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Measuring Belonging in a System of Systems to Influence Architectural Decisions

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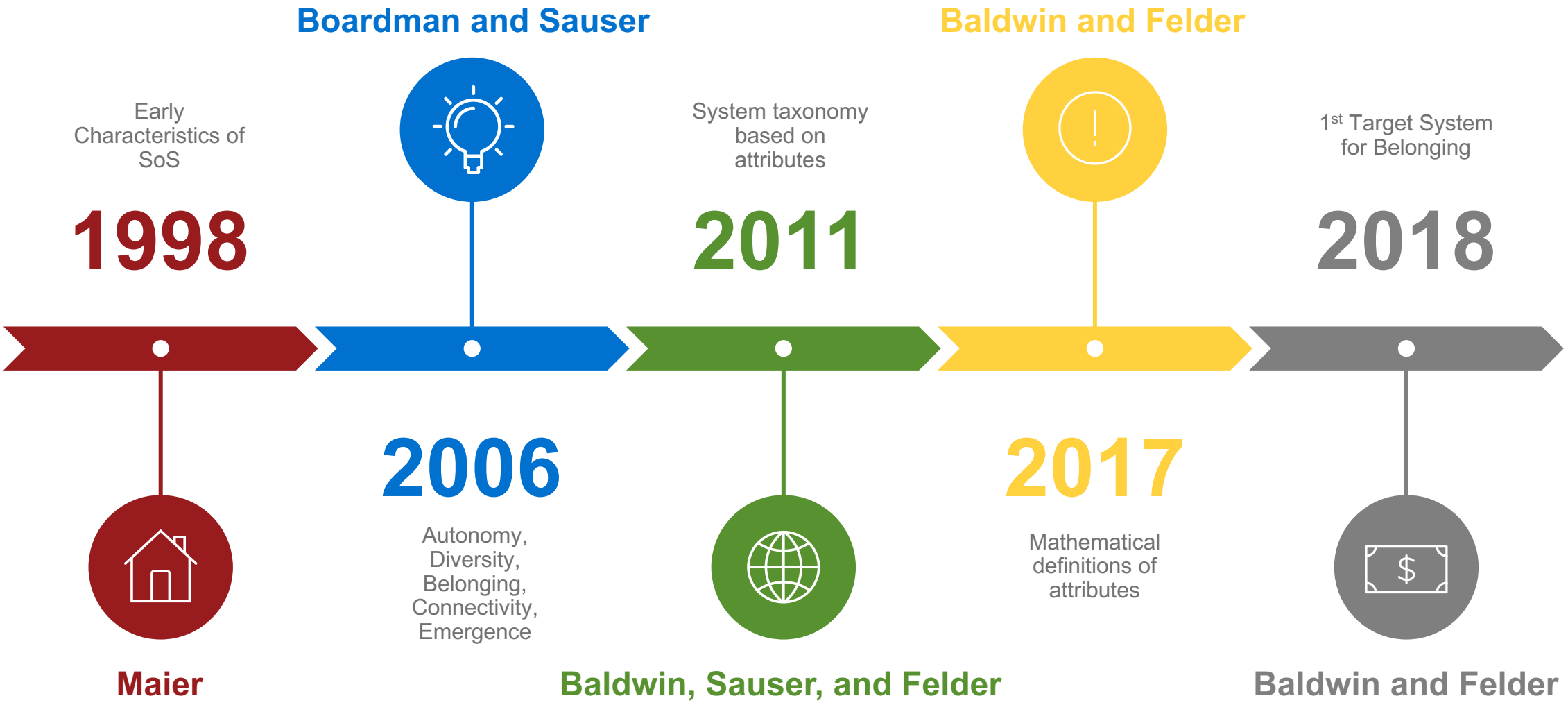
Question

- *How can we understand better system-of-systems (SoS)?*
  - Specifically, the collaboration of constituent systems and its influence on the SoS architecture?
    - We call this collaboration “Belonging”

