The role of Systems Engineering in Innovation

Professor Michael Henshaw

Loughborough University

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Professor Michael Henshaw

- Group Leader: Engineering Systems of Systems
- BSc. (Hons), PhD – Applied Physics, U. of Hull, MBA – U. Lincoln & Humberside
- British Aerospace (later BAE Systems): 1989-2006
- Professor of Systems Engineering, Loughborough University: 2006 –
- Lead – Loughborough University Secure and Resilient Societies Research Challenge
- Programme Director: MSc in Systems Engineering
- Co-chair: Ieee Technical Committee on Systems of Systems Engineering

m.j.d.henshaw@lboro.ac.uk

Systematic **or** Systemic

Systematic

Concerned with the detail of how a system's parts interact and are put together

F117 (wiki)

Ufimtsev paper

- Electromagnetics
- Aerodynamics
- Control
- Propulsion
- Etc.

Richard Trewthick's locomotive

- Thermodynamics
- Fuel
- Components
- **Network**, Etc.

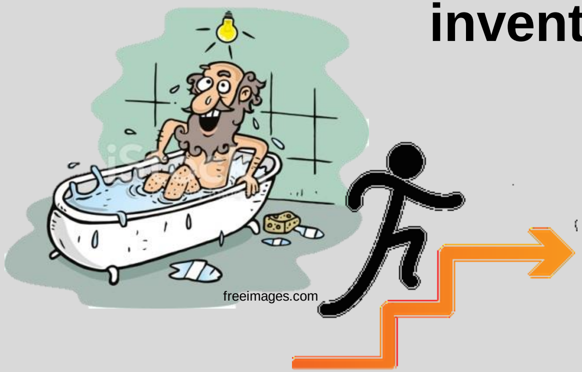
Systemic

Concerned with how a whole system behaves and interacts with its environment

Stealth Capability
B-2: undetectable by radar,
Flies < Mach 1
6,900 nm on single tank
40,000 lbs munitions

Transport capability

Innovation is more than invention



Commercial or societal benefit

Idea

Is there an Innovation Process?

"How do you systemise innovation?"

"You don't" replied Steve Jobs,

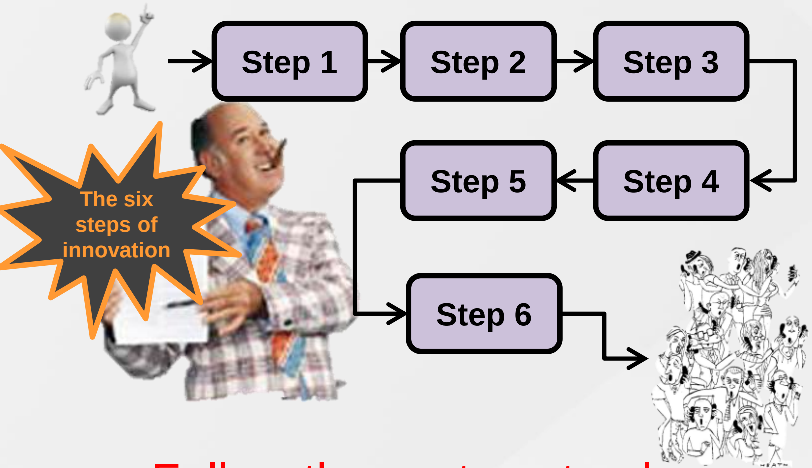
"You hire good people who will challenge each other every day to make the best products possible

	Incremental →		Radical
System level	New versions of motor car, aeroplane	New generation of MP3 and download vs. CD	Steam power, ICT 'revolution' Bio-technology
Component level	Improvements to components	New components for existing systems	Advanced materials to improve component performance
	Doing what we do better	New to the enterprise	New to the world

Dimensions of Innovation according to Tidd, Bessant, and Pavitt, 2005

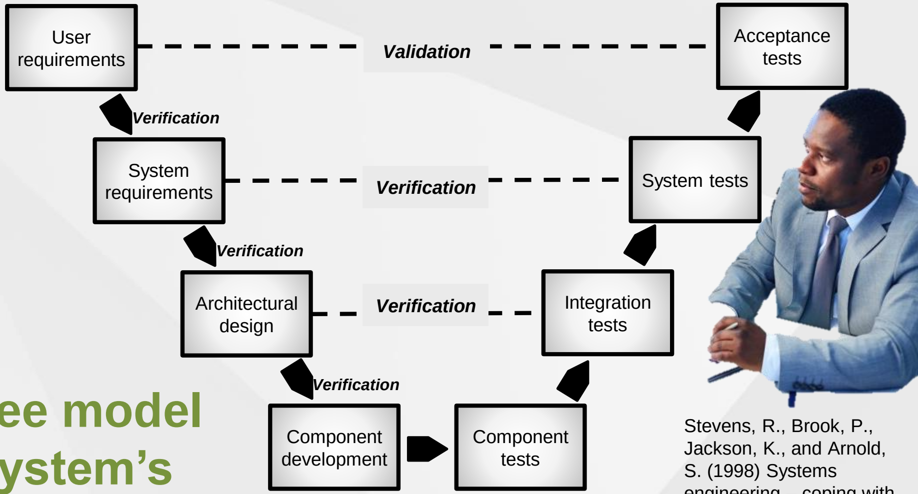
What do we mean by Systematic Innovation?

