FuSE Project:
Foundations for Systems Engineering (F4SE)

David Rousseau   Ron Luman   Paul Schreinemakers   James Martin

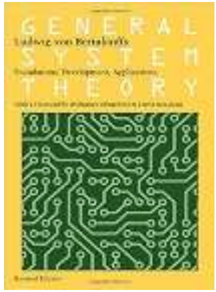
Foundations for Systems Engineering (F4SE)

History and Focus

Section Lead: James Martin

SE’s need for Theoretical Foundations

- **Von Bertalanffy:** “[Given scale-free and composition independent patterns in natural systems] it seems legitimate to ask for a theory, not of systems of a more or less special kind, but of universal principles applying to systems in general”



L. von Bertlanffy

General System Theory (1956, 1968)

- **NSF:** “Rising complexity has eroded SEs’ ability to predict the outcome of design decisions… …SE methods are based on heuristics, and has no recognized theoretical foundation”

INCOSE/NSF/SERC Workshop Nov ‘14

- **INCOSE:** “It is therefore important to develop a scientific foundation that helps us to understand the whole rather than just the parts, that focuses on the relationships among the parts and the emergent properties of the whole...
Systems Science seeks to provide a common vocabulary (ontology), and general principles explaining the nature of complex systems”

INCOSE Vision 2025, publ. 2014

History

- Future of SE (FuSE) Initiative:
  - FuSE kicked off at INCOSE Workshop (IW) in Jan 2018
  - 33 members from across industry, academia, government, societies
  - 3 meetings per month, panel presentations at community events
  - Many projects [see presentation by Bill Miller]
- Foundations for SE (F4SE) project:
  - Spinout from FuSE, kicked off at INCOSE IW in Jan 2019
  - Core team:
    - David Rousseau (Dir Centre for Systems Philosophy, Past President ISSS, Visiting Fellow Univ. of Hull Centre for Systems Studies)
    - Ron Luman (Chief of Staff, Johns Hopkins University (JHU) Applied Physics Lab (APL), Program Chair for SE in the JHU Whiting School of Engineering)
    - Paul Schreinemakers (Dir INCOSE EMEA Sector, past Tech Dir INCOSE)
    - James Martin (Chair INCOSE SSWG, Principal Engineer at The Aerospace Corporation)

Founding Charter v1 Jan 2019

Title: Foundations for Systems Engineering
(F4SE, pronounced "fore-see")
(a FuSE project addressing INCOSE Vision 2025 pp. 40-41)

Owner: David Rousseau
Core Team:
David Rousseau, Ron Luman, Paul Schreinemakers, James Martin

What will good look when we have used F4SE to deliver systems?

1. Systems engineering will academically be on a par with other engineering disciplines.
2. SE processes are consistent with an established scientific general theory of systems (GTS/GST) and its specialized extensions.
3. An actionable scientific general systems theory is used to deliver tangible value.
4. Systems thinking is a standard practice for problem structuring and conceptualization, and is based on a scientific theory.

What is stopping us from doing this now?

1. SE is not theoretical enough for the academic community to take it seriously.
2. No critical mass of potential researchers/contributors in academia and INCOSE.
3. No adequate materials and theories to help us defend the SE brand against criticism of processism and lack of rigor.
4. The struggle to be relevant in practice has squeezed out interest in developing the rigorous theoretical foundation.

What will good look like in 3 years?

1. We will be able to explain what SE is, how it works, how it can be used & how it adds value, via standard means, methods, and materials.
2. A systems engineering research institute associated with INCOSE will exist with strong alliance partners.
3. There will be solid research programmes yielding a scientific general theory of systems, and case studies and review studies that demonstrate value of systems engineering (SE) and systems thinking (ST).
4. SE and ST will be empowered by established connections with diverse academic disciplines beyond the physical sciences, such as philosophy, ethics, social sciences.

What will good look like in 10 years?

1. There will be a generally accepted and applied theory of system complexity, design elegance, and system potential.
2. Engineering systems and engineered systems are able to adapt to change in a timely manner, including context of use/mission.
3. We will have operationalized our ethical and humanistic commitment as part of our SE process and practice. That is, SE will have moved beyond purely technical decisions in a value-adding way.
4. SE is applied in many areas that ignore it today, because the general systems theory is transdisciplinary and hence SE will have compelling value across application domains and market sectors.

What will good look like in 12 months?