Evolution of the Belonging Attribute



Definition of Belonging

- The collaboration of goal-directed actions by constituent systems
- The Belonging attribute captures the transfer of benefit between individual systems and the collective
  - Represented mathematically, $B^* = \begin{bmatrix} b_{11} & b_{12} & b_{1n} \\ b_{21} & b_{22} & b_{2n} \\ \cdots & \cdots & \cdots \\ b_{n1} & b_{n2} & b_{nn} \end{bmatrix}$

Problem

- How do we expand and validate this theory of Belonging?
  - Need well-defined, quantifiable data
  - Difficult to acquire data from engineered SoS
    - Security reasons
    - Proprietary reasons

Inspiration for the Target System

- Migrating Waterfowl
  - A well studied system-of-systems
  - Biology and Physics are well understood
  - Meets the System-of-systems definition
    - Each bird is clearly a system in its own right (has autonomy)
    - Both individual birds and the flock benefit from flock formation (has belonging)

History of bird flock simulations

- Reynolds (1987) BOIDS model
- Dimock and Selig (2003) extended Reynold's model to include aerodynamic effects
- Seiler *et al* (2003) modeled the behavior of trailing birds following the leader and estimated its effect on flock formation.
- Nathan and Barbosa (2008) looked specifically at rules to produce vee-shaped formations

None of these were suitable for our purpose

Agent Based Model Features

Physics determines range and fuel consumption

Agents adhere to biological requirements

Drag reduction influences Flock Formation

Fuel Savings captured in Belonging Matrix

But, this is NOT about the Birds!!

Environmental Calculations

- Endurance form of Breguet range equation

$$E = \int_{W_i}^{W_f} \frac{L}{D} \cdot \frac{1}{C} \cdot \frac{\mathrm{d}W}{W}$$

- Range version

$$R = V \cdot E = \frac{L}{D} \cdot \frac{V}{C} \cdot \ln\left(\frac{W_i}{W_f}\right)$$