Systematic Innovation



Follow these steps to always achieve innovation success

"Systematic as an enabler of innovation"



The Vee model of a System's Development lifecycle

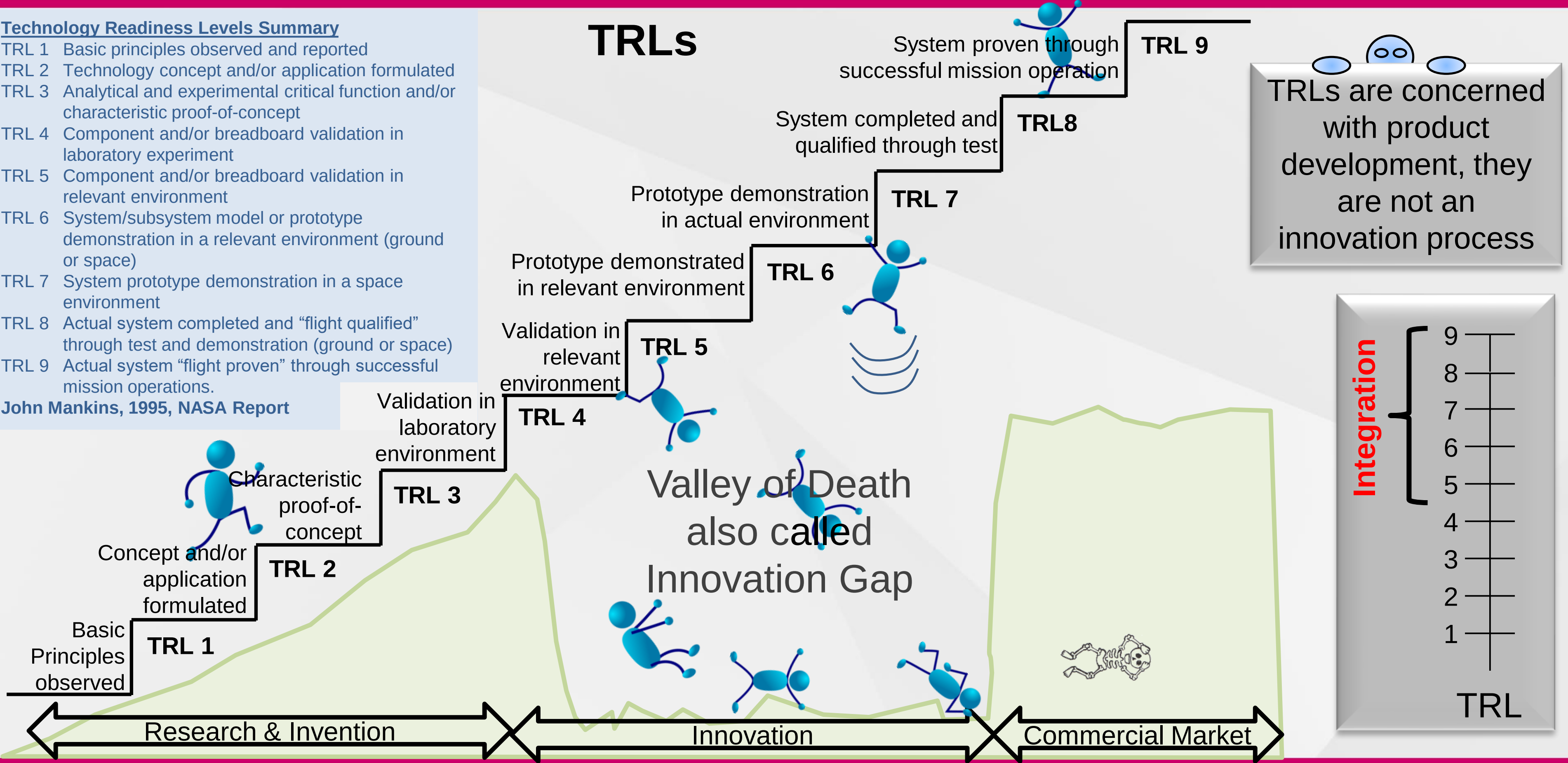
Stevens, R., Brook, P., Jackson, K., and Arnold, S. (1998) Systems engineering – coping with complexity, pg. 8, Prentice Hall, Europe

TRLs

Technology Readiness Levels Summary

TRL 1 Basic principles observed and reported
TRL 2 Technology concept and/or application formulated
TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4 Component and/or breadboard validation in laboratory experiment
TRL 5 Component and/or breadboard validation in relevant environment
TRL 6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7 System prototype demonstration in a space environment
TRL 8 Actual system completed and “flight qualified” through test and demonstration (ground or space)
TRL 9 Actual system “flight proven” through successful mission operations.

