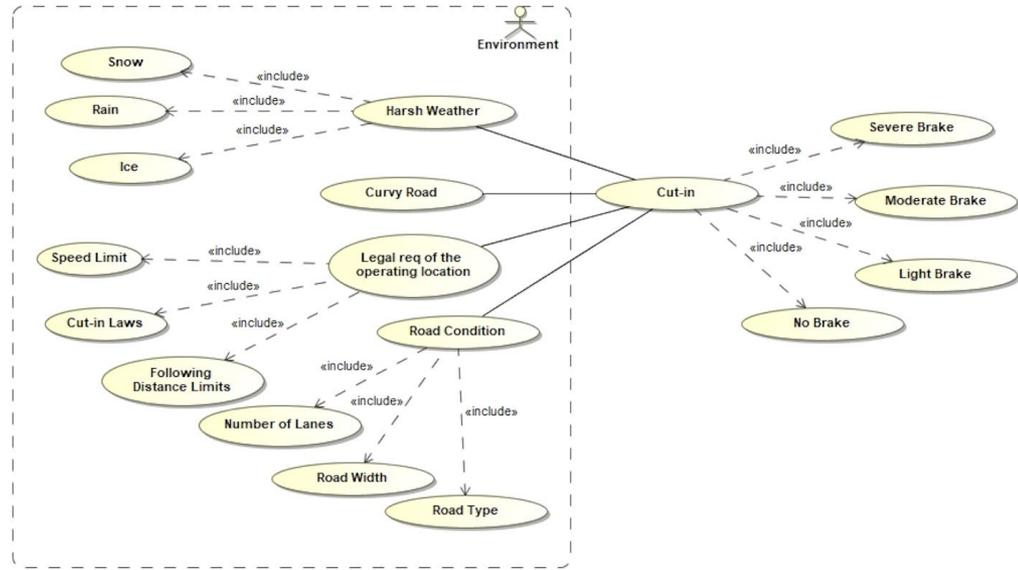
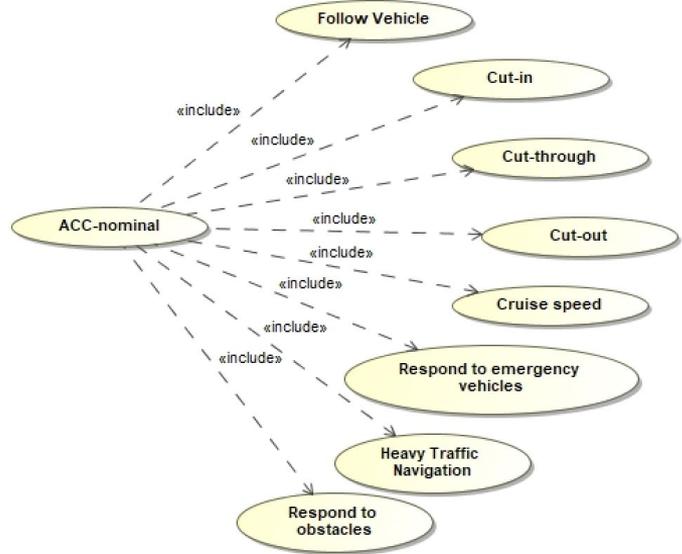
$$I(S_n^C; E_n^O) \geq H(S_{n+1}^C, S_n^C) - H(S_{n+1}^C, S_n^C | E_n^O)$$

Theorem 1 provides the relation for the level of mutual information being presented in the boundary of an informationally closed system.

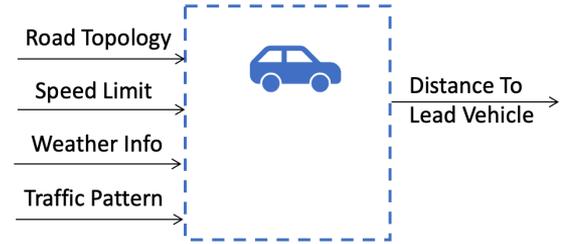
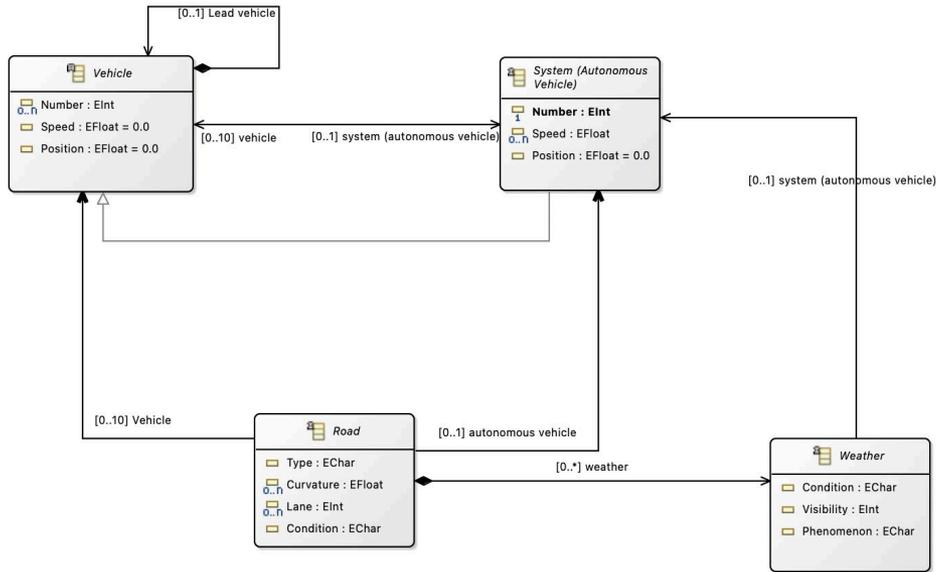