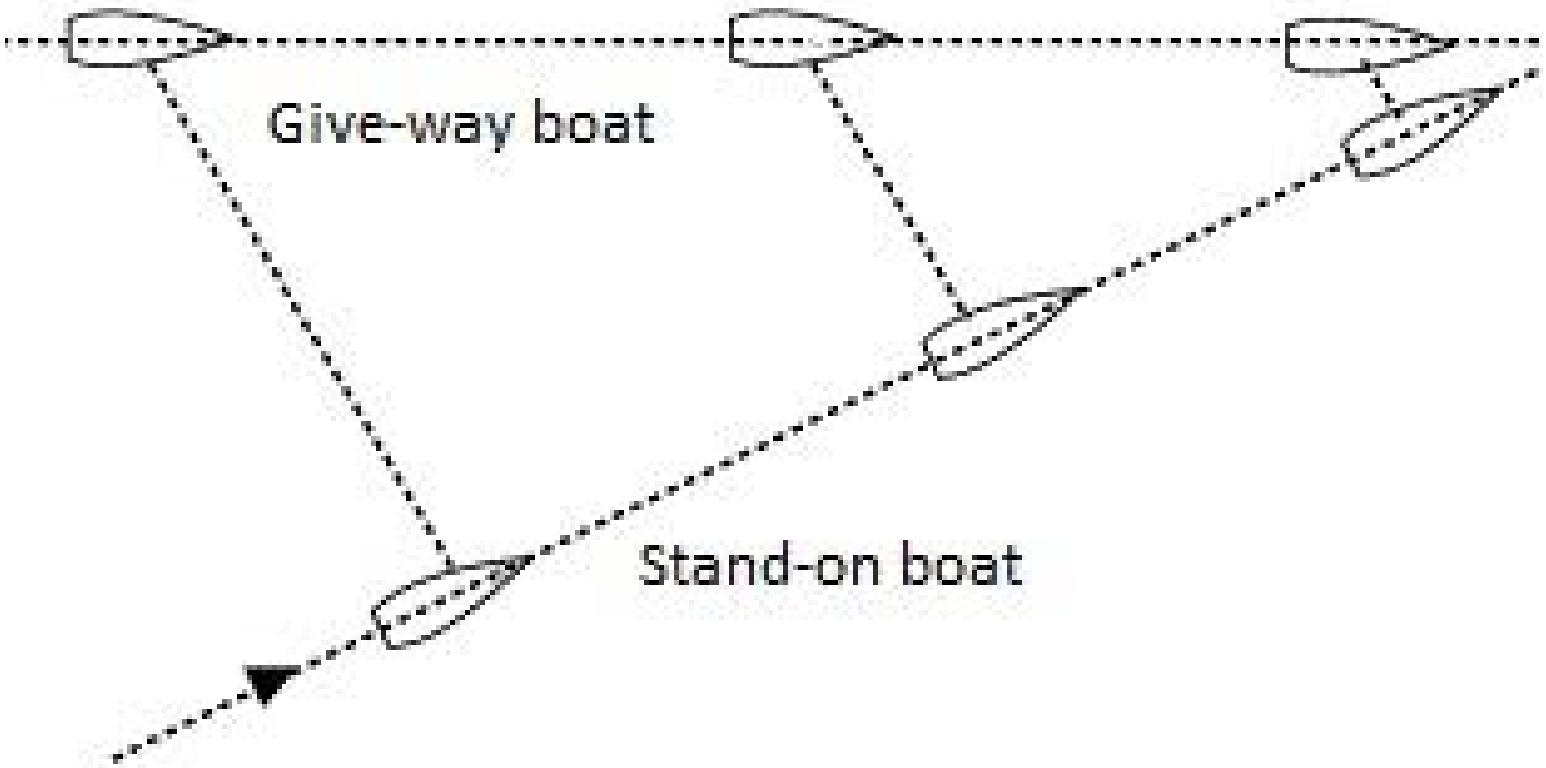
- Specific fuel consumption

$$C = \frac{L}{D} \cdot \frac{1}{E} \cdot \ln\left(\frac{W_i}{W_f}\right)$$

- Drag effects

$$\Delta W' = F' \cdot \Delta W$$
$$\Delta W'' = F'' \cdot \Delta W$$

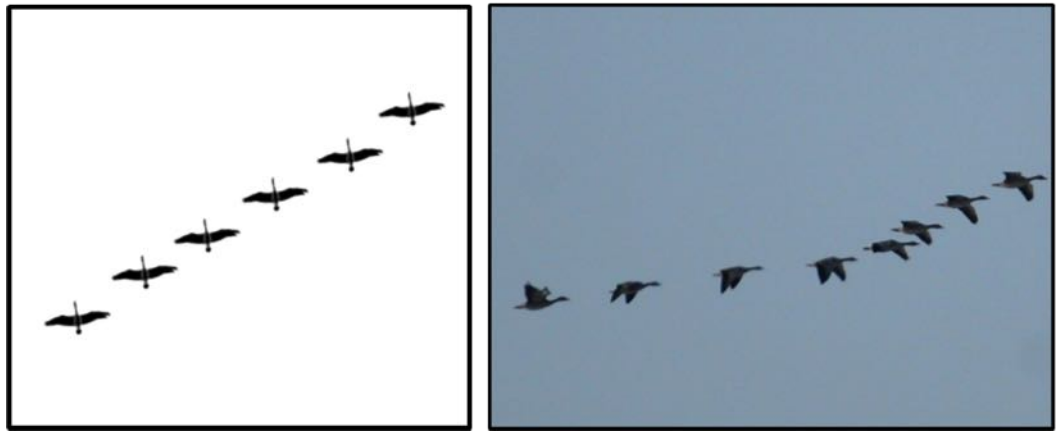
But Birds Do Not Do Mathematics…



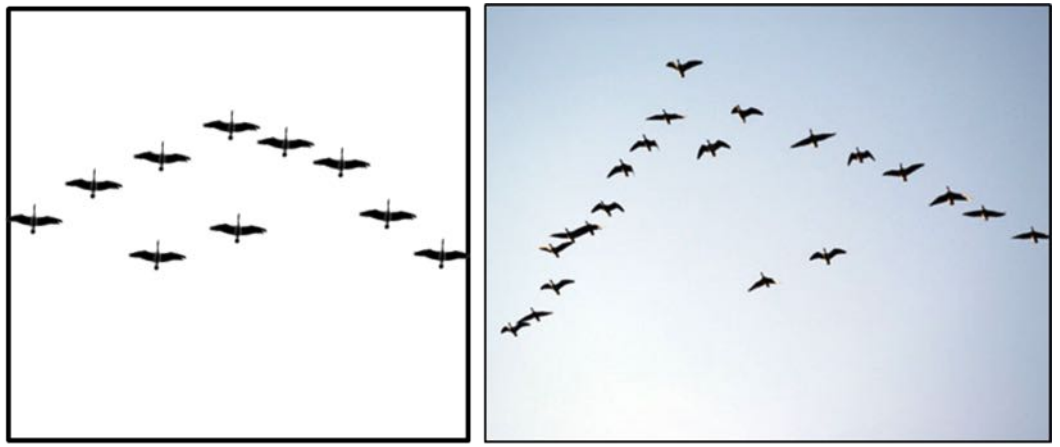
Constant Bearing, Decreasing Range