John Mankins, 1995, NASA Report



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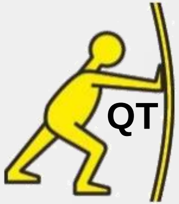
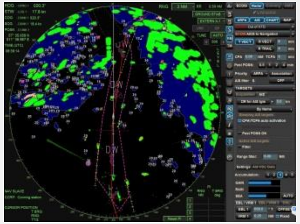
What customers want

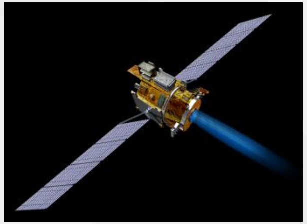
- Practical devices
  - Room temperature operation
  - Robustness
  - Size and weight
  - Scalability

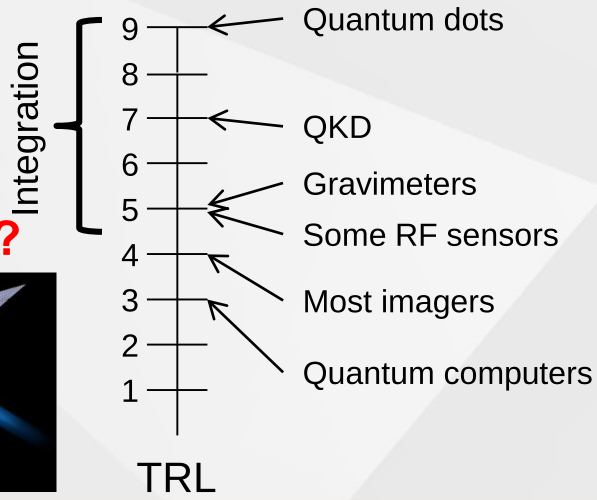
The Eureka moment is not the sudden emergence of an idea, but rather fitting the last piece of a jigsaw that shows the inventor how a change may be achieved.

Does the customer care if it's quantum?









Iconic Example of Innovation

How the Wright Brothers Exemplified Systems Engineering(1)

Based on Jakab, P.L., 1990, Visions of a Flying Machine – the Wright Brothers and the Process of Invention, Smithsonian Books.

- Conducted literature review
  - Contacted the Smithsonian and Chanute to assemble information, then learned what worked but also what didn't work
- Effective Decision Making
  - Used family court to resolve dispute. Effective teamwork allowed disagreements but always resolved in a positive manner
- Holistic thinking
  - conceived the aeroplane as a whole system – control/stability, aerodynamics, propulsion, structure
- Understand the problem
  - first to recognise the control/stability problem properly
  - Control/stability – use of foreplane (different angle of attack) to restore stable flight condition rather than relying on human control (like Lielenthal)
- Include humans/users in the system
  - understood the need to learn to fly before attempting the first flight (powered) by glider practise
- Knowledge of essential science
  - knew relevant laws of physics to make appropriate mathematical modelling. E.g. for sizing the vehicle.
- Visual thinking/analysis
  - could picture the system in its operation (forces, airflow, etc.) – note the movement of centre of pressure with curved surface. Also prone pilot to reduce drag

How the Wright Brothers Exemplified Systems Engineering(2)

- Synergistic thinking
  - bicycle knowledge of balance and user interaction assisted understanding; also cardboard box for understanding wing warping.
- Practical
  - understanding of bicycle building enabled them to be good at making machines to appropriate quality.
- Experimentation
  - Determined the most efficient aerofoil.
- Manufacturability
  - built glider in modular parts for easy construction onsite (also concerns logistics of moving vehicle to test site)
- Prototyping
  - use of kites to understand forces and behaviours.
- Documentation
  - kept log books and recorded information – though some was recorded afterwards and not all records are clear.
- Critical thinkers
  - tested the theory for force due to flow; corrected Smeaton coefficient (long believed to be correct at 0.005) and found accurate value of 0.0033.
- Re-used appropriate data
  - Leilenthal's data sheets for aerofoil forces.

First flight: Kitty Hawk, North Carolina; December 17, 1903

http://archive.org/details/WrightBrothersFirstFlight

What is Systems Engineering?

And why do we do it?

An Engineered System…

Satisfies a **Need** — *Useful and usable power*

Has an **Operational Purpose** — *To generate electricity*

Has a **Functional Purpose** — *To convert the wind's kinetic energy into electricity*

Actually the wind’s kinetic energy is first converted into rotary mechanical energy and then into electricity

An Engineered System…

Has a **Lifecycle**

Design
Build
Operate
Retire

Wind turbine lifecycle, as viewed by Kilmac (2014)
http://www.kilmac.co.uk/kilmac-energy/Wind+Turbine+Life+Cycle/

