FuSE
Future of Systems Engineering

Systems Engineering Foundations: Experiment on the Conservation of Complexity.

25 April 2023

EMEA WSEC 2023 – Sevilla Spain

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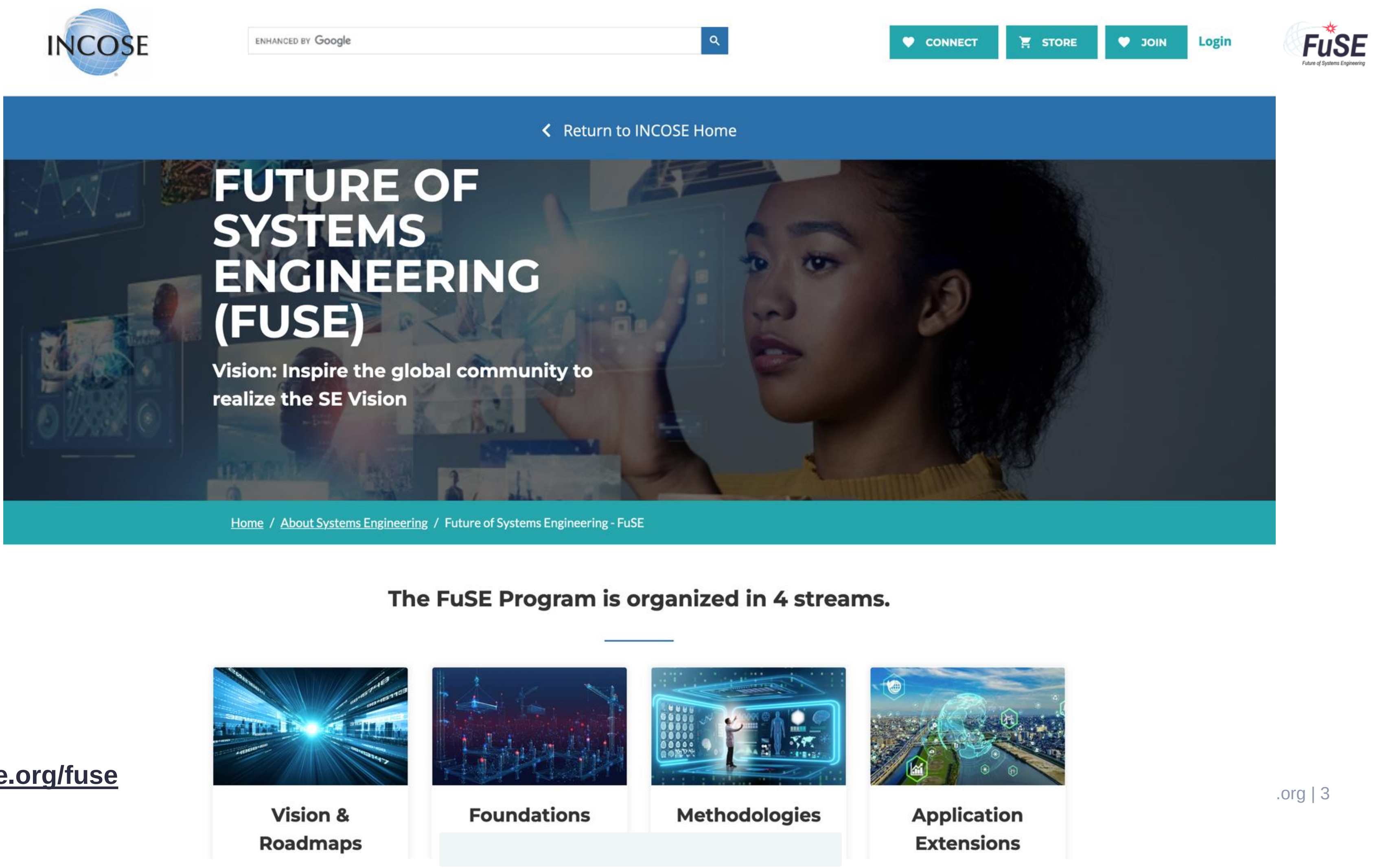
Agenda.

This is a repeat of the experiment we ran at IW 2023 in Los Angeles.

Please DON'T do it again...