Doug Logan, Collision Course with a Crossing Boat? How to Know.
http://www.boats.com/reviews/collision-course-with-a-crossing-boat-how-to-know/

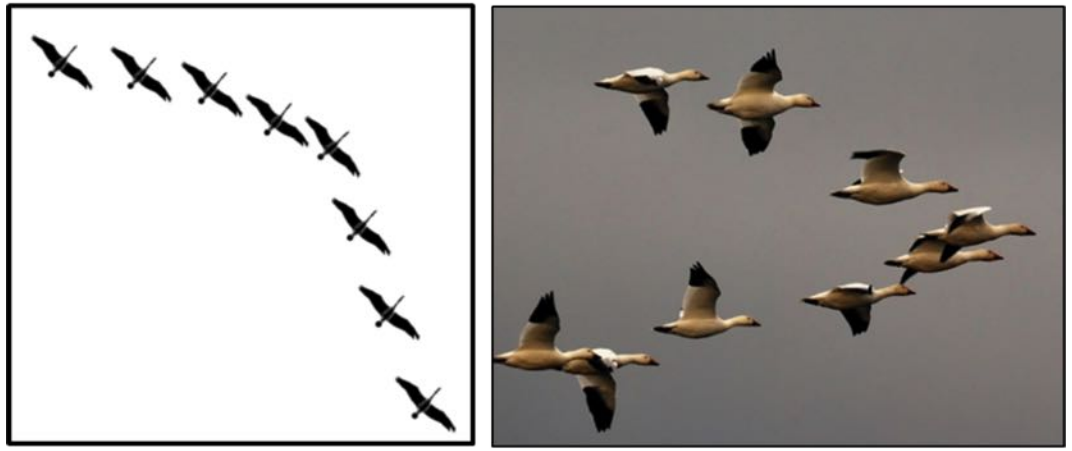
Simulation Output – Natural Formations



Examples of Gould and Heppner formation type (1): Column/Echelon (40% of observations). Left, from model Run 164-15-F (step3645). Right, photo of migrating Black Brants (Janusz Arts photo.)