Initial gate

Main gate

Concept → Assess-ment → Demon-stration → Manuf-acture → In-service → Dispo-sal

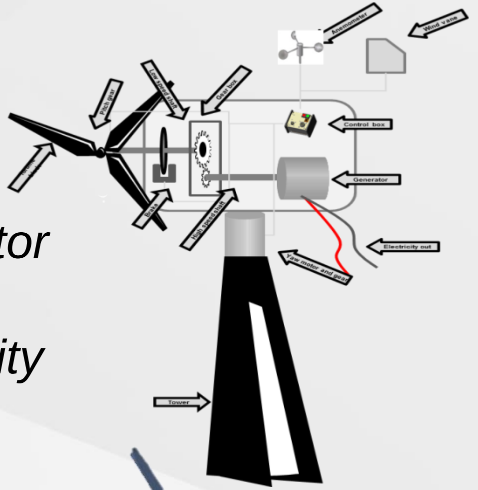
An Engineered System…

Is composed of **Subsystems and Related Components**

Is composed of a **Combination of Resources**

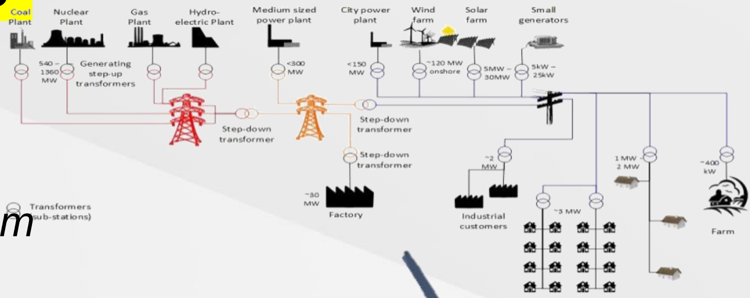
Support structures (tower, nacelle), rotor blades, gearbox, control system, utility box (for energy conversion),

Steel, fibreglass, copper, aluminium, plastic foam, etc. … *wind*



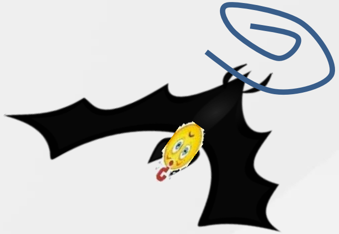
An Engineered System…

Exists within a **Hierarchy of Systems**



Integrated into a wider electricity distribution system (grid)

Is embedded in the **Natural World**



Natural World Interactions: Principal interaction is with the wind; Other interactions include bird kill, disorientation of bats, aesthetic impact.

ISO 15288:2015 Systems and Software: Systems Lifecycle Standard

Agreement Processes
- Acquisition
- Supply

Organizational Project-Enabling Processes
- Life Cycle Model Mgt
- Infrastructure Mgt
- Project Portfolio Mgt
- Human Resource Mgt
- Quality Mgt
- Knowledge Mgt

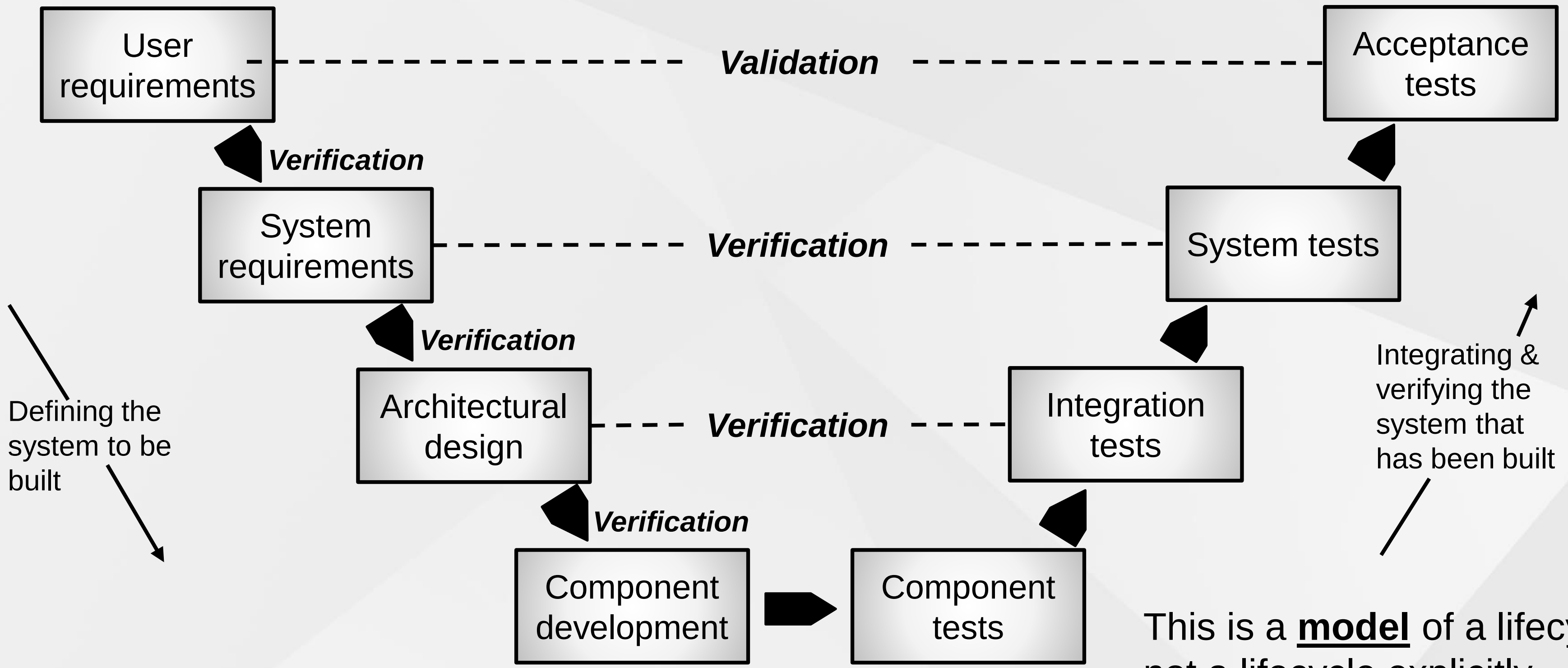
Technical Management Processes
- Project Planning
- Project Assessment & Control
- Decision Mgt
- Risk Mgt
- Configuration Mgt
- Information Mgt
- Measurement
- Quality Assurance

