An Objective-based Approach for Semantic Validation of Emergence in Component-based Simulation Models

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Motivation

“The whole **is greater** than the sum of its parts” - Aristotle

Outline

- Introduction
- Related Work
- Objective-based Validation Approach
- Example: Flock of Birds
- Conclusion

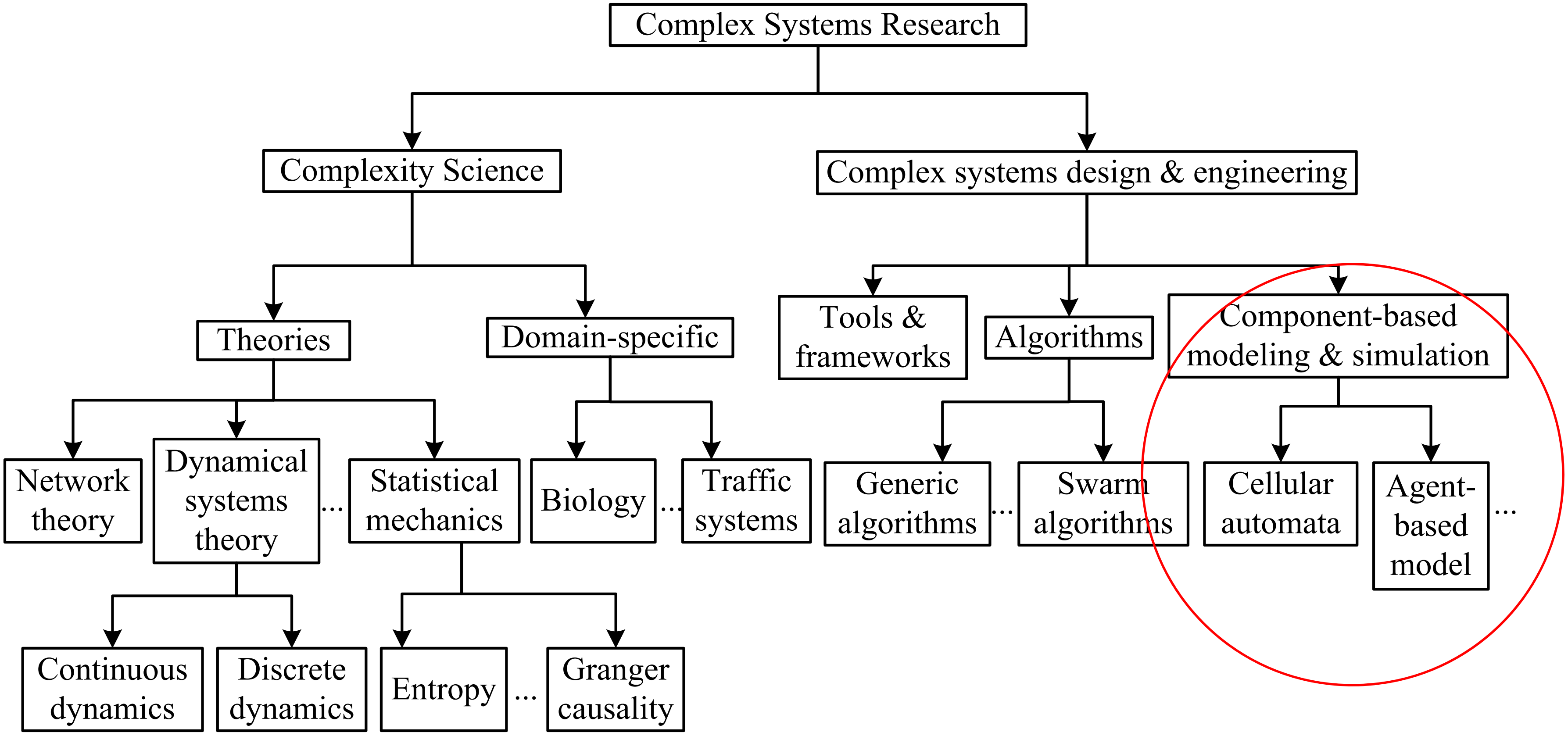
Complex Systems, Simulation & Emergence

- Ubiquitous in today’s systems
  - Single component => many components
  - Simple components => large number of states and attributes
- Simulation
  - Increased flexibility
- Co

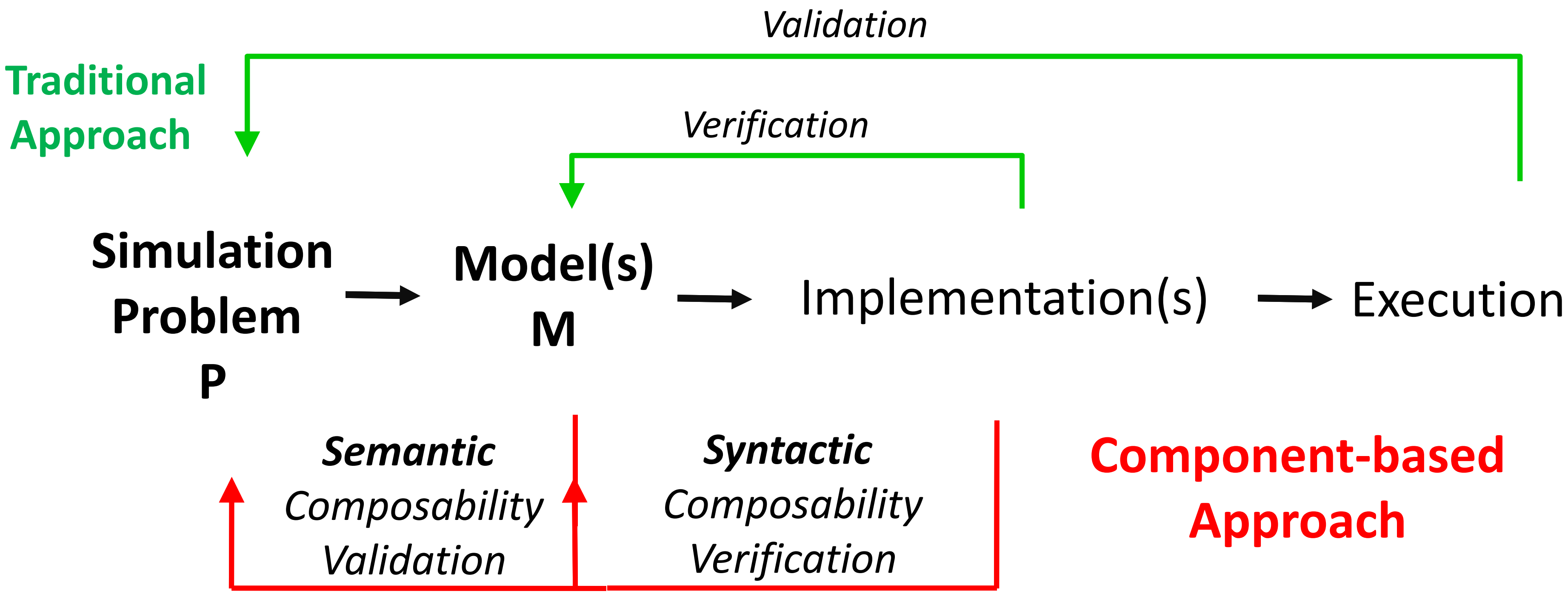
A system is complex if it exhibits one or more properties not resulting from the properties of its interconnected parts.