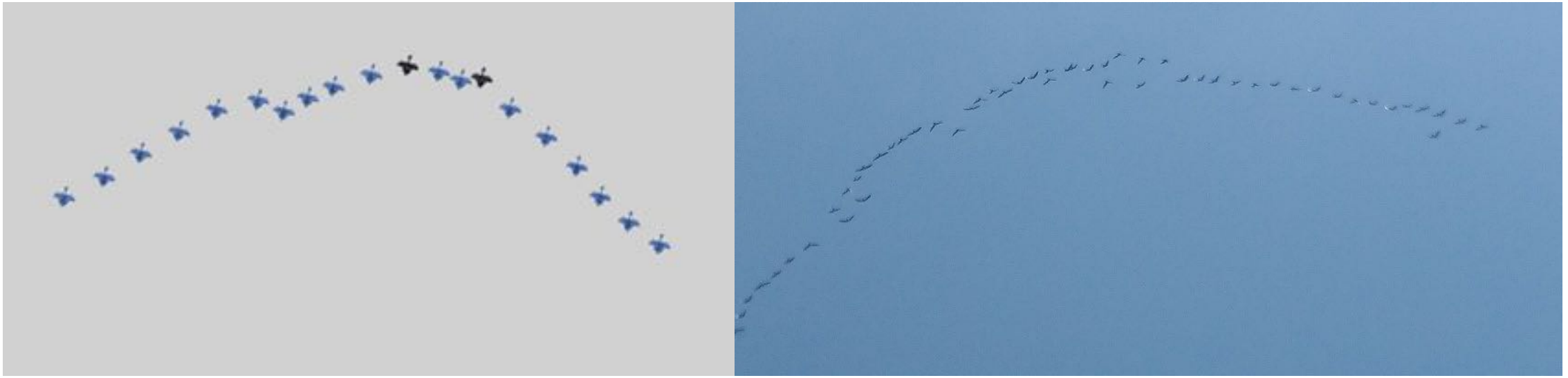


Examples of Gould and Heppner formation type (8): Vee with birds inside, 1% of observations. Left, from model Run 164-15-F (step5950). Right photo Blog: Canadá Segundo os Brasileiros, 6 May 2015



Examples of Gould and Heppner formation type (2): Vee 17% of observations. Left, from model Run 171-10-F (step49423). Right, from “What Can Birds Teach Us About Leadership”; Civil Society Cookbook, by Arseh Sevom.