- FuSE Intro
- SE Foundations Stream Intro (15 min)
  General overview
- Experiment Introduction (10 min)
  Introduction of a simple experiment related to System Complexity
- Experiment (30 min)
  Carry out experiment at tables in teams of 2 or 3
- Experiment Debrief (10 min)
  Feedback and Q&A related to the experiment
- Discussion Questions (20 min)
  Guided discussion
- Closure



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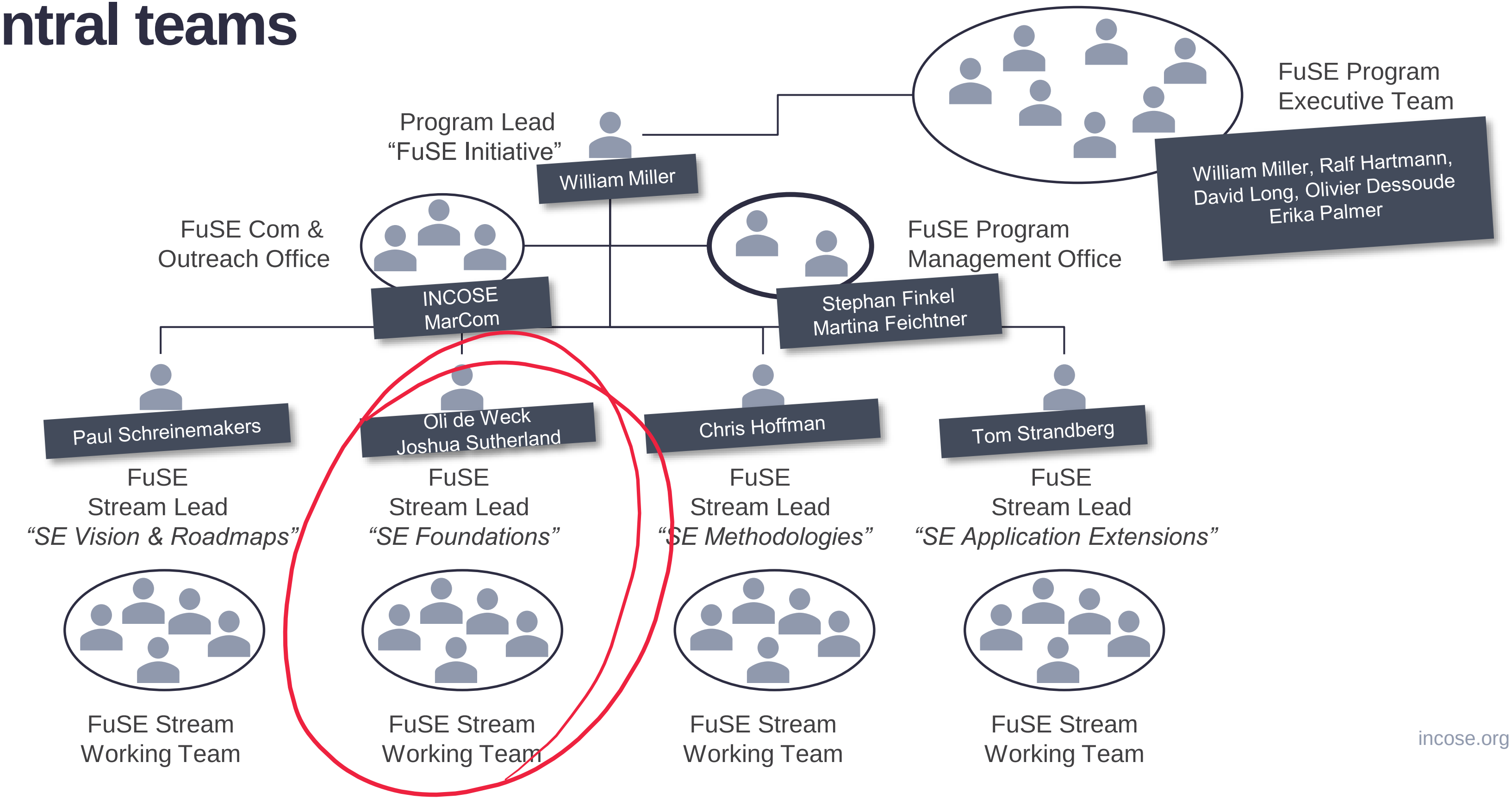
The FuSE program is organized in 4 streams with additional central teams



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SE Foundations

- The SE Foundations stream has its basis in both theory and industrial practice. The intermediate stream goal is to assess the adequacy of the foundations and identify gaps to determine future directions. Special consideration will be given to the **theoretical foundation of the SE as a discipline** on one hand and the practical application foundations using principles and heuristics on the other hand.

