Future research requirements for the Systems Engineering discipline:

Lessons learned from the autonomous solar boat racing project of students of the University of Tokyo and the KTH Royal Institute of Technology.

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Presentation Overview

- US National Academy of Engineering - Grand Challenges
- Current situation of Systems Engineering and Systems Development
- SolarBoat 2014
  - Project overview
  - Race analysis
  - Development problems
  - Proposed improvements
- How Systems Engineering should be improved
  - Latest thinking from literature
  - What questions should researchers be asking

US National Academy of Engineering, “Grand Challenges - Engineering Challenges,” 2012

- Make solar energy economical
- Provide energy from fusion
- Develop carbon sequestration methods
- Manage the nitrogen cycle
- Provide access to clean water
- Restore and improve urban infrastructure
- Advance health informatics
- Engineer better medicines
- Reverse-engineer the brain
- Prevent nuclear terror
- Secure cyberspace
- Enhance virtual reality
- Advance personalized learning
- Engineer the tools of scientific discovery

All require complex systems development

Systems Engineering and Systems Development

Definitions from the International Council of Systems Engineering (INCOSE)

- **Systems Engineering** is an **interdisciplinary approach and means** to enable the **realization of successful systems**. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while **considering the complete problem**: Operations, Cost & Schedule, Performance, Training & Support, Test, Disposal and Manufacturing.
- **Systems Engineering integrates all the disciplines and specialty groups** into a team effort forming a **structured development process that proceeds from concept to production to operation**. Systems Engineering considers **both the business and the technical needs** of all customers with the goal of providing a quality product that meets the user needs.

INCOSE, "INCOSE - What is System Engineering?," 14-Jun-2004.

Criticism of what Systems Engineering has become

- Griffin, M.D., 2010. *How do we fix System Engineering?* Presented at the 61st Annual International Congress, Prague, Czech Republic.
  - 2005-2009:
    - Head of NASA
  - Now:
    - Professor of Mechanical and Aerospace Engineering University of Alabama
  - Quite a frank reflection on the state of the industry