1. A draft prioritized research agenda and roadmap will exist.
2. Individuals and organizations that can contribute will have been identified and committed
3. Key resources have been identified: funding sources; advisors; collaborators willing to review and adopt and advocate; patrons

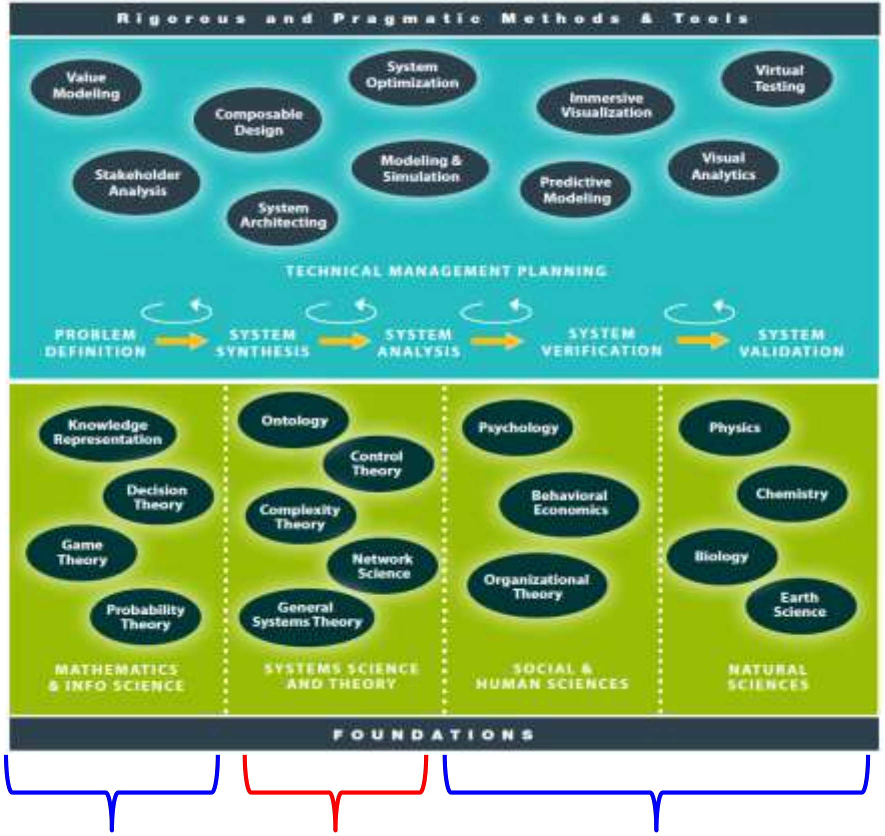
Action Plan

1.	Develop a summit and community outreach activities	James Martin	Oct 2019
2.	Develop an outline F4SE research vision for summit	David Rousseau	
3.	Develop an outline F4SE execution vision for summit	Ron Luman	
4.	Develop an outline F4SE impact vision for summit	Paul Schreinemakers	

The Problem Scenario

- Rising complexity is taxing SE's capability/relevance
  - Complexity is exploding, and SE is struggling to keep project and mission risks contained
  - This could get much worse very soon (4th Industrial Revolution)
  - SE methods have a large heuristic component, which is increasingly challenged by the rapid emergence of novel technologies and complex new scenarios
- Currently, SE's credibility is controversial
  - SE is not academically or industrially on a par with other engineering disciplines
  - SE is not theoretical enough for the academic community to take it seriously
  - No adequate materials and theories exist to help us defend the SE brand against criticism of processism and lack of rigor
  - Value proposition is not established – many academies and engineering organizations do not consider SE necessary nor distinctive as a discipline in its own right
- Currently, SE's theoretical foundations are incomplete and under-researched
  - SE does not a have an cohesive 'native' theoretical foundation to ground and unify its inherent methods and perspectives
  - No critical mass of potential researchers/contributors exist in academia and INCOSE to develop such a foundation
  - The struggle to be relevant in practice has squeezed out interest in developing the rigorous theoretical foundation
  - Foundational research has historically been very limited
- Upshot:
  - *SE must strengthen its foundations so that it can evolve its capability and increase its adoption*

What INCOSE is calling for that F4SE is responding to:



Other FuSE projects

F4SE

Other FuSE projects

- INCOSE Vision 2025 p.40-41
- SE is only weakly connected to its disciplinary foundations
- A Key foundational element is Systems Science:

Systems Theories Across Disciplines

Engineered systems increasingly derive their behavior from complex interactions between tightly coupled parts, covering multiple disciplines. It is therefore important to develop a scientific foundation that helps us to understand the whole rather than just the parts, that focuses on the relationships among the parts and the emergent properties of the whole. This reflects a shift in emphasis from reductionism to holism. Systems Science seeks to provide a common vocabulary (ontology), and general principles explaining the nature of complex systems.