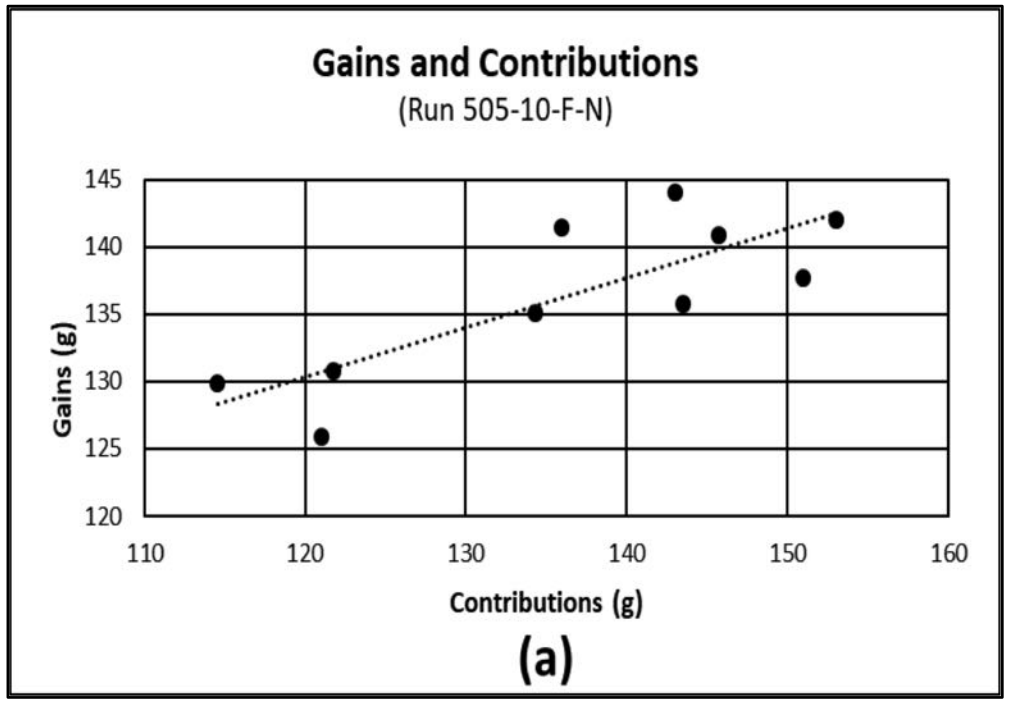
More Simulation Output

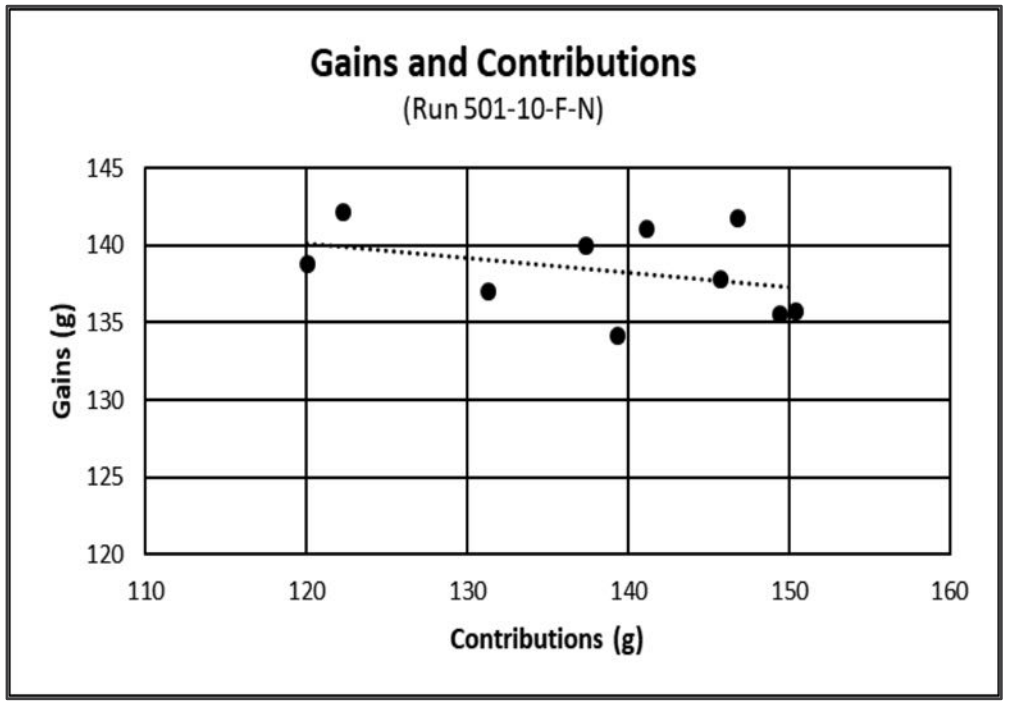


Photograph by Clifton Baldwin on October 24, 2016 in Bayville, NJ using 18 megapixel Schneider-Kreuznach camera on BlackBerry Priv