From Alchemy to Chemistry

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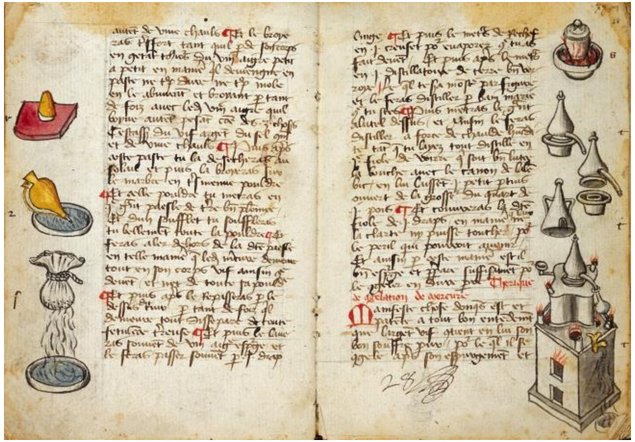
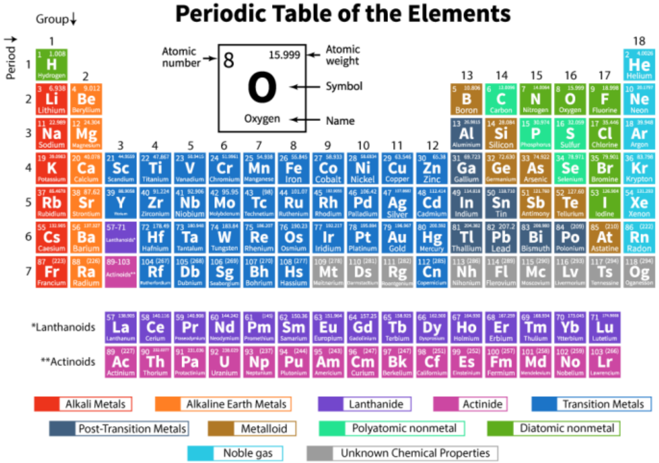


Book on Alchemy (recipes) – 1600s

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

Alchemy – Chemistry – Chemical Engineering → **300+ Years**

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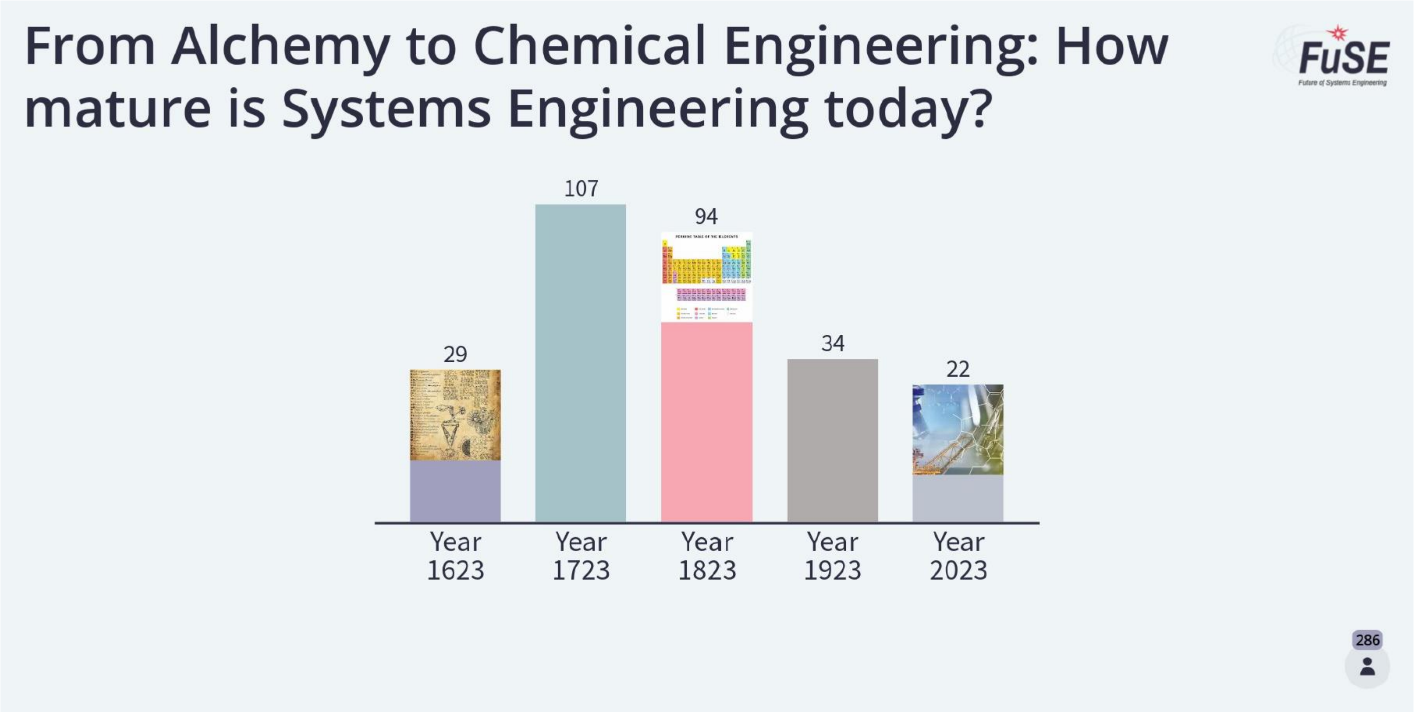
IW 2023 Audience survey result:
“Where are we on our SE journey?”