Wikipedia

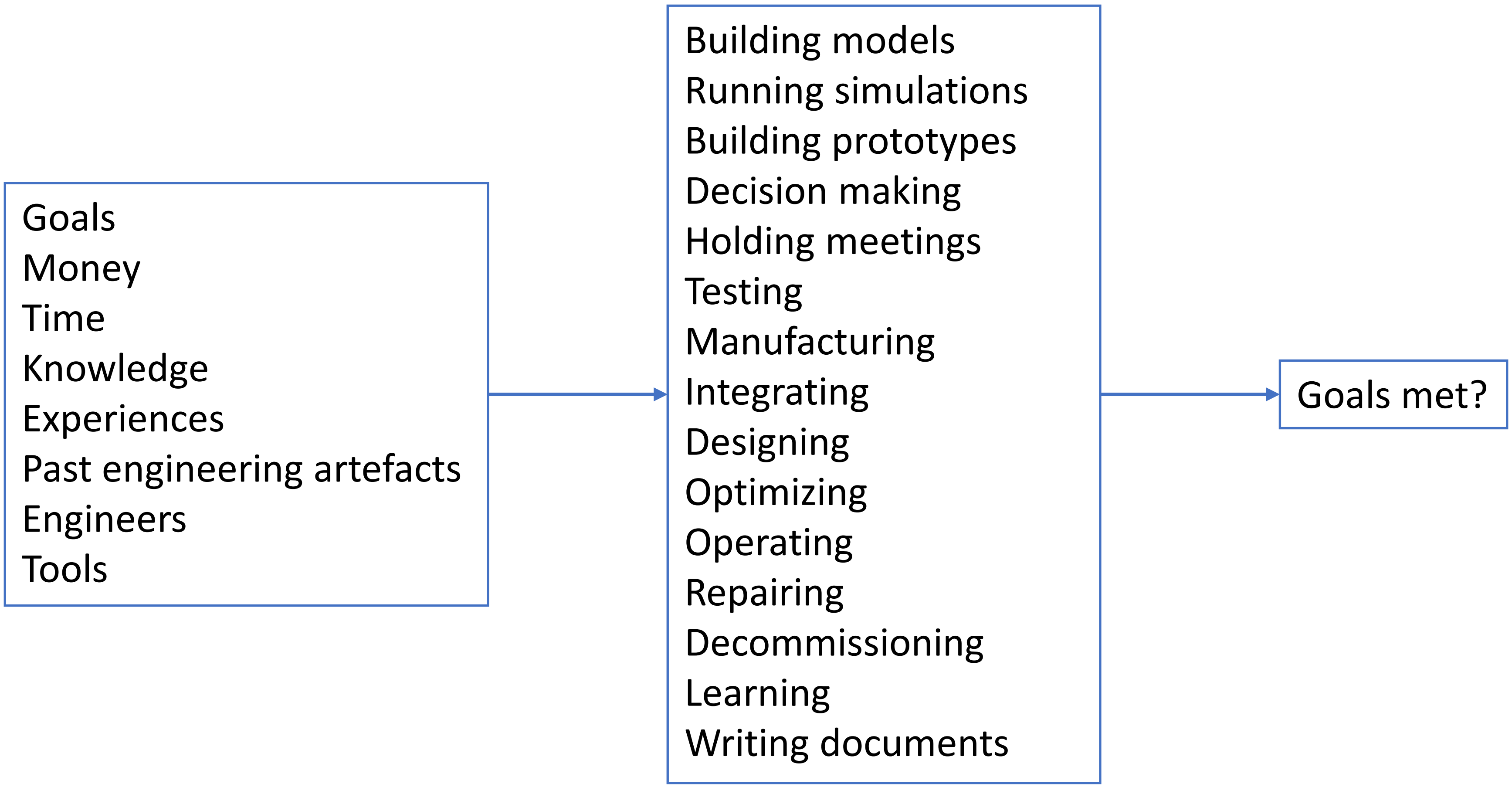
Current issues with Systems Engineering (Griffin 2010)

- Systems Engineering has become process heavy:
  - Expensive
  - Inefficient
  - Un scalable
  - Often ineffective
  - Document creation and modification driven
    - Not systems creation
  - **<u>Follow the process rather than thinking about the purpose and suitability of the design</u>**
  - When failure occurs more process is added

Current issues with Systems Engineering (W. N. Felder and P. Collopy 2012)

- “The current approach to systems engineering applies industrial revolution methods to information revolution problems”
- “Industrial Revolution giants such as Henry Gantt built the tools … to manage the chaos of their time… Two centuries later, we apply their best ideas to our quite different problems.”

Systems development



SolarBoat 2014

Why investigate a student run engineering project?

- Such projects provide opportunity for alternative methods to be explored / developed without an individual corporation taking risk upon its own projects
- Students today will be the future developers of complex systems in industry. What they learn on such projects for better or worse **will be carried into industry** and used

SolarBoat project requirements

- Lake Biwa (Japan) competition rules:
  - Max 2m^2 of solar panels
  - Max 20Wh of lead based batteries
  - Complete the 20km course autonomously
  - Possibility to repair boat on route