… a scientific foundation…

… a shift in emphasis from reductionism to holism…

… a common vocabulary…

… general principles explaining the nature of complex systems.

Foundations for Systems Engineering (F4SE)

F4SE Summit

Full Day Event, 10 Oct 2019
Utrecht, Netherlands

Sponsorships from INCOSE EMEA Sector, INCOSE SSWG, ISSS

Agenda for the F4SE Summit Oct 10, 2019

1. Opening: welcome, logistics and ground rules
2. Overview of history and focus
3. Identify and prioritise foundational research questions and projects
4. Develop options and plans for executing the research projects
5. Develop options and plans for ensuring impact
6. Next Steps

Attendees

- Jon Wade
- Hillary Sillitto
- Bill Schindel
- Paul Schreinemakers
- David Rousseau
- Swami Natarajan
- Bill Miller
- Tom McDermott
- James Martin
- Ron Luman
- Duncan Kemp
- Chuck Keating
- Gerard Hoeberigs
- Omar Hammami
- Richard Doornbos
- Paul Collopy
- Javier Calvo-Amodio
- Maarten Bonnema
- Julie Billingham

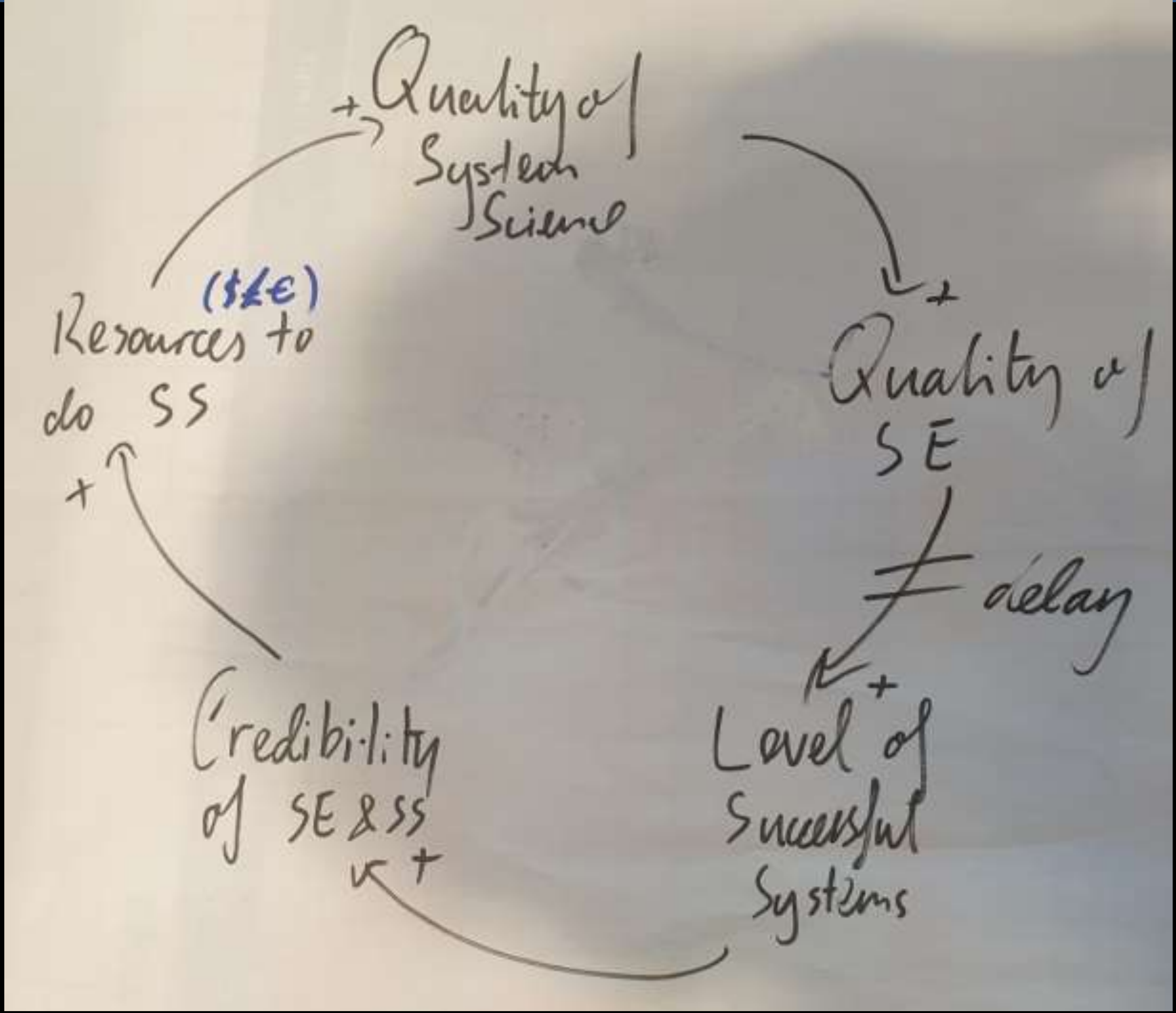

Session 3: Develop a Research Agenda

Research Priorities

Section Lead: David Rousseau

Where are the leverage points for the foundations of SE?

Duncan's Flywheel



Systems Science as a Foundation for SE

- SE's identity and distinctive capability derives from its use of Systems Science
- …but Systems Science itself has challenges: it is fragmented, uneven in maturity, non-standardized terminology, and has major theoretical gaps
- "Systems Science" is currently comprised of two well-developed "movements" that are somewhat disjunct:

"Complexity Science"

- ✓ Deals with phenomena **difficult to describe** but eventually **easy to explain**
- ✓ Highly **scientific** and widely used, but can be considered as largely **reductionistic**

"Systems Research"

- ✓ Deals with phenomena **easy to describe** but increasingly **difficult to explain**
- ✓ Largely **holistic** but not widely used and mostly grounded in **heuristics**




Comparing the Two "Movements" of Systems Science

Aspect	Complexity Science	Systems Research
Subject matter	Behaviourally complex (typically natural) systems (e.g. bird flocking, dissipative solitons, flow optimization networks)	Complex adaptive (typically social) problems (e.g. poverty, vandalism, crime, addiction, domestic abuse, inequality)