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 !

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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."

https://violin-strawberry-9kms.squarespace.com/theoretical-foundations

How are we approaching SE Foundations?

- **1. Quantification:**
  - Unless we can quantify what we speak about we are not really masters of the fundamentals
  - The deeper theoretical understanding of what drives performance, complexity, effort, cost, safety in systems requires this.
- **2. Experimentation:**
  - Claims will be subjected to the rigors of careful and repeatable experimentation (at different organizations, individuals at different locations) to either support or refute them.
  - Remain skeptical of any claims related to SE Fundamentals unless there is experimental evidence (either from natural or controlled experiments) to validate these ideas.
- **3. Work with other FuSE streams to make our findings operationalizable to doing great Systems Engineering**
  - What we discover will be made useful for doing work

INCOSE Systems Science WG

Javier Calvo-Amodio, Ph.D., F.ASEM (He/Him) · 2nd

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Systems Science Working Group

Mission & Objectives

Promote the advancement and understanding of Systems Science, Systems Theories and their application to SE.

We have the following objectives:

- Encourage advancement of Systems Science principles and concepts as they apply to Systems Engineering.
- Promote awareness of Systems Science as a foundation for Systems Engineering.
- Highlight linkages between Systems Science theories and empirical practices of Systems Engineering.

Systems science provides a rigorous, underlying basis to the empirically derived practices to systems engineering that have evolved over time.

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The Foundations Stream's objectives during EMEA 2023.

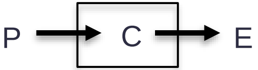
The SE Foundations stream aims to:

- Validate (or refute) the proposed First Law of Systems Science and Engineering: **"Conservation of Complexity"**

First Law of Systems Science and Engineering (proposed)

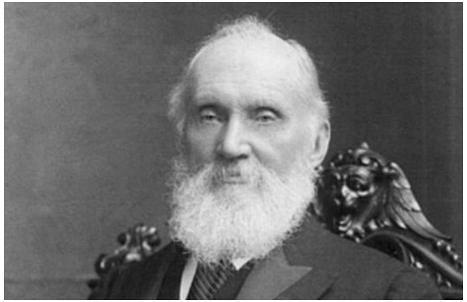
Conservation of Complexity

The change in **complexity C** of the system is equal to a proportional change in expected **performance P** minus the change in **effort E** expended by the enterprise