- Emergence: malign and benign effects
  - Ethernet capture effect [20]
  - router synchronization problems [9]
  - load-balancer failures in multi-tiered distributed systems [17]
  - herding behavior among clients
  - flocking of birds, ant colonies, crowd behaviors
  - …

Complex Systems Research



Modeling and Simulation



Validation

Traditional Approach

Verification

Simulation Problem P → **Model(s) M** → Implementation(s) → Execution

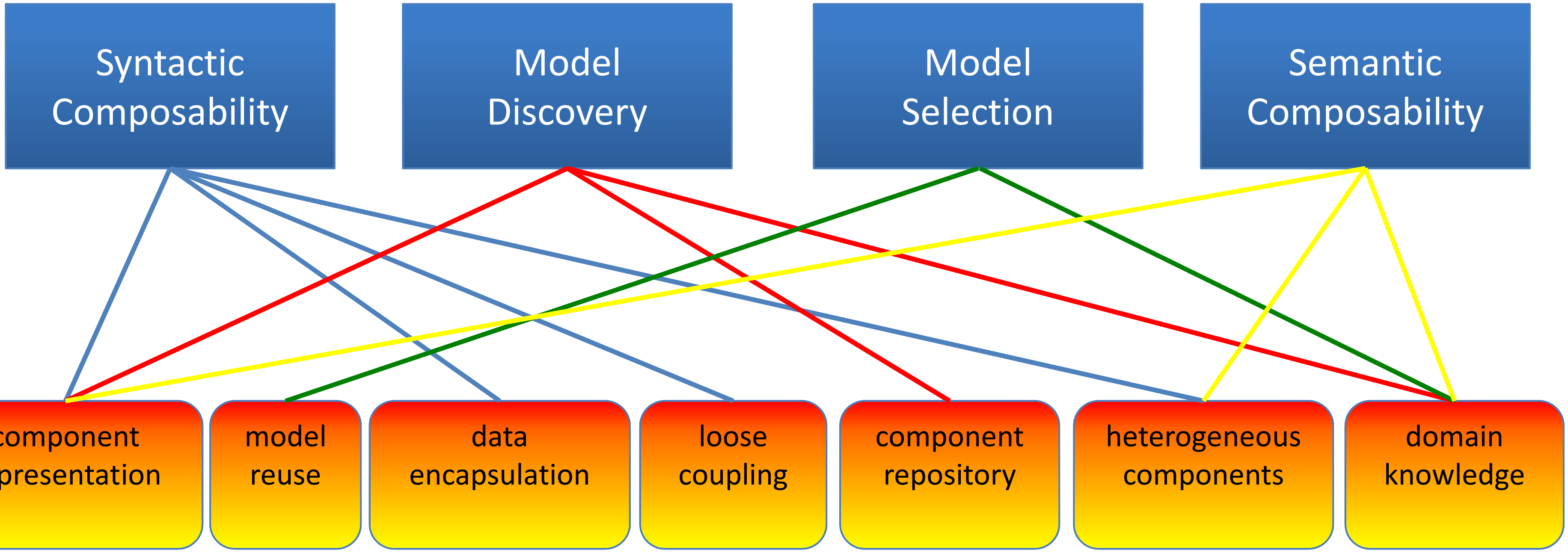
Semantic *Composability Validation*

Syntactic *Composability Verification*

Component-based Approach

Previous Work

Crosscutting Issues in Component-based Model Development



Syntactic Composability

Model Discovery

Model Selection

Semantic Composability

component representation

model reuse

data encapsulation

loose coupling

component repository

heterogeneous components

domain knowledge

Previous Work

1. C. Szabo and Y.M. Teo, **An Analysis of the Cost of Validating Semantic Composability,** Proc. of 25th ACM/IEEE/SCS Workshop on Principles of Advanced and Distributed Simulation, pp. 62-69,, Nice, France, June 14-17, 2011. [Also in Journal of Simulation, Palgrave-Macmillian, 2012 (advance online publication)].

