# The First Law of Systems Science: Conservation of Complexity 

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Prof. Olivier de Weck Massachusetts Institute of Technology<br>deweck@mit.edu

## From Alchemy to Chemistry



Book on Alchemy (recipes) - 1600s
Islamic and European alchemists developed a basic set of laboratory techniques, theories, and terms, some of which are still in use today. However, they did not understand the underlying building blocks of matter, still relying on the 4 elements of Greek philosophy.


## Periodic Table of Elements - 1800s

In 1817, German physicist Johann Wolfgang Döbereiner began to formulate one of the earliest attempts to classify the elements. In 1829, he found that he could form some of the elements into groups of three, with the members of each group having related properties. It took 100+ years to fill the table

Audience Survey

Go to www.menti.com and use the code 21705205

## Instructions



Or use QR code

## Where are we on our Systems Engineering (SE) journey?

- We are in a transition phase between practice (with plenty of heuristics and data) and the beginnings of a deeper theory
- What are the laws that can accurately predict the behavior of complex systems under a set of given assumptions?
- In order for any "laws" to be accepted as true, there needs to be a set of experiments and data to validate (or falsify) them


## Systems Engineering in 2023 is where Chemical Engineering was in 1823 !

## Fundamental Laws in Science

- First Law of Thermodynamics
- Conservation of Energy
- Rudolf Clausius 1850
- Second Law of Classical Mechanics
- Conservation of Angular Momentum
- Leonhard Euler 1736


What is the conserved quantity in Systems Science (and therefore Systems Engineering)?


## Structural DSM of Wright Flyer



| Legend |
| :---: |
|  |  |
|  |
| Energy flow |
| Information flow |
| DSM 18x18 |
| Connections |
| 62 Physical |
| 4 Mass Flow |
| 11 Energy Flow |
| 9 Info Flow |
| Total: 86 |
| NZF = 86/1,224 |
| = 7\% density |
| <k>=~5 |

Design Structure Matrix (DSM) - captures structure of elements of form

## Augustine's $16^{\text {th }}$ Law



Norm Augustine, Augustine's Laws, 6 ${ }^{\text {th }}$ Edition, AIAA Press, 1997.

Functional Requirements Explosion in Aviation


## F-35 JSF

IActive Matrix Liquid Crystal Display image display

I Integrated day and night camera

IEjection Safe to 600 knots equivalent air speed

## What is driving this escalation of cost?

SYSTEMS, AND SOCIETY

Contributors to Price Escalation from the F-15A (1975) to the F-22A (2005)


## Three Dimensions of Complexity



## The Structural Complexity Metric

Structural Complexity, $C=C_{1}+C_{2} \cdot C_{3}$


Complexity due to components alone (number and heterogeneity of components)


Complexity due to pair-wise component interactions(number and heterogeneity of interactions)


Sinha, Kaushik, and Olivier L. de Weck. "Empirical validation of structural complexity metric and complexity management for engineering

## Experiment: We slow down w/complexity




Complexity $=351$


Complexity increase $+42 \%$

|  | $\mathbf{C}_{\mathbf{1}}$ |  | $\mathbf{C}_{\mathbf{2}}$ |  | $\mathbf{C}_{\mathbf{3}}$ |  | $\mathbf{C}$ |  | $\mathbf{C}_{\mathbf{M L}}$ |  | $\mathbf{C}_{\text {new }} / \mathbf{C}_{\text {old }}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Old | New | Old | New | Old | New | Old | New | Old | New |  |
|  | 161 | 188 | 126 | 184 | 1.51 | 1.69 | 351 | 499 | 1 | 1 | 1.42 |
| Mean | 179 | 244 | 141 | 240.4 | 1.51 | 1.69 | 392 | 650.3 | 1.12 | 1.30 | 1.65 |
| Median | 178 | 242 | 139 | 238.9 | 1.51 | 1.69 | 388 | 646.8 | 1.10 | 1.29 | 1.66 |
| 70 percentile | 181 | 247.9 | 145 | 246.2 | 1.51 | 1.69 | 399.6 | 663.94 | 1.14 | 1.33 | 1.66 |

Trend towards more distributed architecture with higher structural complexity and significantly higher development cost ${ }^{*}$. Similar trend was observed in Printing Systems.

## Diminishing Returns with Complexity



(a)

(c)

(b)

(d)

## SYSTEMS ENGINEERING

## VISION 2035

## Theoretical Foundations

"TO" state:
"The systems engineering foundations have a stronger scientific and mathematical grounding based on advanced practices, heuristics, systems observable phenomena, and formal ontologies. The foundations are shared across application domains, and provide additional rationale for selecting and adapting practices to maximize value for the particular application."

## Complexity and Value Maximization

Complexity budget C* is the level of complexity that maximizes system Value!


## Example: Complexity Target to optimize Value



Pmax=2;
k=4;
$\mathrm{n}=2.5$;
a=1;
$\mathrm{m}=1.5$


## The First Law of Systems Science and SE: Conservation of Complexity

- First Law of Thermodynamics:

$$
\Delta U=Q-W
$$

- Conservation of Energy
- The change in internal energy $\Delta U$ is equal to the heat $Q$ added to the system minus the work $W$ done by the system.
- The First Law of Systems Science and Engineering:
- Conservation of Complexity

$$
\Delta C=\mu \Delta P-\varepsilon \Delta E
$$

- The change in complexity $\Delta \mathrm{C}$ of the system is equal to a proportional change in expected performance $\Delta P$ minus the change in effort $\Delta \mathrm{E}$ expended by the enterprise

$$
\varepsilon=-\frac{C^{1-m}}{2 a m} \quad \mu=\frac{\left(1+k C^{n}\right)^{2}}{2 \text { PmaxknC }^{n-1}\left(1-k C^{n}\right)}
$$

## Validation of the $1^{\text {st }}$ Law: Successful vs Failed Systems

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- CoBRA (Aerospace Corp., 2008) - Complexity Index based on analysis of historical data.
- Projects that were highly complex but tried to cut development cost had high failure rates



## Key Messages

- Complexity C of artificial (and natural?) systems has been increasing
- This is driven by customers, competition, and regulation $\rightarrow$ functional performance $\mathrm{P} \rightarrow$ structural complexity $\mathrm{C} \rightarrow$ organizational effort E
- A rigorous measure of complexity is based on graph energy of DSM
- C = C1+ C2*C3;
- C3: Graph Energy is a measure of topological complexity
- Explicit complexity-based budgeting with clear targets is needed in SE
- First Law of Systems Science and Engineering (according to de Weck-Sinha):
- Conservation of Complexity
- Given a set of functional requirements P, establish minimum needed structural complexity C, and calculate organizational effort E (NRE) to satisfy the first law
- Violating the first law can lead to project or system failure !


## INCOSE IW 2023

Future of Systems Engineering (FuSE)

Foundations Stream