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

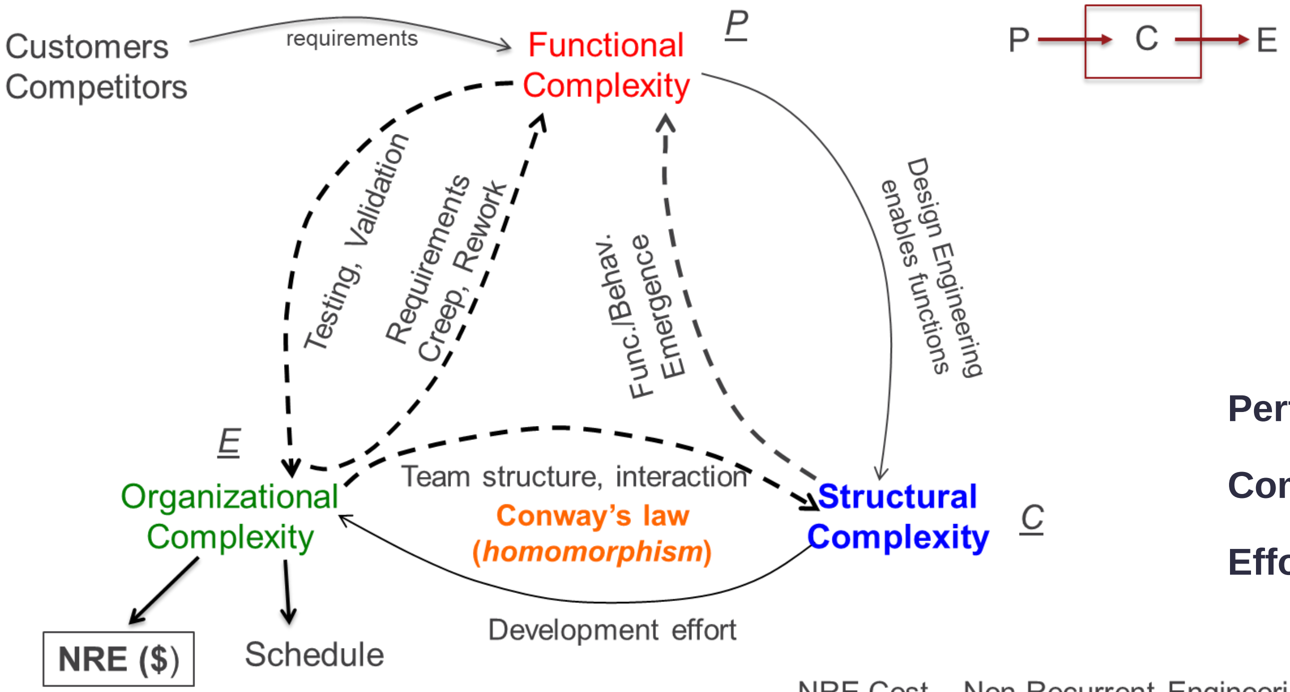
Is this "law" true?



"When you can measure what you are speaking about, and express it in numbers, you know something about it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarely, in your thoughts advanced to the stage of science."

William Thomson, Lord Kelvin (1824–1907)

Three Dimensions of Complexity in Systems Engineering



Performance P

Complexity C

Effort E

NRE Cost – Non-Recurrent Engineering Cost

In groups of 2-3 you will design a road network

Los Angeles "Freewaytopia"

Source: https://www.engadget.com/hitting-the-books-freewaytopia-paul-haddad-santa-monica-press-153036975.html

Test the (proposed) 1st Law of Systems Science & Engineering

Conservation of Complexity:

The change in complexity C of the system is equal to a proportional change in expected performance P minus the change in effort E expended by the enterprise

P → C → E

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

Performance P

- minimum average path length (i.e. less road is built)