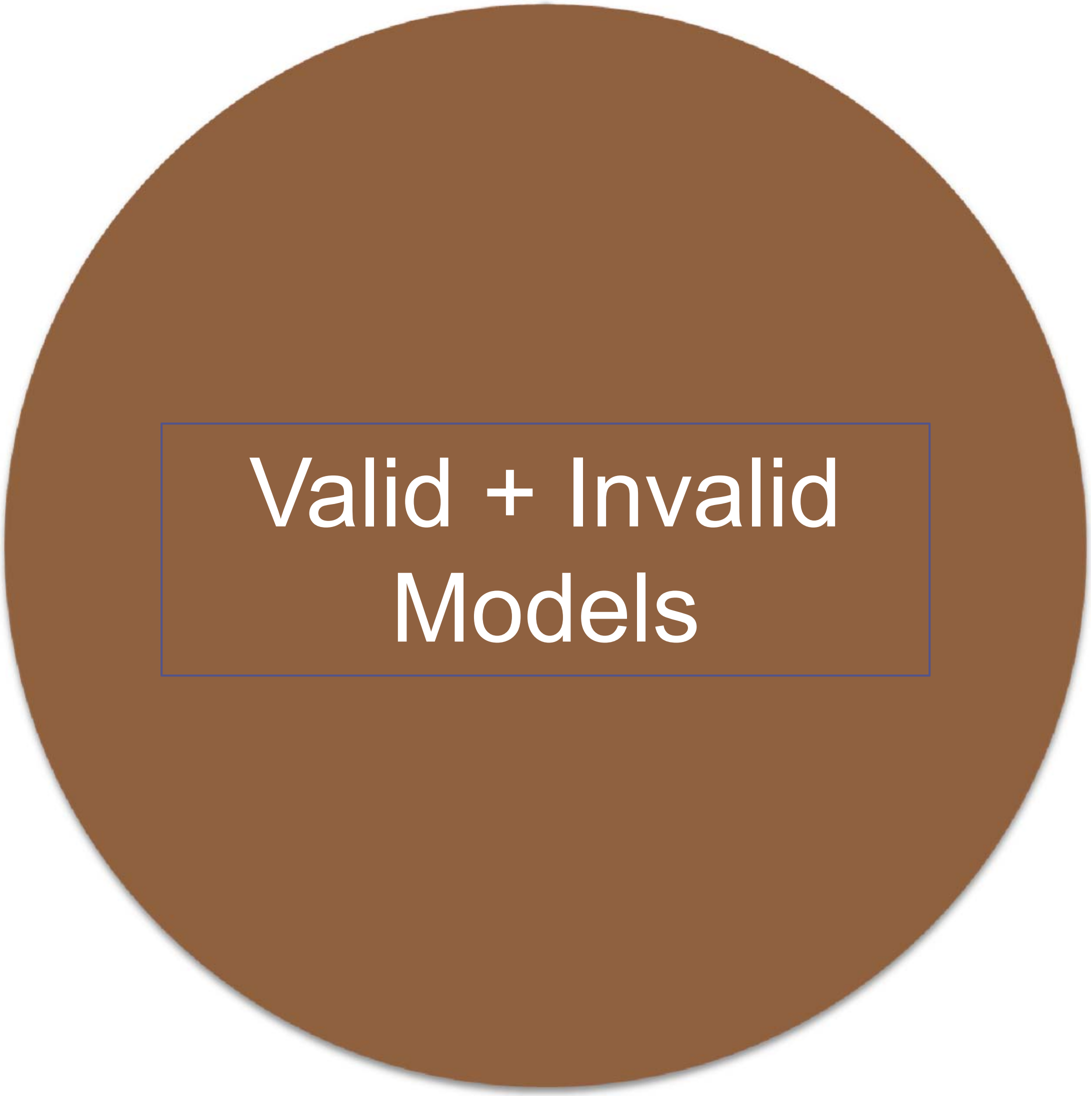
2. C. Szabo, Y.M. Teo and S. See, **A Time-based Formalism for the Validation of Semantic Composability**, Proc. of the Winter Simulation Conference, pp. 1411-1422, IEEE Computer Society Press, Austin, Texas, USA, December 13-16, 2009, (ACM SIGSIM Best PhD Student Paper Award).

3. C. Szabo and Y.M. Teo, **On Validation of Semantic Composability in Data-driven Simulation**, Proc. of 24th ACM/IEEE/SCS Workshop on Principles of Advanced and Distributed Simulation, pp. 73-80, Atlanta, USA, May 17-19, 2010.

4. C. Szabo and Y.M. Teo, **An Approach for Validation of Semantic Composability in Simulation Models**, Proc. of 23rd ACM/IEEE/SCS Workshop on Principles of Advanced and Distributed Simulation, pp. 3-10, New York, USA, Jun 22-25, 2009.

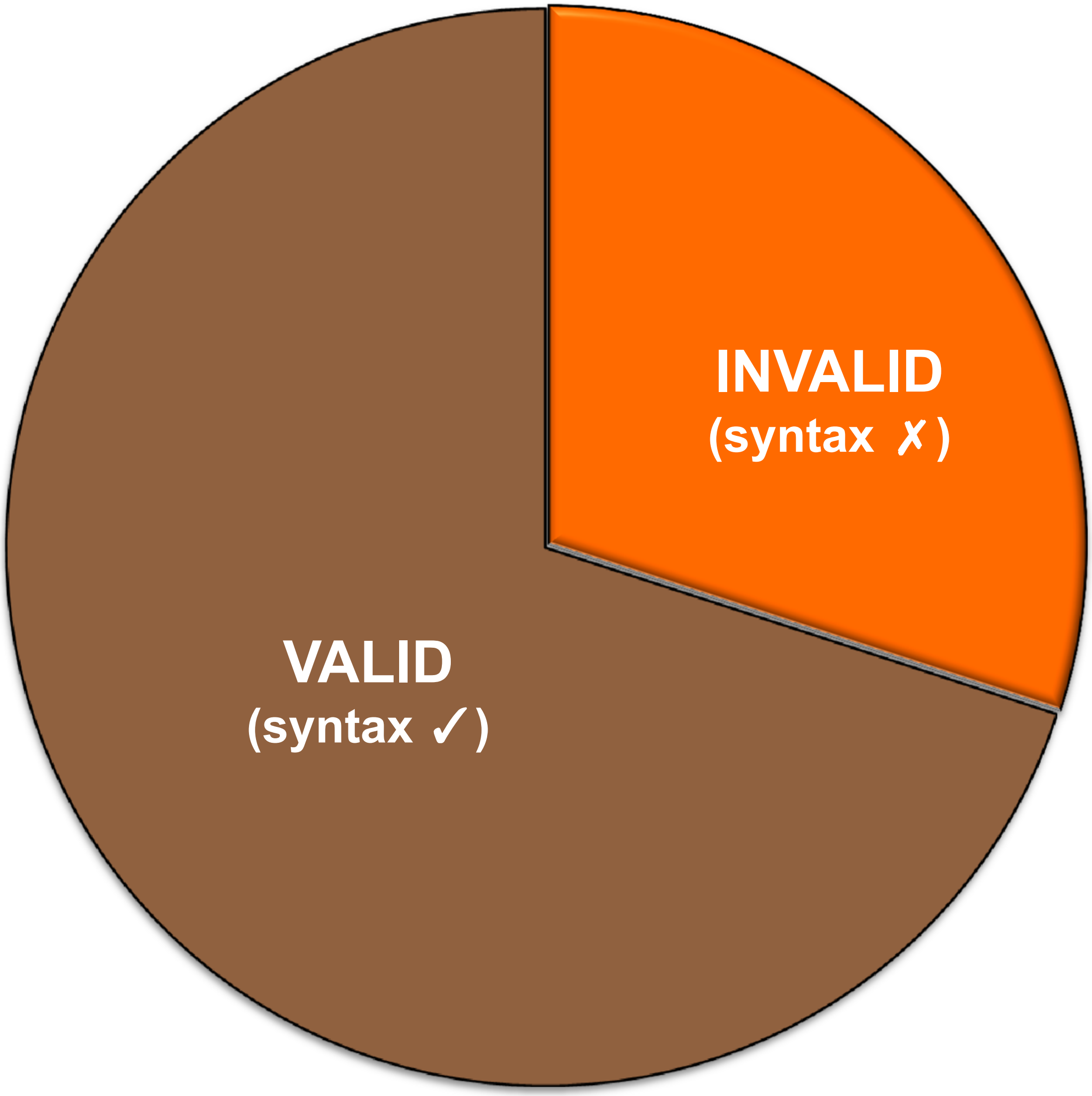
5. Y.M. Teo and C. Szabo, **CODES: An Integrated Approach to Composable Modeling and Simulation,** Proc. of 41st Annual Simulation Symposium, pp. 103-110, IEEE Computer Society Press, Ottawa, Canada, Apr 13-16, 2008.