Technical Processes
- Business or Mission Analysis
- Stakeholder Needs & Req. Definition
- Requirements Analysis
- Architecture Design
- Design Definition
- System Analysis
- Implementation
- Integration
- Verification
- Transition
- Validation
- Operation
- Maintenance
- Disposal

System Life Cycle Processes

Based on BS ISO/IEC/IEEE 15288: 2015 figure 4

The Vee Model (after Stevens, et. al., 1998)

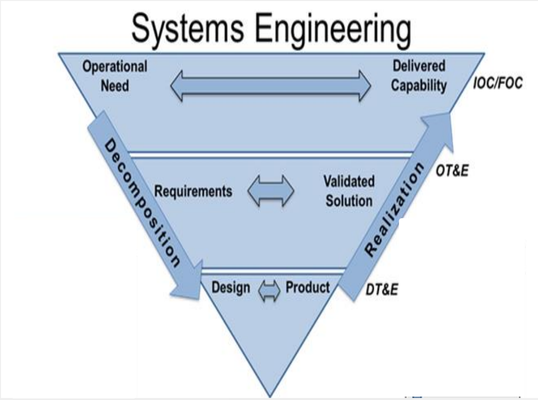


This is a **model** of a lifecycle not a lifecycle explicitly

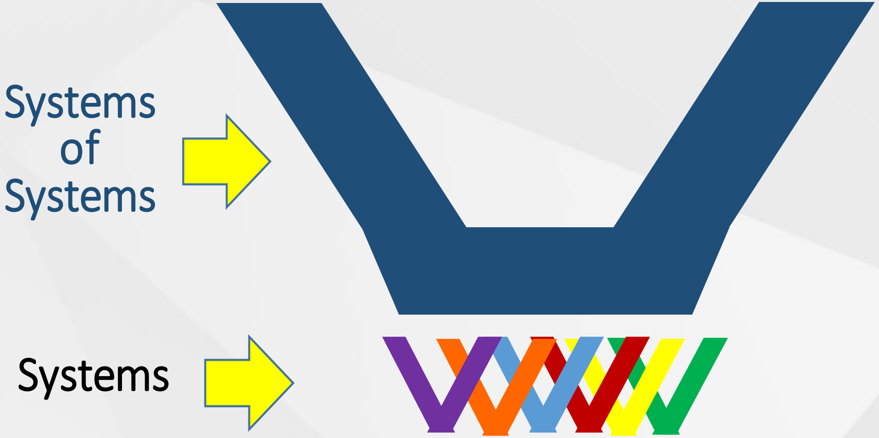
Slide from Judith Dahmann, Mitre Corp

SoSE and the SE ‘V’ Model

System



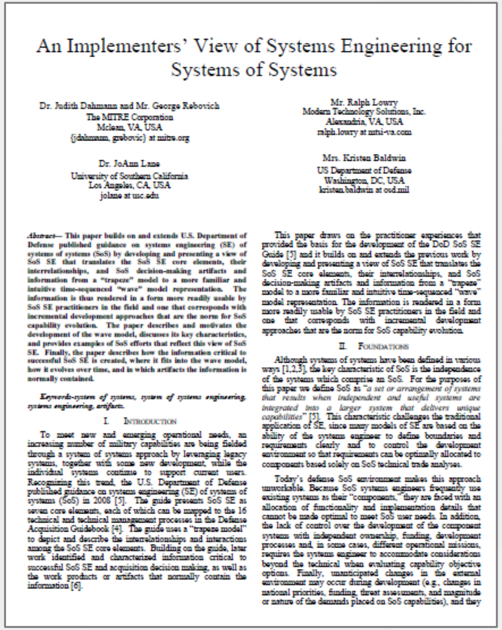
SoS



An SoS is a system (systemic statement) which results from the coupling of a number of constituent systems at some point in their life cycles (systematic statement).

Peter Brook, 2016

Implementers View of SoS SE: SoS Wave Model



An Implementers' View of Systems Engineering for Systems of Systems

Dr. Judith Dahmann and Mr. George Rebovich
The MITRE Corporation
Mclean, VA, USA
{jdahmann, grebovic} at mitre.org

Mr. Ralph Lowry
Modern Technology Solutions, Inc.
Alexandria, VA, USA
ralph.lowry at mtsi-va.com

Dr. JoAnn Lane
University of Southern California
Los Angeles, CA, USA
jolane at usc.edu

Mrs. Kristen Baldwin
US Department of Defense
Washington, DC, USA
kristen.baldwin at osd.mil

***Abstract*— This paper builds on and extends U.S. Department of Defense published guidance on systems engineering (SE) of systems of systems (SoS) by developing and presenting a view of SoS SE that translates the SoS SE core elements, their interrelationships, and SoS decision-making artifacts and information from a "trapeze" model to a more familiar and intuitive time-sequenced "wave" model representation. The information is thus rendered in a form more readily usable by SoS SE practitioners in the field and one that corresponds with incremental development approaches that are the norm for SoS capability evolution. The paper describes and motivates the development of the wave model, discusses its key characteristics, and provides examples of SoS efforts that reflect this view of SoS SE. Finally, the paper describes how the information critical to successful SoS SE is created, where it fits into the wave model, how it evolves over time, and in which artifacts the information is normally contained.**

Keywords-system of systems, system of systems engineering, systems engineering, artifacts.