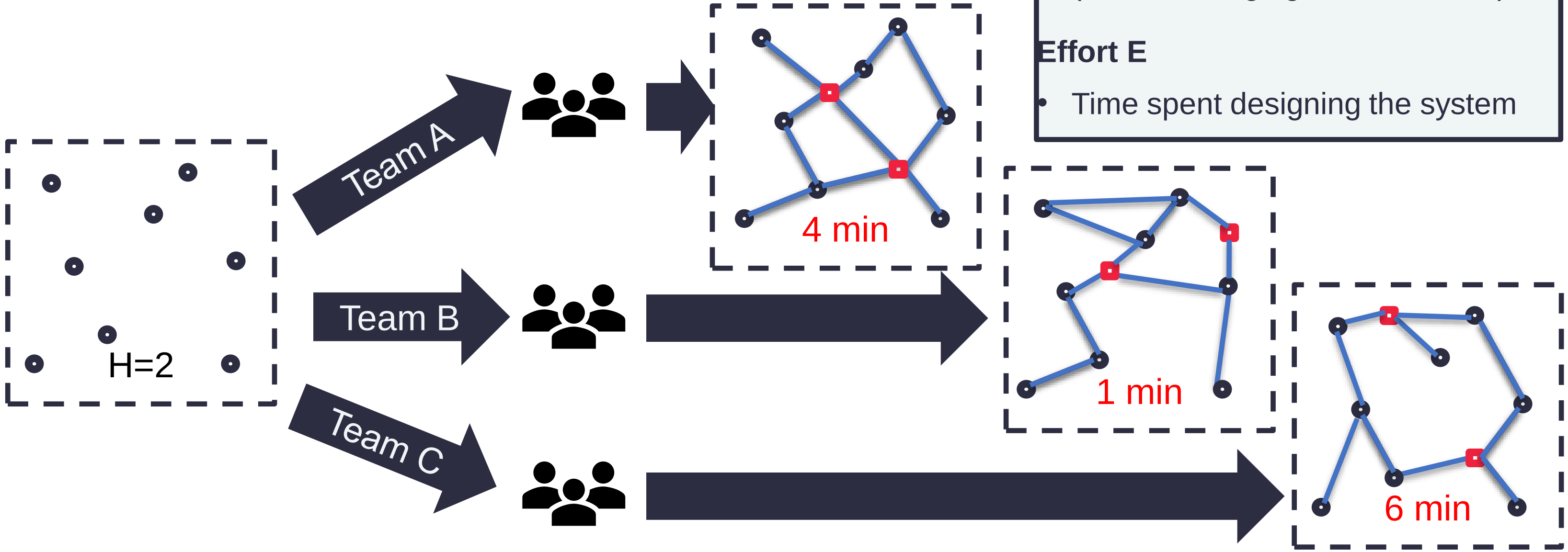
Complexity C

- normalized graph energy of network (how challenging the network is)

Effort E

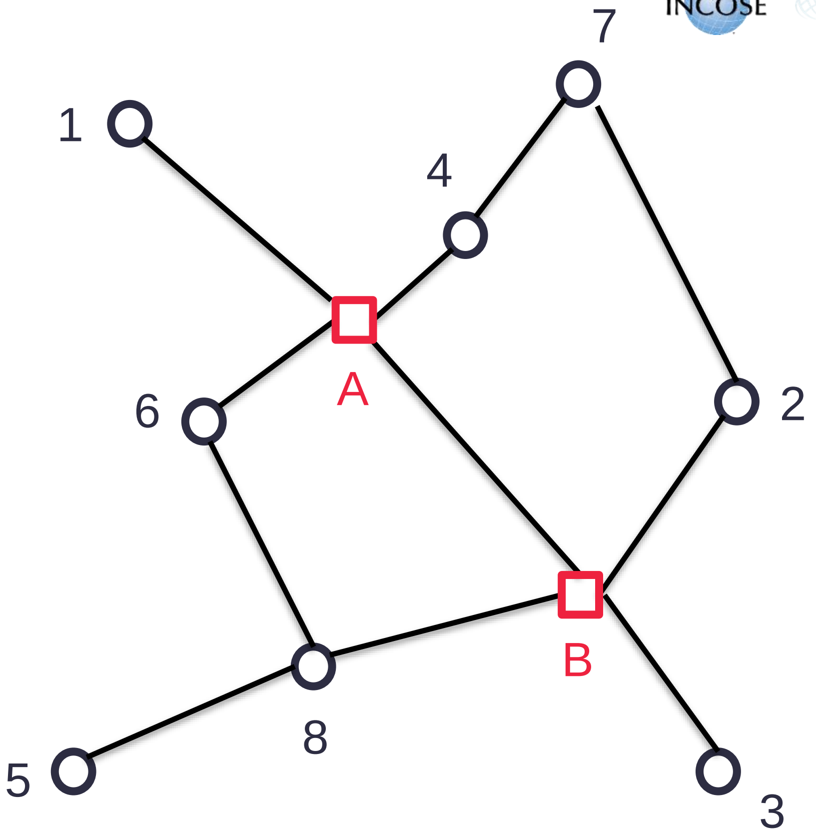
- Time spent designing the system

Designing a new transport system for a city.