An Observation about System Architectures

- Gains and contributions for different starting conditions



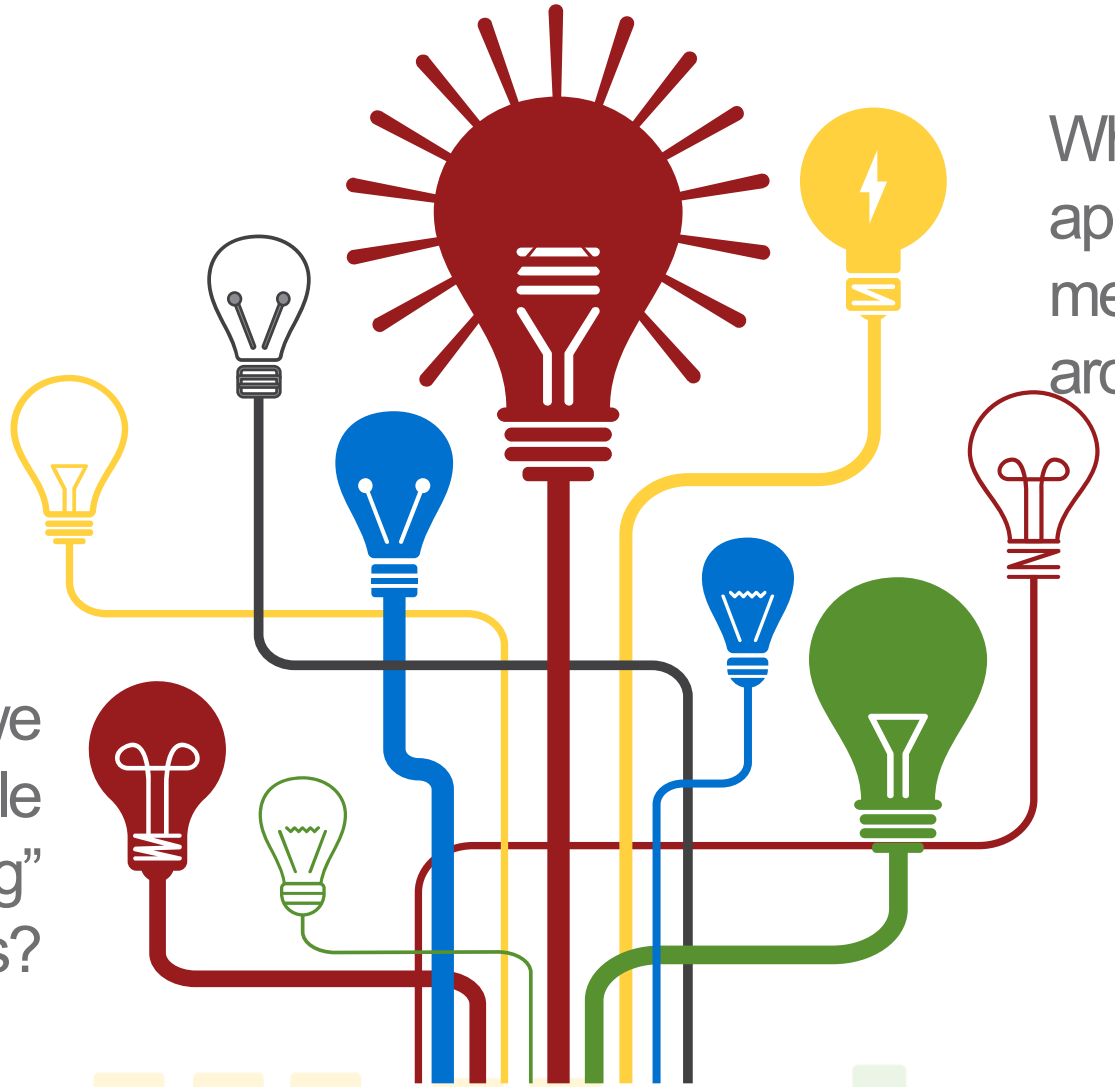


- These reflect systems-of-systems with very different characteristics – although identical in all respects except the starting condition!
  - And expected architectures (i.e. formations) formed

Discussion Questions

What other elements could be measured as "belonging"?

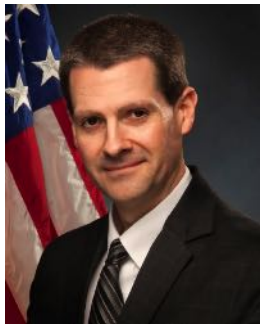
How could we measure multiple "belonging" elements?



What would be an appropriate measurement of architecture?

To what other SoS could this model apply?

Bios



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