Composability Verification & Validation in Component-based Model Development

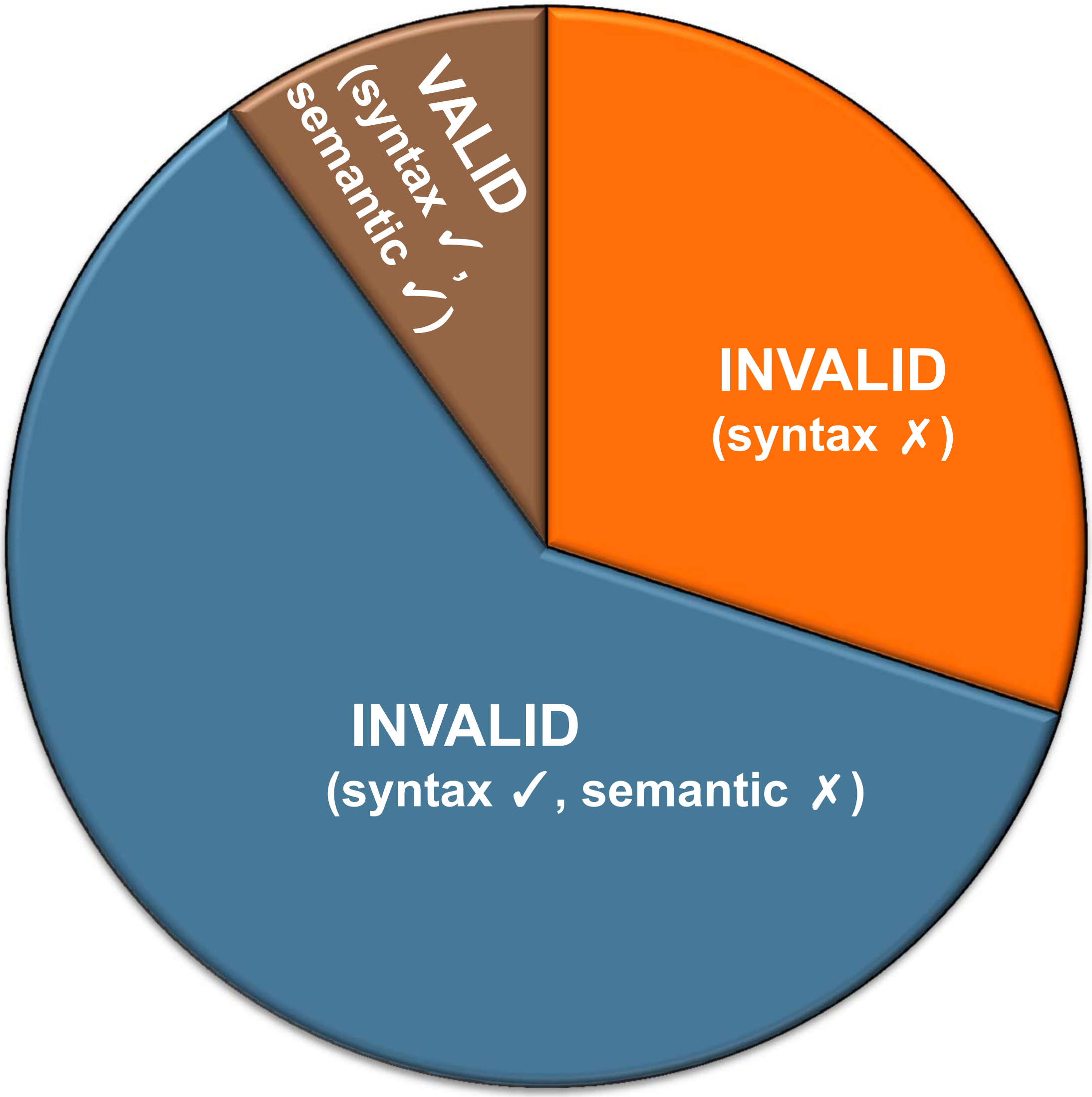


Valid + Invalid Models

Composability Verification & Validation in Component-based Model Development

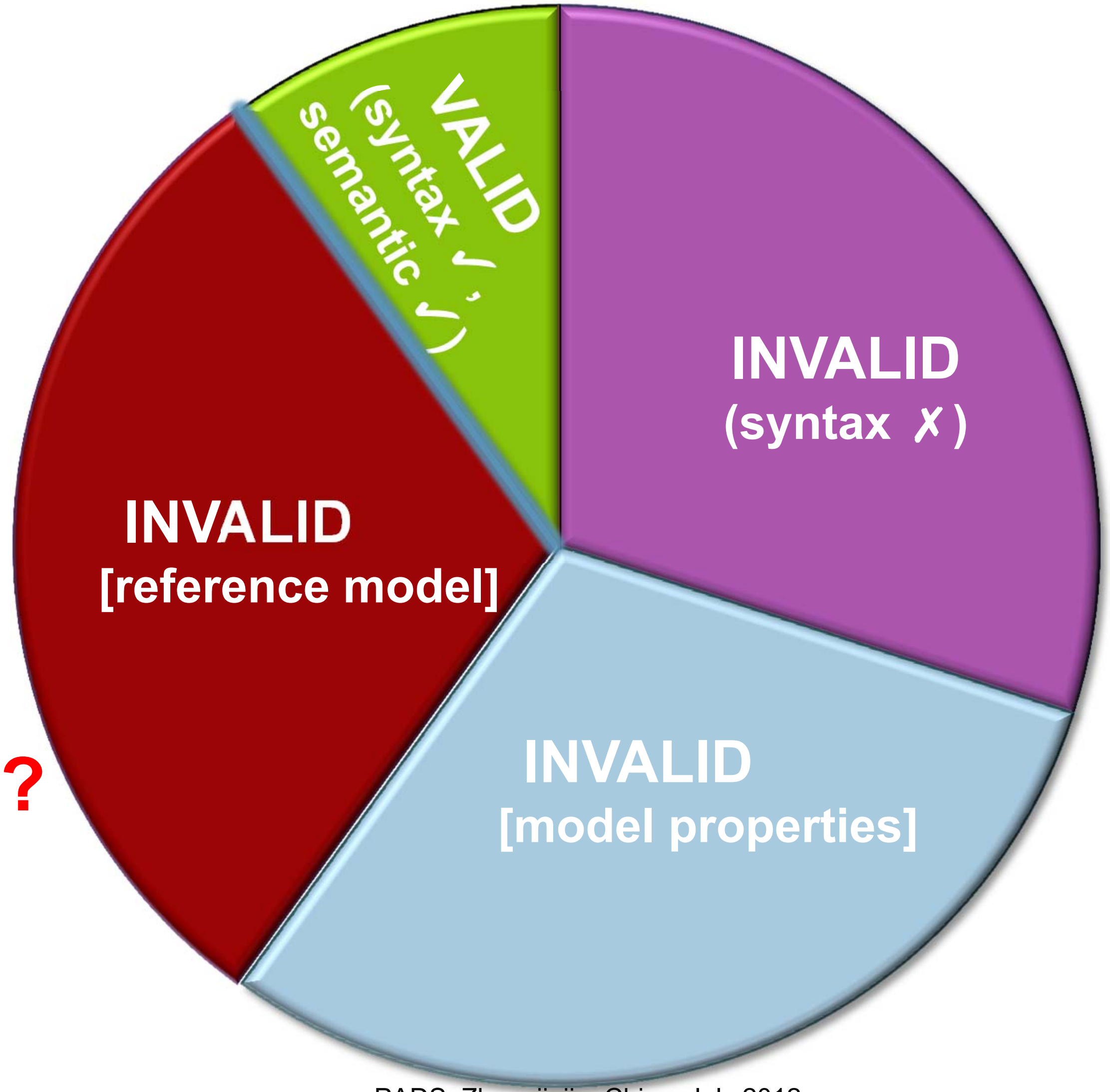


Composability Verification & Validation in Component-based Model Development



Composability Verification & Validation in Component-based Model Development

Model Validity = Syntactic + Semantic

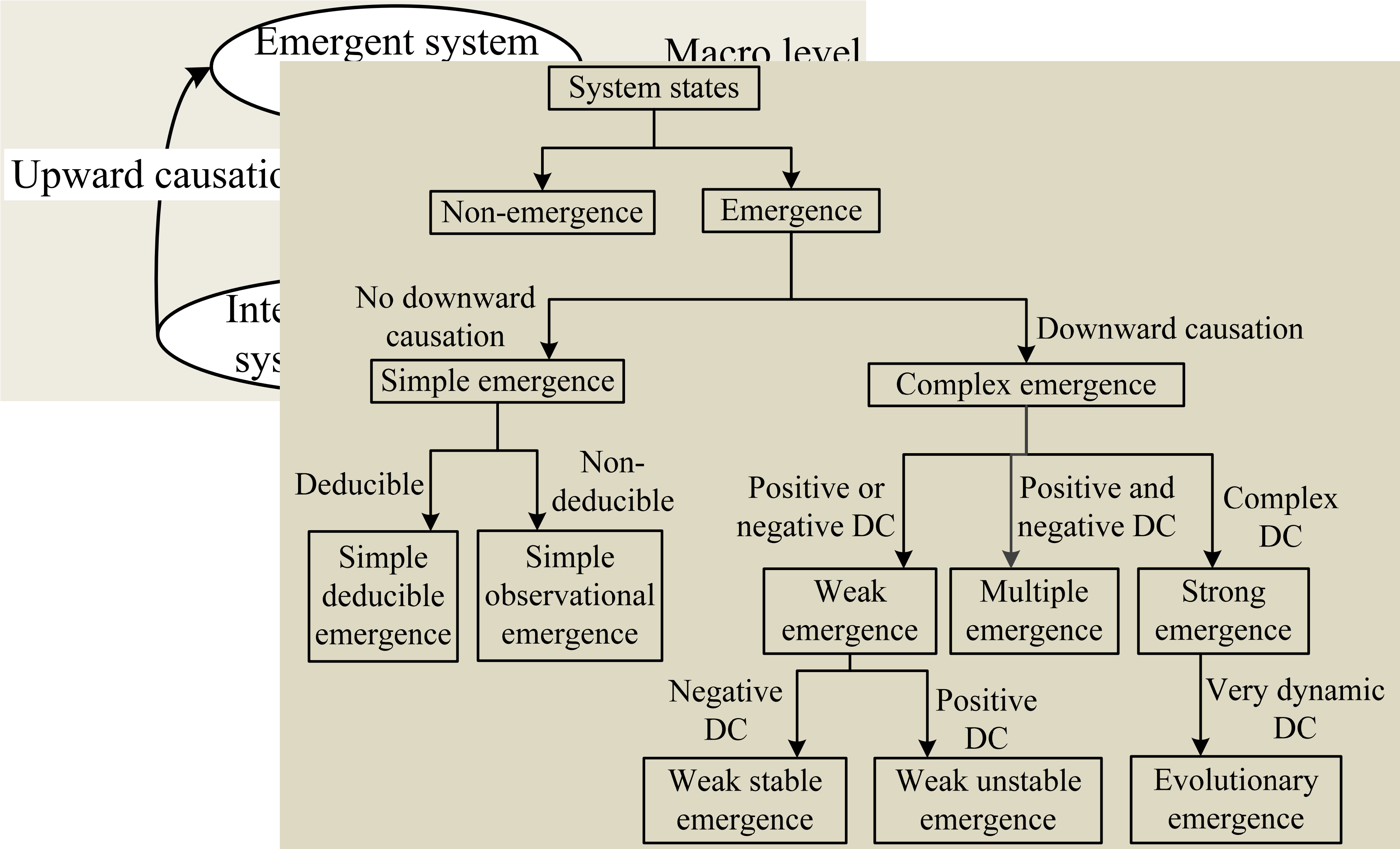


But what about **emergent properties?**

What is Emergence?

- “Manifested discernible regular formations and interesting irregular phenomena of actions or patterns” [4]
  - Static/dynamic; deterministic/stochastic
- Behavior of the whole that cannot be identified analytically from the parts, ….. [1]
  - Types of emergence: nominal, weak, strong

Classification of Causation-Based Emergence



Emergence Perspectives

Perspective	Main Problem	Key Ideas about Emergence		Examples	Issues
		Common	Specific		
Philosophy	How intelligence emerges from unintelligent matter?	More than the sum, surprise, novelty Upward & downward causation Hierarchy Supervenience	- Limitations in our knowledge - Prediction	General	Cannot tell the causes of emergence
Natural Sciences	*Biology*: How life emerges from inanimate matter? *Chemistry*: how a completely new substance emerges from other ones?		Self-organization	Bird flocking, ant colonies	Heavily depends on self-organization concept
Social Sciences	How human behaviors emerges from the interactions between them		-	Crowd behavior	??
Computer Science	- Predict, detect, and validate emergent properties - Understand the causes of emergence		Shifts in complexity	- Disk drives performance - Priority inversion in O/S	- Lack of emergent formalism - Emergence validation

Philosophy’s Perspective

- Does not answer the following questions:
  - Where are emergent properties from?
  - What are the causes of emergence?