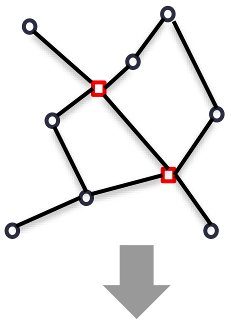
Experiment

- You are designing a new transportation system for a city.
- Given: N randomly placed origin-destination (OD) points (“o”)
- Your task: connect all points via M straight edges using a maximum of H hubs (‘☐’) such that the average travel distance between any OD pair is minimized
- Record: 1. Your final system design (on paper), 2. Clock time used



N=8, H=2, M=11

Postprocessing



DSM$_c$=

1								1	
	1					1			1
		1							1
			1			1		1	
				1			1		
					1		1	1	
	1		1			1			
				1	1		1		1
1			1		1			1	1
	1	1					1	1	1

Performance P

- minimum average path length

Complexity C

- normalized Graph energy of network

Effort

- Time spent designing the system

$$DSM_c = \begin{bmatrix} \alpha_1 & \dots & \beta_{n1} \\ \vdots & \ddots & \vdots \\ \beta_{1n} & \dots & \alpha_n \end{bmatrix}$$

$$Complexity, C = C_1 + C_2 * C_3$$

$$C_2 = \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij}, where\ i \neq j$$

$$C_1 = \sum_{i=1}^{n} \alpha_i$$

$$C_3 = \frac{1}{n} \sum S[SVD(A(DSM_c - trace(DSM_c)))]$$

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Experiment Instructions

1. **Form groups of 2 or 3 at your table**
2. **Flip over your experiment sheet**
3. **Write on sheet in marker pen:**
   - Group ID
   - Completion Order (i.e. is this your 1st, 2nd, 3rd… sheet)
   - Subject IDs for each team member
4. **Start your stopwatch (e.g. on your phone)**
5. **Work out your solution (use pencils & erasers)**
   - There is no time limit for each sheet.
6. **Agreed on your final solution? – Stop the clock**
   - Write on sheet in marker pen how long your team took in seconds
   - Draw your final solution using marker pen. Make any hubs very clear.
7. **Submit your sheet**

Rules:

A. Every Node (& Hub) must be connected to network

B. It must be possible to travel to every Node from every other Node through the network you designed

C. Each Node (& Hub) can be connected an unlimited number of times

D. You must use all your allocated Hubs (H). No more & no less

E. Hubs must have at least 4 connections (think of them like interchanges)

F. Each group is given random sheet each time with very different difficulty, so don't worry if your speed is very different than other groups

Measurement:

A. Performance (P) will be measured as minimum average path length between Nodes

B. Effort (E) will be measured as time spent designing the transport system

C. Complexity (C) will be calculated by us as normalized Graph energy of network

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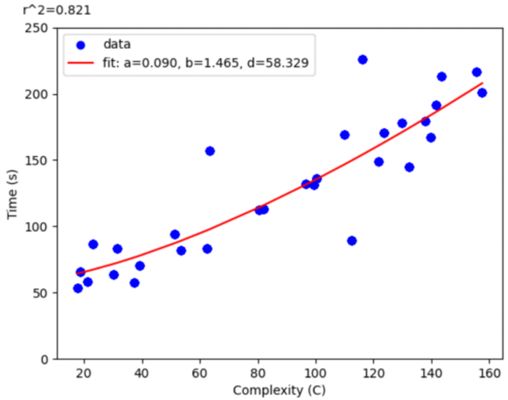
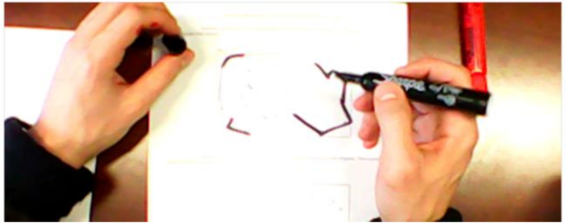
Hypothesis

We expect these results

- Effort E (time) increases super-linearly with Complexity C=f(N,M,H)
- The more effort a team spends the better the solution will be (P) – smaller distance
- There are diminishing returns for P with increasing C (same N)
- As E increases, C can be reduced for the same P





Bortot Hopker, Ricardo. "A Canonical Experiment on System Complexity Metric and Its Impact on Engineering Management." SM diss., Massachusetts Institute of Technology, 2022.