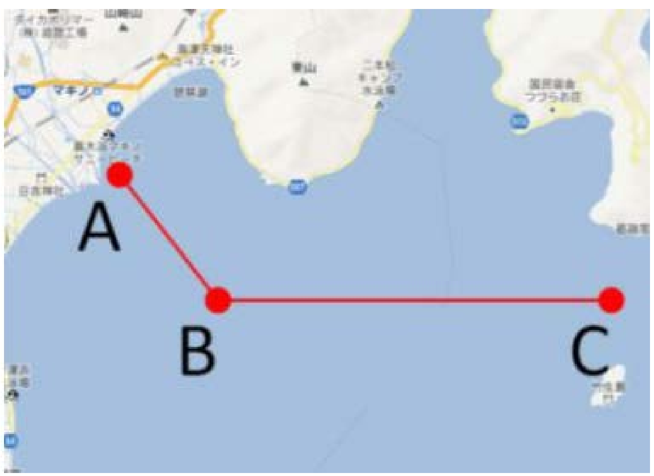


Image from: Frithiof et al. 2013

SolarBoat 2014 schedule and resources

	# of members	Location
UoT	12	Japan
KTH	9	Sweden

	Jan-14	Feb-14	Mar-14	Apr-14	May-14	Jun-14	Jul-14	Aug-14	Sep-14	Oct-14	Nov-14	Dec-14
UoT hr/wk	0	0	0	4	4	4	10	Full time	0	0	0	0
KTH hr/wk	20	20	20	20	20	0	0	Full time	20	20	20	20

Racing
August 23-24

The UoT / KTH raced boats, August 2014

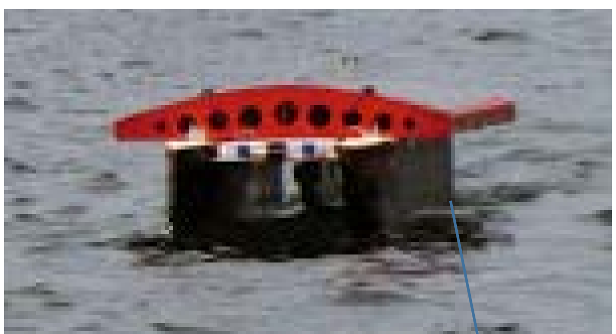
2014-A
Ranked 3rd in race

2014-B
Ranked joint 4th in race
Tail, side hulls and V-Foils brought from Sweden

Race competitors, August 2014

Ranked 1st in race

Ranked 2nd in race



Ranked joint 4th in race with 2014-B

Ranked 5th in race

2014-A & 2014-B race failures

- Water damage to electronics
- Lack of sufficient voltage to run electronics
- Lack of yaw control
  - Too weak servos
  - Too weak rudder connection structures
- Tail pitch control fin structural failure

- Both boats of very similar design failed in very similar ways

- It is recognised by both teams that these problems could have been diagnosed and repaired prior to the race with:
  - **<u>More real world testing prior to the race</u>**

Analysis of lack of testing

- Testing time was sacrificed due to the delay of the design being ready for manufacturing

	Apr-14	May-14	Jun-14	Jul-14	Aug-14
Activity	Design	Design	Design	Build	Build, test and race

- Starting the project was slow
- Project Manager, during the start-up period was not being provided information as to the activities of team members

- Despite the long "design" period:
  - Multiple components failed in the race
  - The complex craft was beaten by significantly simpler craft
  - The design needed further significant modifications (e.g. integration of a gearbox)

Exploring the design period Interviewed Tokyo and KTH team indicate:

- Goal definition:
  - Far off ambiguous objectives failed to get work done with sufficient time for testing
    - E.g. Max speed? Coolest boat? Lightest boat? Everyone learns what they want to learn?
  - Unrealistic requirements documents were written but not actively reviewed
- Resource management:
  - Skills gaps were not actively identified and plugged
  - Time was wasted by not clearly understanding the problem and past work
  - Project Manager was unclear as to the progress of the work
  - Resources available for the project were not clear
  - The level of collaboration between the Tokyo and KTH teams was not clear
- Engineering design:
  - Designs were completed in isolation, optimization was for small parts not completed systems
  - It was unclear as to how design parameters should be selected
  - Many knowledge gaps were only identified with testing in the real race
  - Technology was developed which was never needed or used

Summarizing the design stage

- Design stage problems are summarized as:
  - Uncertainty was not actively managed and used to drive decision making
    - Critical assumptions were not validated until racing
    - Unclear as to how to set parameters
  - Lack of communication between team members lead to the underutilization of resources
  - Students were attempting to optimize the boat design for multiple goals by way of individual components rather than creating a successful product lifecycle

- Improved design process should:
  - Enable the making of a large number of decisions under considerable uncertainty which lead to a product lifecycle which meets its goals