- Emergence cannot be understood without more advanced tools and knowledge

Emergence

- 2 levels & their interactions:
  - micro – individual components
  - macro – the system as a whole

- Key issues:
  - Identifying micro and macro levels
  - Defining micro-macro relationship to facilitate emergence identification
  - Identifying emergence as it happens, **without previous knowledge**
  - Determining if emergence is beneficial => **emergence validation**
  - …

Related Work

- Variable-based [22]
  - One or more variables describe emergent properties
  - The system run is recorded and relationships are deduced
  - Assumes prior knowledge about emergence

- Event-based [5]
  - Behavior as series of simple and complex events
  - Emergence defined as sequence of complex events
  - Assumes prior knowledge about emergence

- Grammar-based [16]
  - L_{WHOLE}: properties of the system as a whole
  - L_{PARTS} : properties obtained from the reunion of the parts
  - Emergence = $L_{WHOLE} – L_{PARTS}$
  - How to calculate L_{PARTS}, L_{WHOLE} ?

Related Work

Formalism	Modeling Methods	Advantages	Issues
Variable-based [22]	Macroscopic models	Given a measure, it is usually not difficult to calculate it	- Hard to choose a good measure - Does not gain much understanding of the causes of emergent properties
Event-based [5]	Microscopic models		Need to define (formalize) event types and emergent behaviors beforehand
Grammar-based [16]	Cellular automata models, microscopic models	Better understanding of causes of emergence	Hard to define the sum operator for individual languages

Proposed Approach

1. Identify emergent properties
    - ✓ **Without prior knowledge** about emergence
    - ✓ Representing components in terms of their *objectives*

2. Visualize and validate emergent behavior
    - ✓ As it happens

Model Component Definition

- Component: abstracted as a *black-box* with *in* and/or *out* communication channel, and represented as a *meta-component*:
  - mandatory & specific attributes
  - behavior:
    - External – constraints on input and output (destination, origin, data type, range, etc.)
    - Internal – a finite timed state automaton

$$[I_l]S_p[\Delta t] \xrightarrow{Cond_n} S_t[O_l][A_m]$$

- Simulator: represented by ***components*** (base, model) linked using ***connectors***

Objective-based Annotation

- Define components in terms of ***what*** it do, not ***how*** it is done

- Each component has an added objective *o(*C_i*)*
  - Defined using both textual and semantically-enriched variables
  - Type and range to signify that the objective is met

$$o(C_i) = \{(description, var) | var \in A_m\}$$

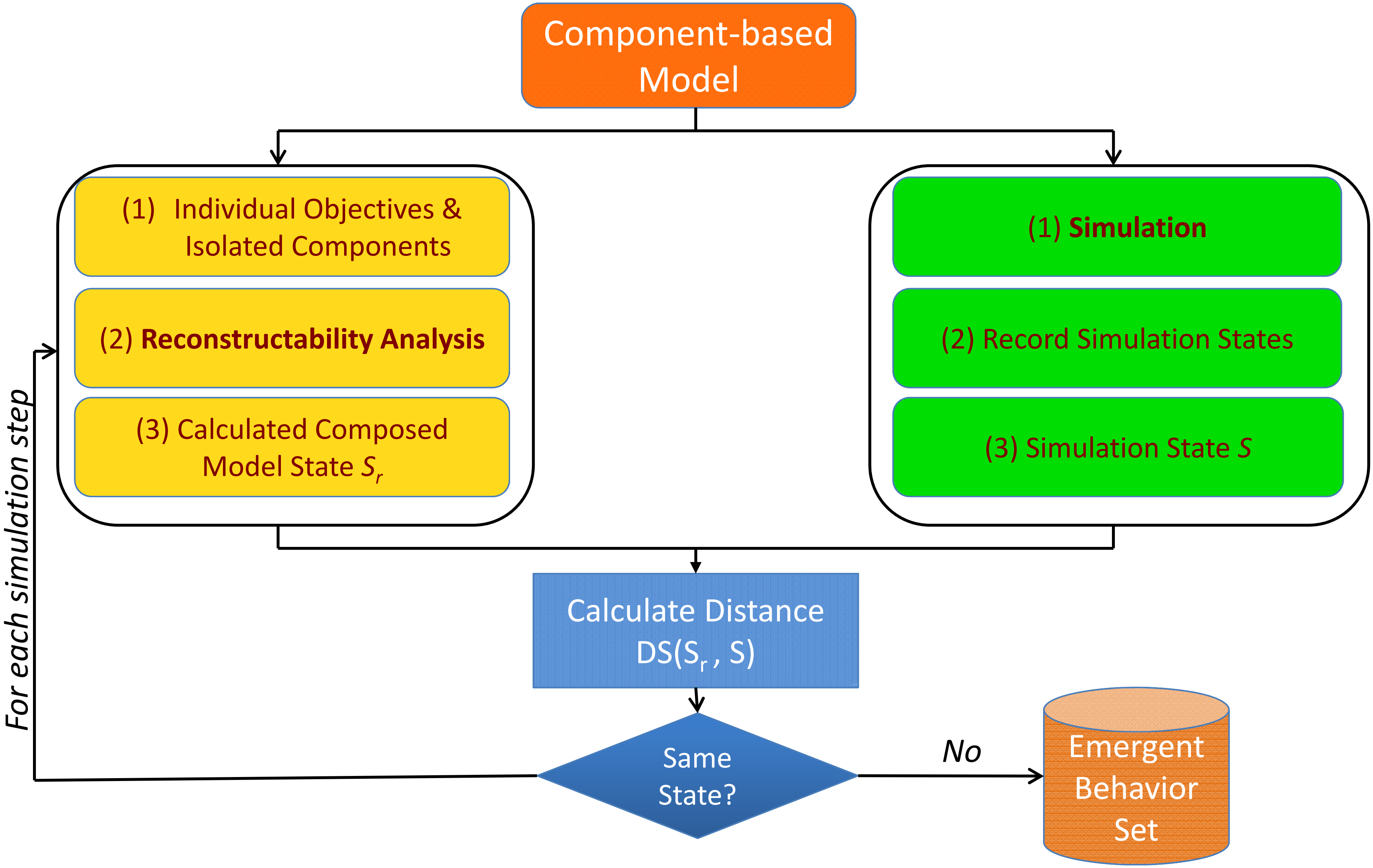
- Example: Birds in a Flock

$o(b_i) = (\text{description}, \text{var}(o(b_i)))$

description = Fly northbound with an
average speed of 20km/hour;

$var(o(b_i))$ = {direction, speed}

Objective-based Approach



Component-based Model

(1) Individual Objectives & Isolated Components

(2) **Reconstructability Analysis**

(3) Calculated Composed Model State S_r

(1) **Simulation**

(2) Record Simulation States

(3) Simulation State *S*

Calculate Distance DS(S_r , S)

Same State?