Results are expected to be stochastic given the inherent variability of human performance

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Let’s connect.

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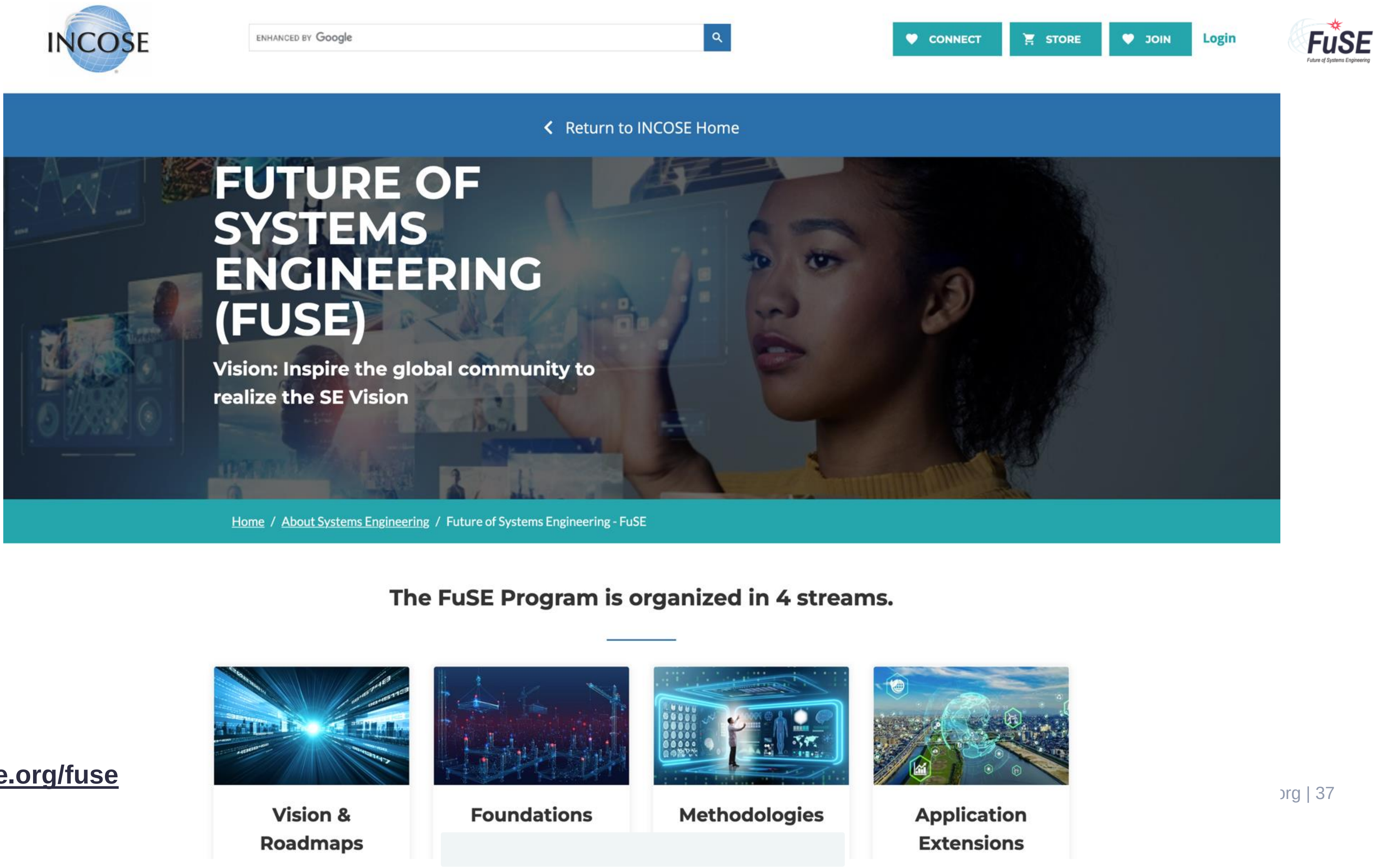

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