Reducing uncertainty and better **utilizing resources (1)**

- Goal definition:
  - Build realistic measurable goals which can steer decision making. Not complex lists of requirements
- Project management:
  - Resource management:
    - Time was spent trying to identify what was available to the team **->** Actively identify available resources early
    - The single Design-Build-Test sequence meant skills were not ready for the later stages of the project **->** Have all activities occur in parallel to upskill the team early
  - Metrics:
    - It was not explicit what was known and not known **->** Actively identify current uncertainty in assumptions being worked on
    - Team progress should be measured to reach goals not ability to follow a fixed plan
    - Analysis of the project for future improvements is aided by such an approach
  - Plan to change the plan

Reducing uncertainty and better **utilizing resources (2)**

- Engineering design:
  - Modelling:
    - Modelling was used on the project to some success. However it is not clear if it always represented good value **->** Use simple modelling for all systems and apply more detail if needed
      - Simple modelling can determine architecture suitability e.g. V-foil vs. C-foil / Direct drive vs. Gearbox
    - Define (and test) how data will be exchange between different systems early
  - Creating prototypes:
    - Only the single final boat was created in Tokyo, but a huge amount of learning came from it **->** Build more prototypes early in the project

August 2014 -> December 2014 KTH development

- KTH students were able to repair and modify based upon craft created in Japan by:
  - Adopting iterative scrum development to better serve the project
  - Rearranging the project team
  - Increasing the level of interaction among the team on a daily basis in their single project room

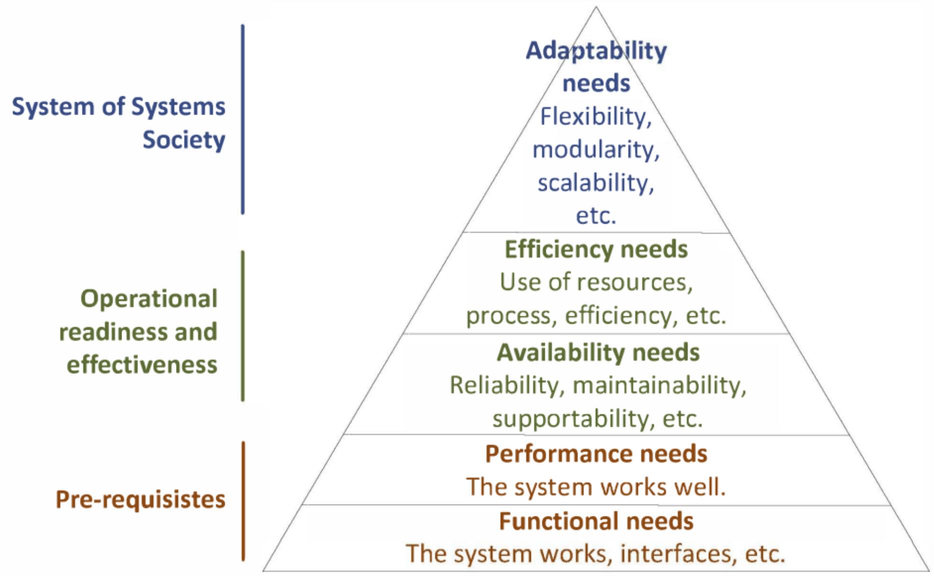
What now for Systems Engineering?

What Systems Engineering should be (Griffin 2010)

- Facilitation of the creation of an **elegant** design; i.e. a design which:
  1. Actually **works**:
     - As to what the customer is expecting
  2. Is **robust**:
     - Does not produce radical departures from expected behaviour with small changes to its operating input
  3. Is **efficient**:
     - Produces the desired result for what is thought to be a lesser expenditure of resources than competing alternatives
  4. Has minimal **unintended actions, side effects,** and **consequences**

Attempting to measure the elegance of an engineered system

- Elegance: "satisfaction of current and future functional, performance, availability, and efficiency needs without a major intervention of the owner."
- An Analogy to Maslow's Hierachy of Needs