No

Emergent Behavior Set

For each simulation step

Reconstructability Analysis

- An approach for inducting modeling relationships and correlations between variables [2]

- Aim: to identify strongly related subsets of variables and to represent this knowledge in a simplified model which eliminates the connection between all other ``almost'' unrelated subsets of variables

- We used a variant called “reconstruction” – reverse process of constructing the whole from its parts

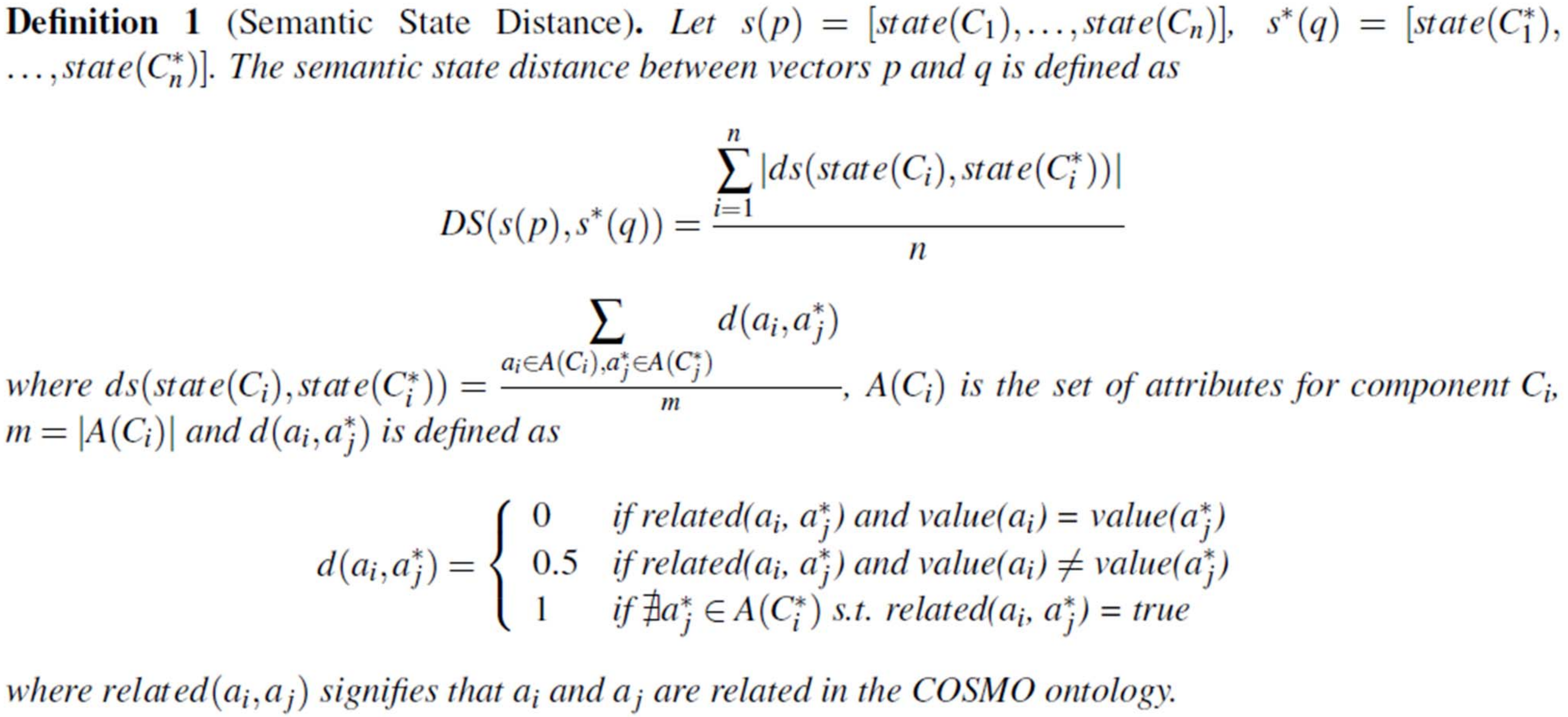
Calculating Composed Model State

- Component state, $s(C_i)|o$, is defined as the reunion of all variables *var* that are defined in its objective $o(C_i)$

- Composed model state, S_r, is the reunion of the states $s(C_i)|o$ of components running in isolation

- At each simulation step
  - Add to S_r only states that are significantly different

DS(S_r , S): Distance between States



Definition 1 (Semantic State Distance). *Let* $s(p) = [state(C_1), \ldots, state(C_n)]$, $s^*(q) = [state(C_1^*), \ldots, state(C_n^*)]$. *The semantic state distance between vectors p and q is defined as*

$$DS(s(p), s^*(q)) = \frac{\sum_{i=1}^{n} |ds(state(C_i), state(C_i^*))|}{n}$$

where $ds(state(C_i), state(C_i^*)) = \frac{\sum_{a_i \in A(C_i), a_j^* \in A(C_j^*)} d(a_i, a_j^*)}{m}$, $A(C_i)$ *is the set of attributes for component* C_i, $m = |A(C_i)|$ *and* $d(a_i, a_j^*)$ *is defined as*

$$d(a_i, a_j^*) = \begin{cases} 0 & \text{if } related(a_i,\ a_j^*) \text{ and } value(a_i) = value(a_j^*) \\ 0.5 & \text{if } related(a_i,\ a_j^*) \text{ and } value(a_i) \neq value(a_j^*) \\ 1 & \text{if } \nexists a_j^* \in A(C_i^*) \text{ s.t. } related(a_i,\ a_j^*) = true \end{cases}$$

where $related(a_i, a_j)$ *signifies that* a_i *and* a_j *are related in the COSMO ontology.*