I. INTRODUCTION

To meet new and emerging operational needs, an increasing number of military capabilities are being fielded through a system of systems approach by leveraging legacy systems, together with some new development, while the individual systems continue to support current users. Recognizing this trend, the U.S. Department of Defense published guidance on systems engineering (SE) of systems of systems (SoS) in 2008 [5]. The guide presents SoS SE as seven core elements, each of which can be mapped to the 16 technical and technical management processes in the Defense Acquisition Guidebook [4]. The guide uses a "trapeze model" to depict and describe the interrelationships and interactions among the SoS SE core elements. Building on the guide, later work identified and characterized information critical to successful SoS SE and acquisition decision making, as well as the work products or artifacts that normally contain the information [6].

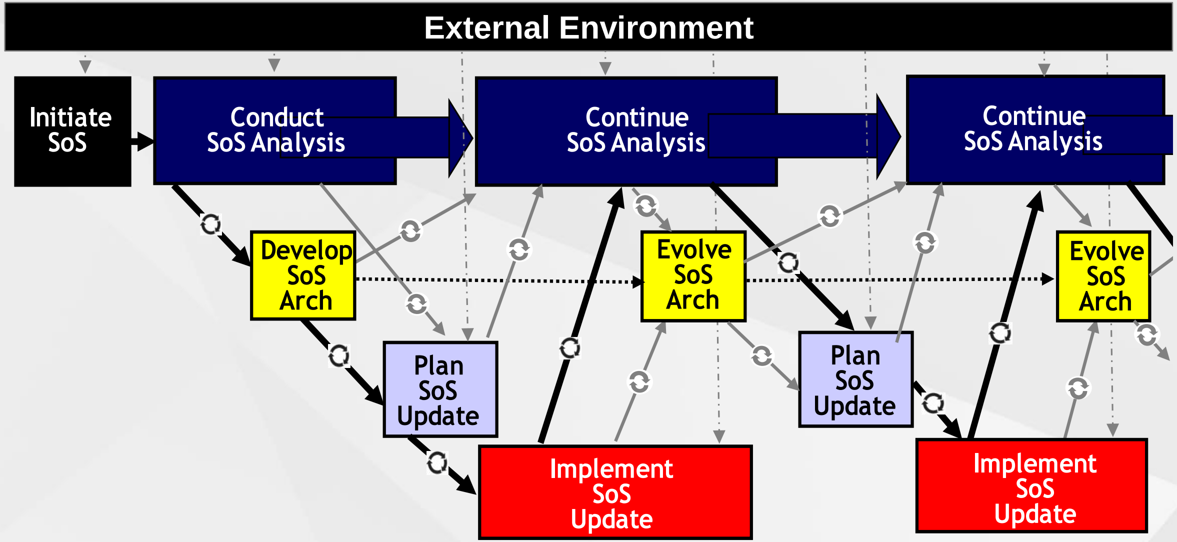
This paper draws on the practitioner experiences that provided the basis for the development of the DoD SoS SE Guide [5] and it builds on and extends the previous work by developing and presenting a view of SoS SE that translates the SoS SE core elements, their interrelationships, and SoS decision-making artifacts and information from a "trapeze" model to a more familiar and intuitive time-sequenced "wave" model representation. The information is rendered in a form more readily usable by SoS SE practitioners in the field and one that corresponds with incremental development approaches that are the norm for SoS capability evolution.

II. FOUNDATIONS

Although systems of systems have been defined in various ways [1,2,3], the key characteristic of SoS is the independence of the systems which comprise an SoS. For the purposes of this paper we define SoS as "*a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities*" [5]. This characteristic challenges the traditional application of SE, since many models of SE are based on the ability of the systems engineer to define boundaries and requirements clearly and to control the development environment so that requirements can be optimally allocated to components based solely on SoS technical trade analyses.

Today's defense SoS environment makes this approach unworkable. Because SoS systems engineers frequently use existing systems as their "components," they are faced with an allocation of functionality and implementation details that cannot be made optimal to meet SoS user needs. In addition, the lack of control over the development of the component systems with independent ownership, funding, development processes and, in some cases, different operational missions, requires the systems engineer to accommodate considerations beyond the technical when evaluating capability objective options. Finally, unanticipated changes in the external environment may occur during development (e.g., changes in national priorities, funding, threat assessments, and magnitude or nature of the demands placed on SoS capabilities), and they

J. Dahmann, G. Rebovich, J. Lane, R. Lowry and K. Baldwin, "An implementers' view of systems engineering for systems of systems," 2011 IEEE International Systems Conference, Montreal, QC, 2011, pp. 212-217.