A. Salado and R. Nilchiani 2013

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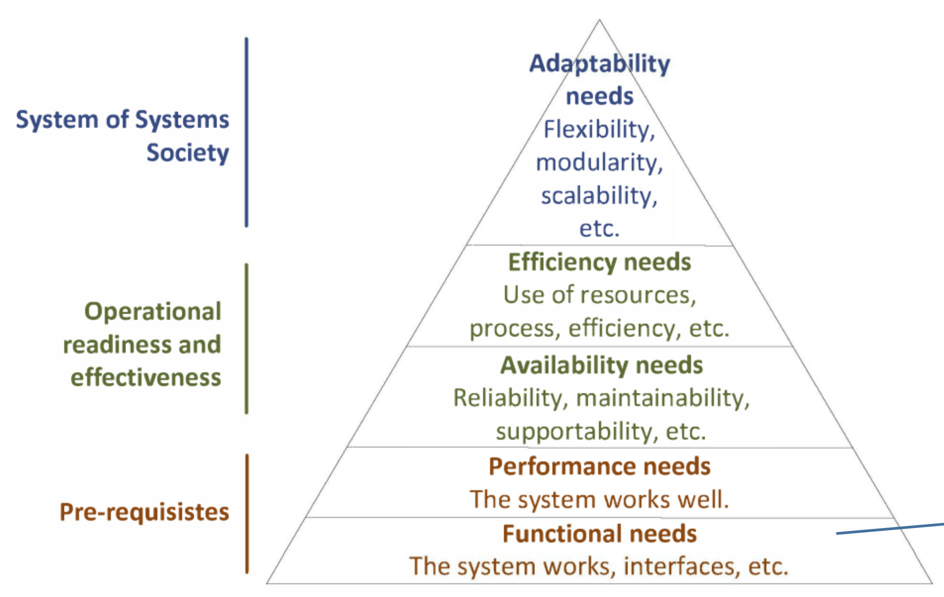


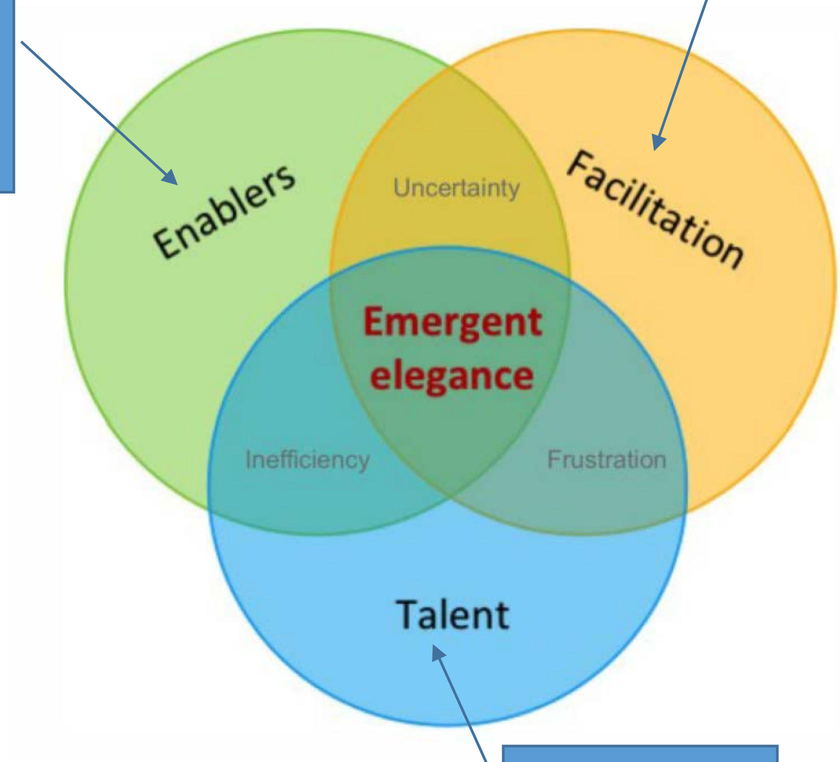
Boat had functional needs which were not met in the race

A. Salado and R. Nilchiani 2013

How can elegance emerge?