Example theories/ methods	Distributed Behaviour Theory, Fractal Theory, Automata Theory, Agent Based Modelling, Cybernetics, Game Theory, Network Theory, Hierarchy Theory, Computational Intelligence, Power Laws	Systems Dynamics, Causal Loop Diagramming, Systems Archetypes, Organizational Design, Second Order Cybernetics, Soft Systems Methodology, Boundary Critique, Action Research, Cynefin Framework
Research paradigm	Seemingly complex behaviour results from iteration of few simple rules executed by similar agents	Seemingly simple behaviours arise through the interaction of a diversity of feedbacks between a diversity of agents
Worldview	Reductionistic: system behaviour traces down to simpler sub-systemic parts and their few simple inter-relationships	Holistic: system behaviour traces outwards to complex relations with and between complex things in the context/environment (metasystem)
Key concern & Motivation	Explanation: find the simple underpinnings of the seemingly complex phenomenon. Seeking a route to more capable & effective technologies	Prediction: try to avoid making an intervention that will generate unintended consequences or make the problem different/worse. Seeking a route to improving system health and vitality
Maturity	Highly quantitative and mathematical, robust scientific theories, extensive empirical validation in experiments	Relatively qualitative, mostly based on heuristic principles and models, limited or no empirical validation in case studies
Applications	Specialised technological challenges, e.g. image compression, distribution networks, robotics, modularization, distributed autonomous systems	Management, Organizational Design, Problem Structuring, Stakeholder Analysis, Conflict Resolution, Mission Command/Leadership

Need & Opportunity for integration

- This duality and uneven maturity is increasingly problematic for SE: current SE practice employs CxSci and SysRes in a phase-partitioned way, but rising complexity, and the ongoing evolution of SoSs, make this increasingly untenable

- SE needs an integrated Systems Science that:
  - Enables a principled contextual shift in emphasis between holism and reductionism
  - Encompasses reductionistic and holistic models/methods as special cases under a wider conception of the nature of systems
  - Provides a principled basis for contextually selecting SE tools and methods