Representation that corresponds with incremental development approaches that are the norm for SoS capability evolution

Concept of Wave Planning was developed by Dr David Dombkins
See "Complex Project Management" Booksurge Publishing, South Carolina: 2007.

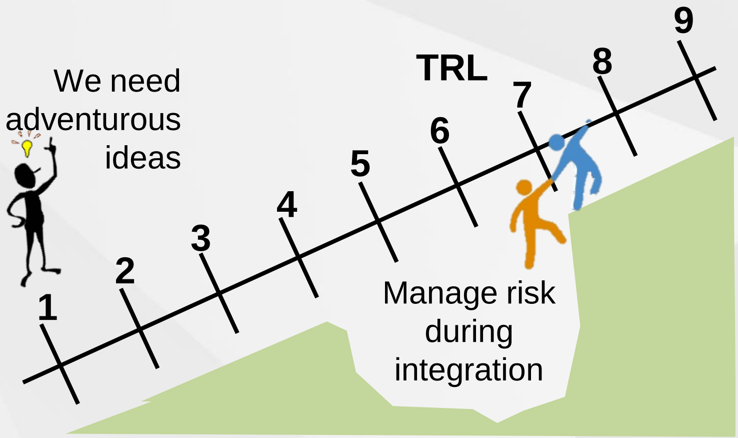
Slide from J Dahmann, Mitre Corp.

Systems Engineering reduces Risk, Cost and Time

Innovation is not an unalloyed good — almost all innovations can cause both benefit and harm. Because of this, discussion of innovation has become almost inseparable from discussion of risk.

Sir Mark Walpole, 2014 (Chief Scientific Advisor)

Surely, risk aversion stifles innovation adventure



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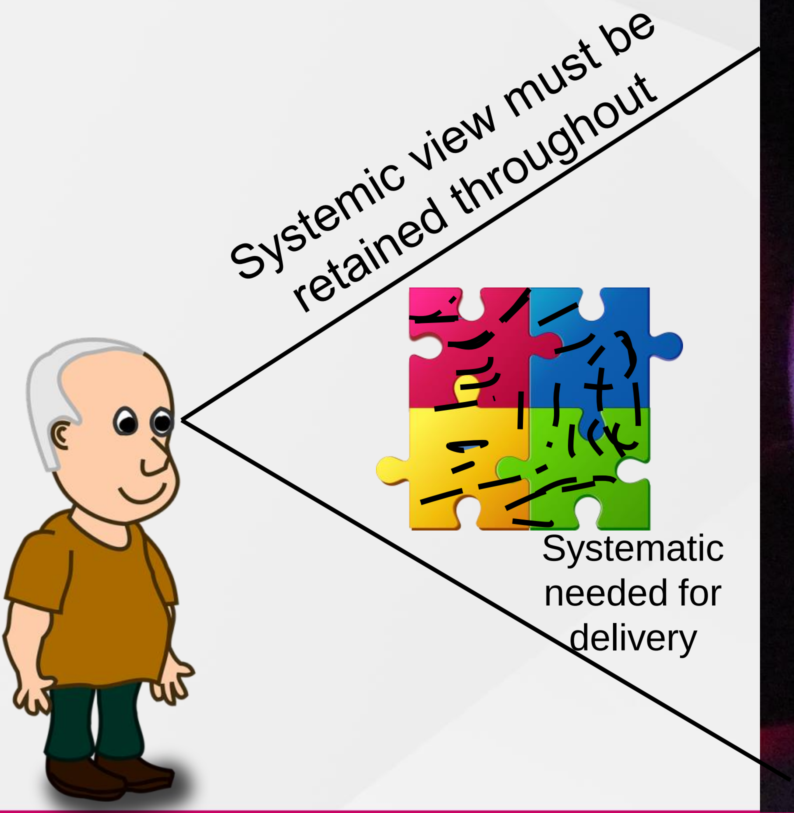
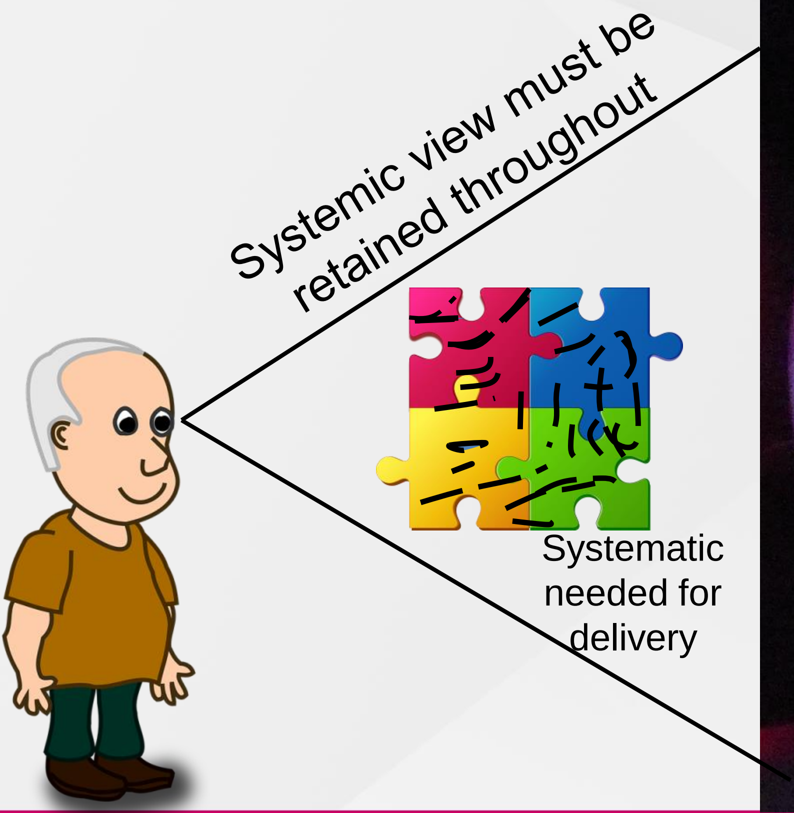
Some concluding remarks