# APPLYING SOLUTION

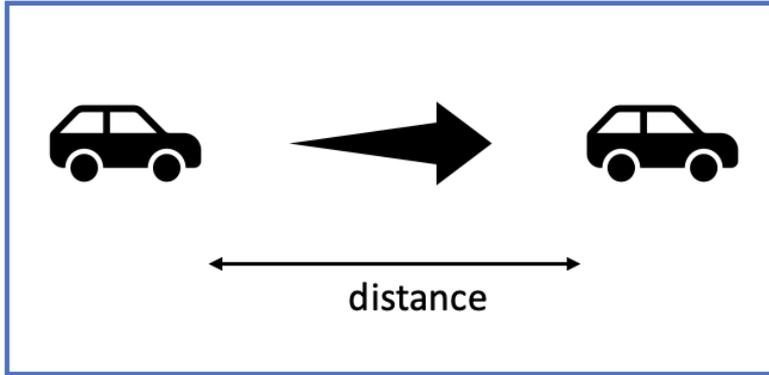
# Scaling and Scoping Challenge for Intelligent Systems



# Current Systems Engineering



# Example of Functional CSE



$F_{FLV} = \text{Time To Collision}$

$F_{FLV} \subseteq \times \{F_{Fact}, F_{Lact}\}$

$S^C \subseteq F_{FLV}$

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

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

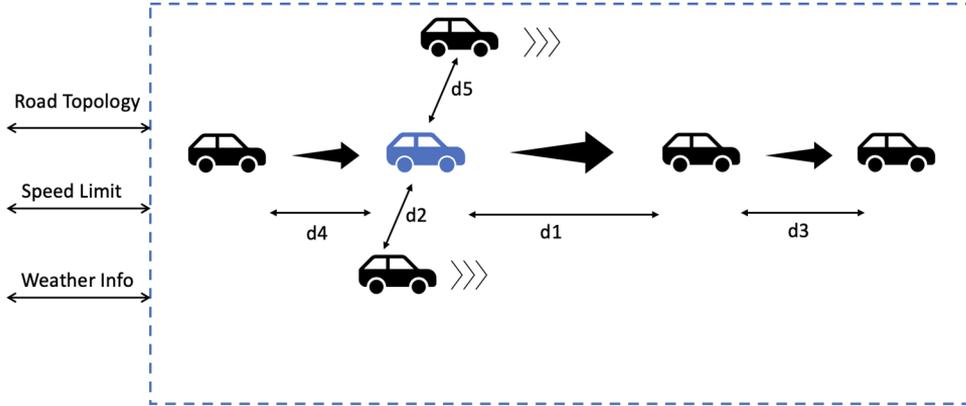
$X_M \subseteq \{V_L, V_F, a_F, a_L, J_L, J_F\}$

$Y_M \subseteq \{D\}$

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

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

# Example of Informational CSE



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

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:

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

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

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

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

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

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

# Causality of Mutual Information

Information Type	Interpretation	Causal Dependency
Relevant Information	Type of information that is required to predict the future state of the closed system and is shared between the current state of the closed system and its environment.	<b>Confirmation:</b> Type of relevant information that confirms the information existing inside of the closed system.  <b>Redundancy:</b> Type of relevant information that adds redundancy to the information that already exists inside of the closed system.
Irrelevant Information	Type of information that exists in the environment of the closed system and is irrelevant to the prediction of the next state of the closed system and needs to be <b>Ignored</b> by the current state of the closed system.	<b>Unnecessary:</b> Type of irrelevant information in the environment that is not necessary in computing entropy or information of the next state of the closed system.  <b>Unavailable:</b> Type of irrelevant information in the environment that is not available to the current state of the closed system and cannot be available through the boundaries of the closed system.

# Conclusion

- We proposed closed systems precepts to overcome some of the gaps in SE4AI
- We formalized closed systems using systems-theoretic framework
- We provided a generic example of using informational closure and functional closure in systems engineering processes.