Inertia (corporations and individuals), contracts allowing innovation

Tools, methodologies and processes



Your people

Adapted from: A. Salado and R. Nilchiani 2013

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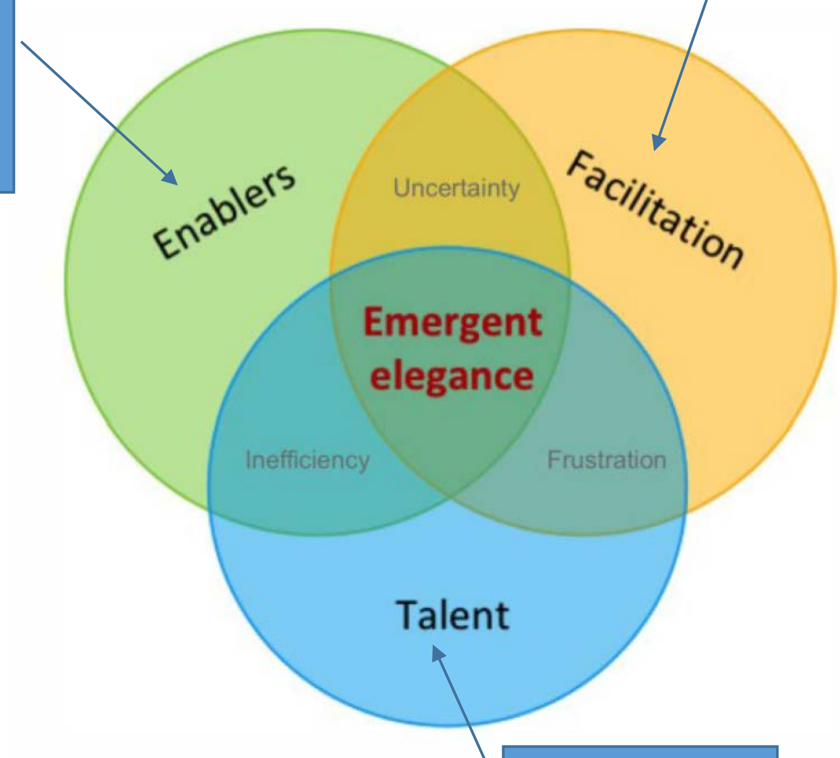

Your people

Salado 2013 reviewed many papers on adoption and found problems were to do with people:

- Awareness and knowledge
- Motivation
- Skills
- Acceptance and beliefs

Adapted from: A. Salado and R. Nilchiani 2013

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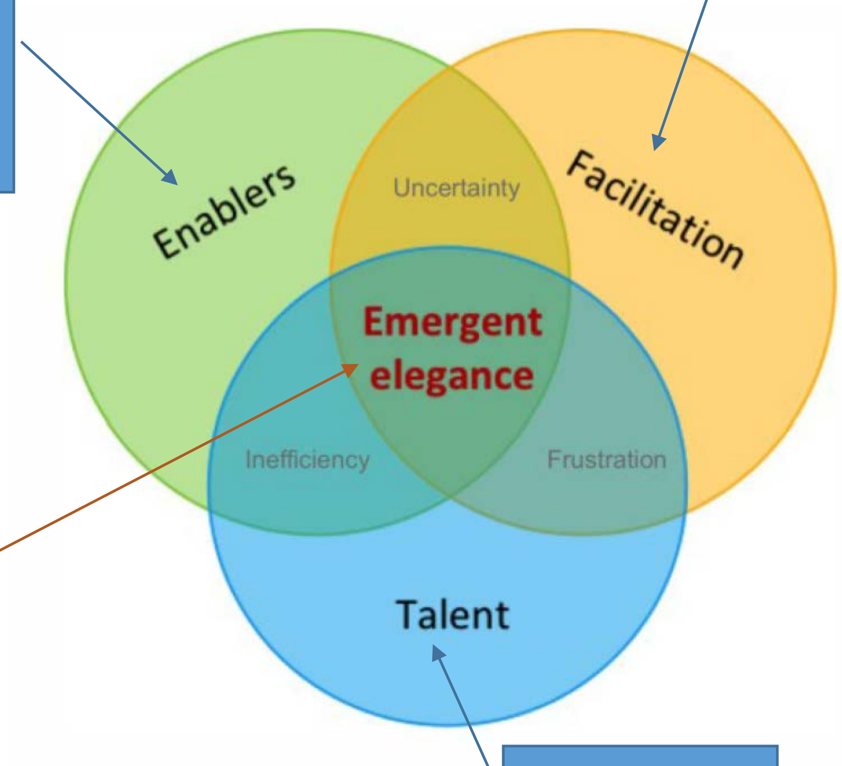