Example: Flock of Birds

- Each component abstracts a moving bird that changes its position
  - separation - avoid crowding
  - alignment - steer towards the average herding of local flockmates
  - cohesion - move towards the average position of local flockmates

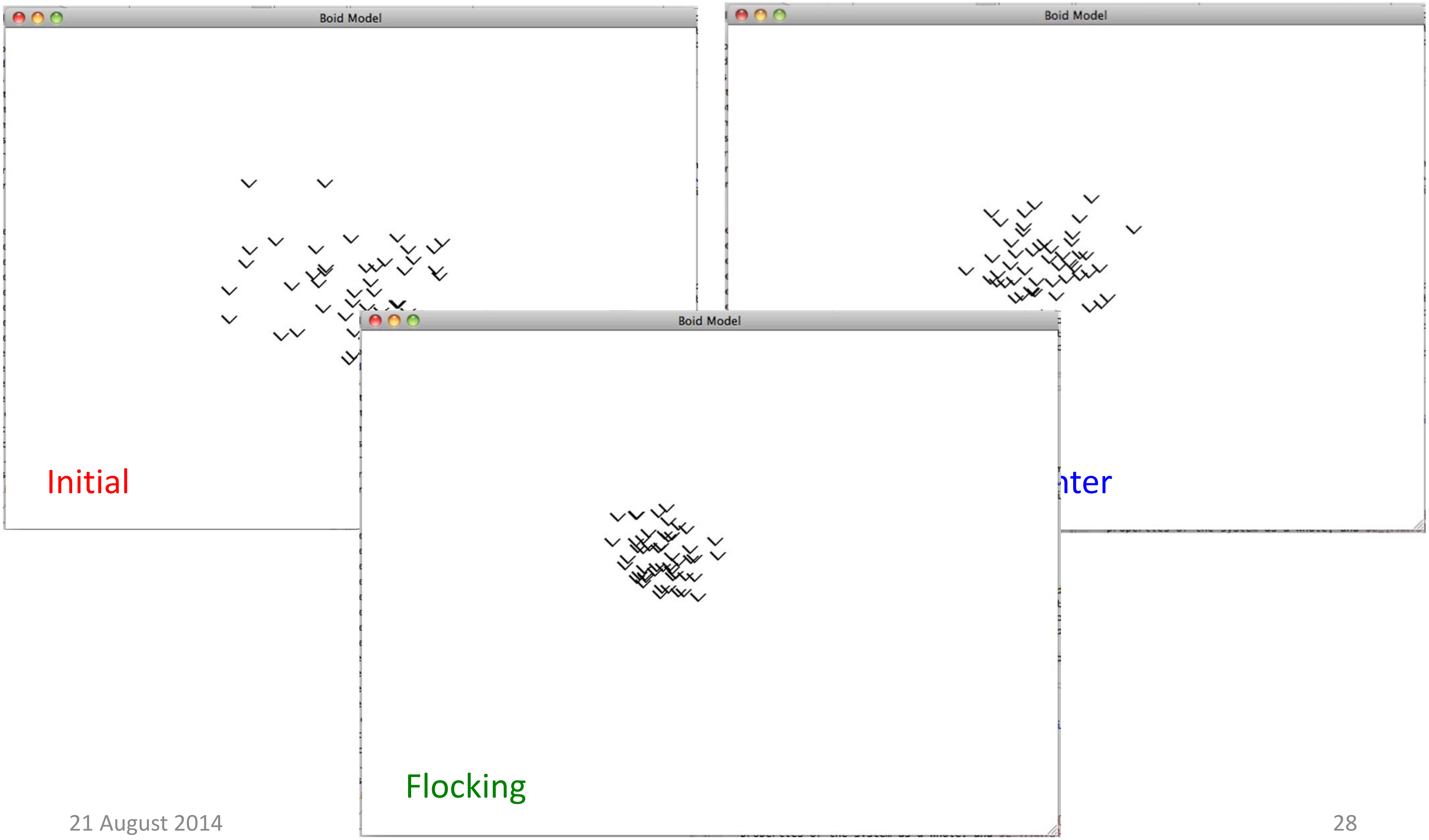
- Objective

$o(b_i)$ = (description,var($o(b_i)$))

description = Fly northbound with an average speed of 20km/hour;

$var(o(b_i))$ = {direction,speed}

Example: Flock of Birds



Snapshots of State Changes

Composed Model
(Reconstructability Analysis)
(independent components)

State Changes

Bird 1	Bird 2	Bird 3	Bird 4	Bird 5
120,N	114,N	135,N	111,N	98,N
155,N	193,N	146,N	180,N	150,N
360,N	394,N	387,N	380,N	350,N
539,N	571,N	560,N	558,N	538,N
-,N	-,N	-,N	-,N	-,N
-,N	-,N	-,N	-,N	-,N

Real System (Simulation)
(component interactions)

Bird 1	Bird 2	Bird 3	Bird 4	Bird 5
53,S	209,N	128,N	67,S	43,N
45,S	174,NW	88,N	65,S	44,N
40,S	129,NW	59,N	60,SW	43,N
39,S	76,NW	42,N	51,SW	38,N
38,N	27,NW	48,N	34,NW	37,N
54,N	71,NW	69,NW	11,NW	57,N

<distance, direction>

where distance is relative to centre of drawing panel

<-, N> – out of viewing range

Conclusions

- Two-step approach:
  - Identification of emergent properties *without prior knowledge of emergence*
    - Objective-based annotation of model components: *what* rather than *how*
    - *Reconstructability analysis*
  - Validation of emergent behavior

- First step in the identification of emergent properties
  - Limiting assumptions
  - Other examples: traffic junctions, social networks, …
  - Visualization & Validation

Limitations

- Objective definition
  - Requires component creator's knowledge
  - Dependent on how the component will be used
- Reconstructability analysis
  - Requires numerous iterations to converge to statistical significant differences
- Sensitivity analysis on threshold values
  - Until which point is emergent behavior normal and expected?
- …

Thank you!

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1. Y.M. Teo and C. Szabo, **Semantic Validation of Component-based Models with Emergent Properties**, Book Chapter in Ontology, Epistemology, and Teleology of Modeling and Simulation – Philosophical Foundations for Intelligent M&S Applications, edited by Andreas Tolk, Springer-Verlag, 2012.

2. C. Szabo and Y.M. Teo, **An Analysis of the Cost of Validating Semantic Composability**, Proceedings of 25th ACM/IEEE/SCS Workshop on Principles of Advanced and Distributed Simulation, pp. 62-69, IEEE Computer Society Press, Nice, France, June 14-17, 2011. [Also in Journal of Simulation, Palgrave-Macmillian, 2012 (advance online publication)].

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