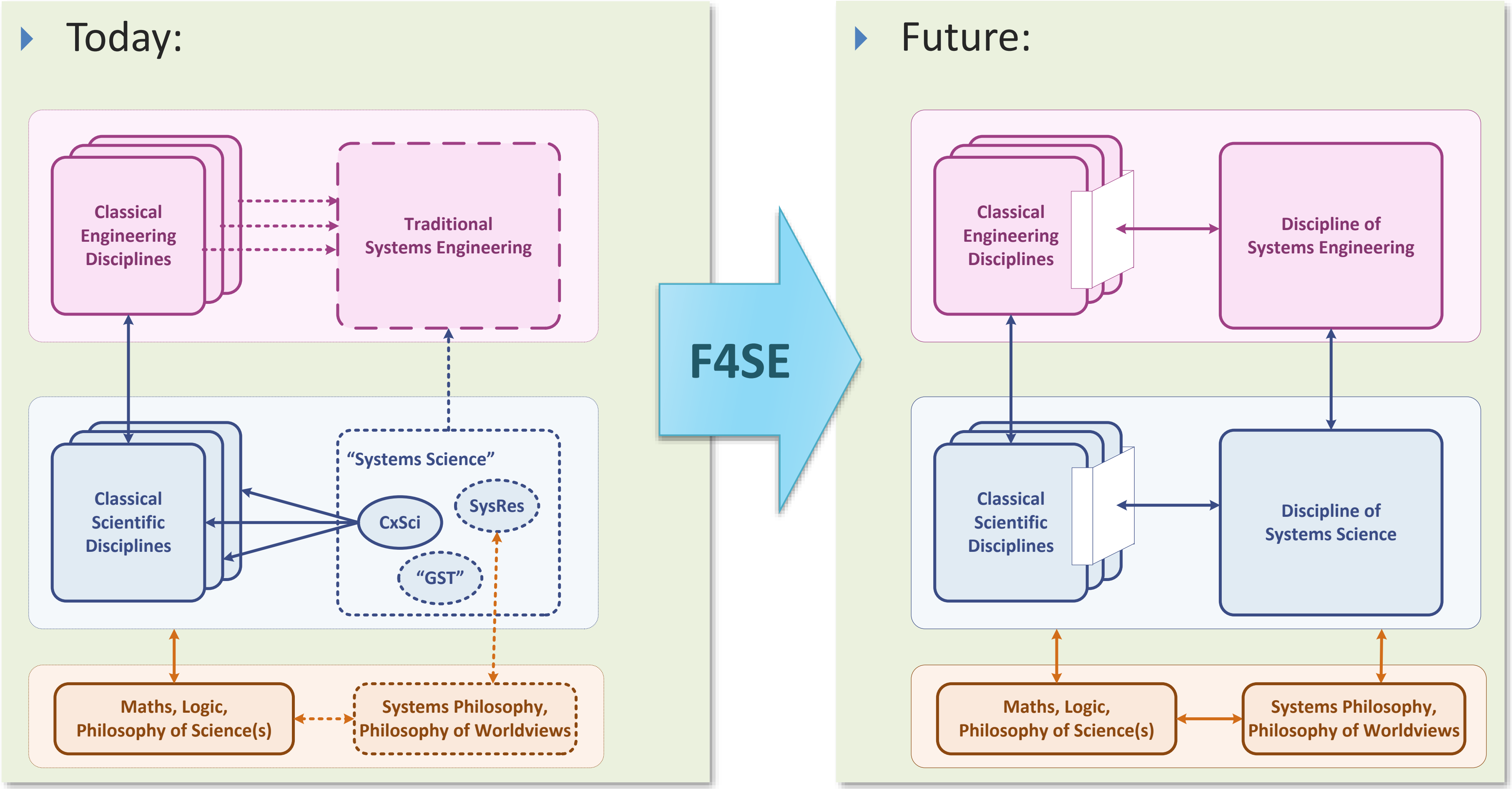
- There are precedents for this in the history of science:
  - Terrestrial Mechanics and Celestial Mechanics via Newton (1687)
  - Botany and Zoology via Darwin (1859)
  - Optics and Electromagnetics via Maxwell (1861)
  - Theories of space and time via Einstein (1905), space and gravity via Einstein (1916)

- The introduction of such unifying general theories have greatly deepened and empowered their relevant disciplines and consequently enabled advances in technology, engineering and practice

- We need a scientific general theory of systems (GST*) to do this for Systems Science




Vision for the Future of SysSci & SE as Disciplines

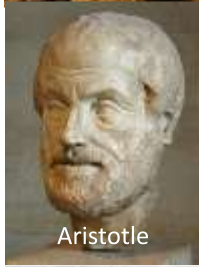


Situation

- Challenge: The SysSci community will not do this by themselves – SE community leadership is essential