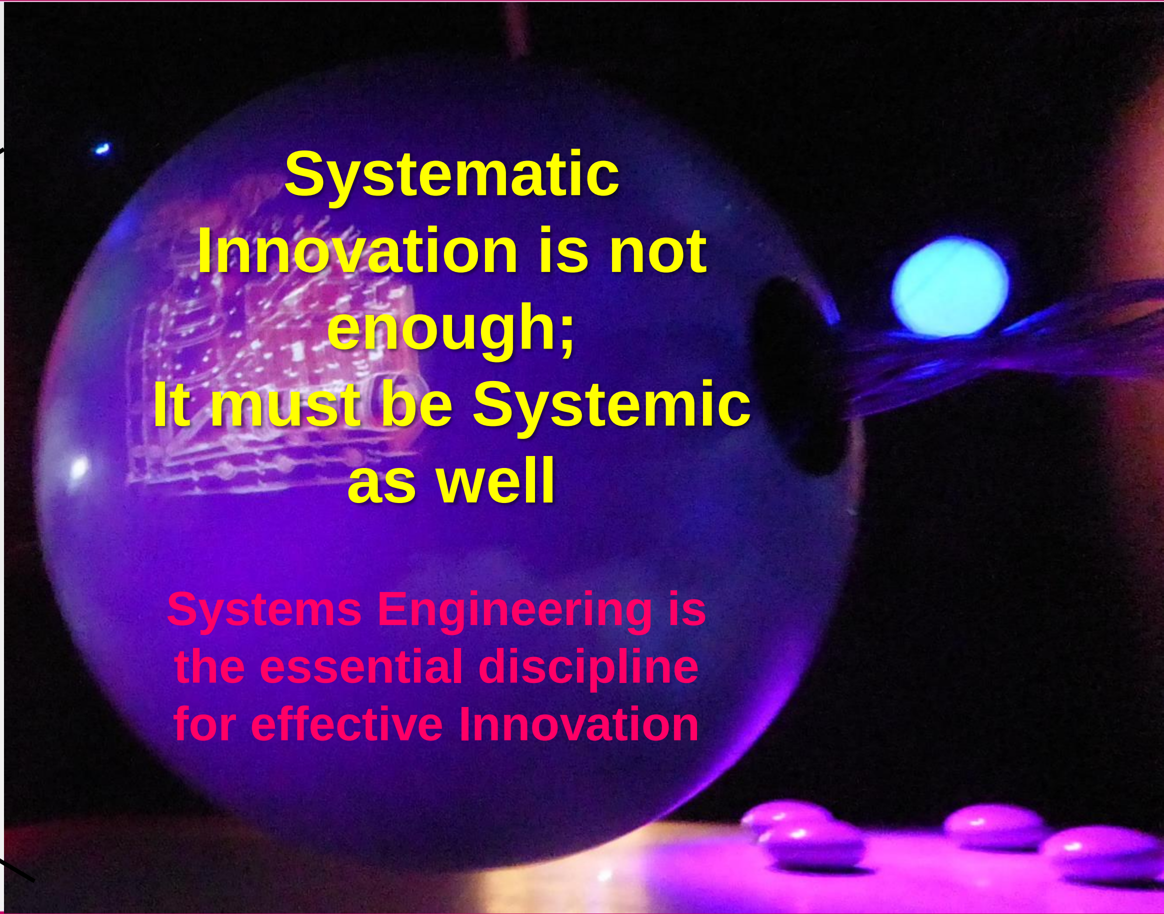
- Ideas are not enough; the ability to turn them into real systems is essential
- Systems Engineering enables management of risk through the integration phase (TRL valley of death)
- Systems of Systems Engineering must be developed; opportunities for innovation during reconfiguration of systems
- Better understanding of risk is required
  - Fail early and cheaply
- Systems Engineering is applicable to complex systems

Successful innovation management is not about doing one thing well, but rather organising and managing a variety of different elements in an integrated and strategically coherent fashion

Bessant (2003)


Systemic view must be retained throughout
Systematic needed for delivery





Systematic Innovation is not enough;
It must be Systemic as well

Systems Engineering is the essential discipline for effective Innovation