There is of course uncertainty to if this will occur

Your people

Adapted from: A. Salado and R. Nilchiani 2013

How to advance elegant design within Systems Engineering (Griffin 2010)

1. Academia to recognise Systems Engineering as a distinct discipline:
   - A research field worth pursuing
   - Train students in systems thinking, not just in how to use specific tools and methodologies
     - As in create ‘CFOs’ rather than ‘accountants’
2. Move away from fixed hard requirements:
   - Use optimization cost and reward functions
   - Requires legal innovation
3. Greater amount of study of human interactions in the creation of complex systems:
   - Train and implement best practice based on the research
4. Academia and Industry to collaborate on Systems Engineering:
   - Academia get involved with actual complex system design
   - Industry adopt latest best practice and feedback to academia improvements

Systems Engineering Grand Challenges (INCOSE 2014):

- A core body of systems engineering foundations is defined and taught consistently across academia.
- System complexity and associated risk is appreciated, characterized and managed.
- Systems engineering provides the analytical framework for designing and predicting the behaviour for trusted, resilient systems.
- Model-based systems engineering is a standard practice and is integrated with other modelling and simulation as well as digital enterprise functions.
- Systems engineering is recognized across industries, governments, and academia as providing significant value for innovation and competitiveness.
- Systems engineering is established as an indispensable discipline for technology assessment and policy analysis.
- Systems thinking is taught at all levels of education.

What questions does this mean researchers should be answering?

- How do we **maximise** the **effectives** and **minimize** the **cost** of **modelling** and **prototyping** of products to **reduce** the **uncertainty** of the completed products **operational behaviour** and **select design parameters**?
  - How do we **link common design data** such that items remain **consistent**?
  - How do we **quantify** the **cost / benefit** of said work?
- How do with gather **meaningful metrics** of the **project's progress** and **uncertainty** without burdening engineers with excessive bureaucracy?
  - How do we use **past development data** to **make decisions** on **future development** projects?
- How to we get a **new project** team **performing** as **fast** as possible on a project?
- What are the **effects** of engineers having to **participate** in **multiple projects simultaneously**?
- Where are currently used system development process going to **fail to scale** as systems become ever **more large and complex**?

But what does the context of systems development mean for research?

- Scalability:
  - Tokyo and KTH teams each had one student who understood the entire control and electrical system in detail. This will not scale to more complex projects
- Adoptability (as shown by Salado 2013):
  - Industry has considerable inertia to the adoption and experimentation with new tools and methodologies:
    - Prove the worth of developed tools -> Although it is unclear as to how possible this is
    - Ensure ease of adoption

Thoughts for engineering education

- Engineering is not just analysis using advanced mathematical tools to solve for set problems with known answers
  - It is making **real decisions** on **real projects** with **real deliverables**
- Projects such as SolarBoat enable students to apply real skills and gain real experience into how to deliver a real system
- Decision making, project management and psychology should not ignored as it has been demonstrated these are critical to successful systems development

Acknowledgements and thanks!

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http://solarboat.sys.t.u-tokyo.ac.jp/ http://www.kthnavaldesign.se/kth-solar-2014

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