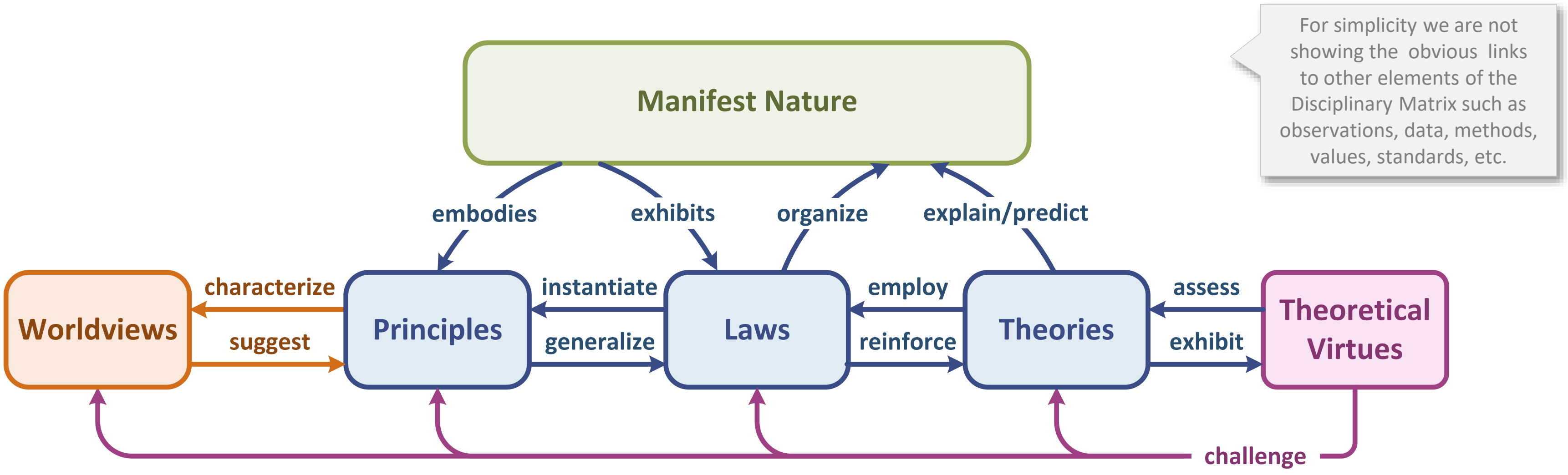
- Proposal: Leverage the SE community to drive a program to:
  - Improve and unify Systems Science to scientifically cover both reductionistic and holistic considerations, initially by research towards a GST*
  - Develop Systems Science into a distinct unified academic discipline, and
  - Operationalize advances in Systems Science for SE practice

- Goals for F4SE Summit Research Agenda development:
  - Explore the scope and significance of our quest via a reflection on the analogy with the emergence of Biology as a unified discipline
  - Refine a strawman model for organizing and assessing the state of the art in Systems Science with particular reference to GST*
  - Explore our understanding of our knowledge scope, maturity and gaps in Systems Science with particular reference to GST*
  - Develop and prioritise a structured list of research questions and project ideas



Contextual elements of scientific theories

- If GST* is to be a scientific theory, it must:
  - embed, and be embedded in, the contextual elements that all scientific theories accommodate, and
  - be subject to the same quality rules and evolutionary processes that all scientific theories are subject to
  - Support the development of the 'Disciplinary Matrix' for the discipline



The Extended Principles-Laws-Theories (PLT) model

General Inquiry Framework Model for GST*

- If GST* is to be a fully-fledged scientific theory, it must provide grounding for all the categories of knowledge relevant to 'higher-order' theories in the discipline
- We have a model of these categories (and the questions they relate to) in the "General Inquiry Framework"
- Here is a simplified example, customized for the case of GST*:

Knowledge Category	Key Questions	Philosophy Category
Identity	1. Are systems real or are they only cultural projections? 2. What denotes the presence of a system? 3. What is not a system? 4. What concepts are needed to study systems?	Ontology (about the existence and identity of things)
Character	1. What is the nature of systems (systemness)? 2. What properties and capabilities are present in all systems? 3. What mechanism(s) produce systemness? 4. What principles and laws enable/constrain these mechanisms?	Metaphysics (about the inherent nature and inherent behaviour of things)
Lifecycles	1. What kinds of systems exist, and how are they related? 2. What determines the boundary between a system and its context/environment? 3. What enables/prevents the emergence of which kinds of systems? What kinds are possible or impossible? 4. What mechanisms, laws and principles enable/constrain increasing the diversity, complexity and evolvability of systems?	Cosmology (about the origins, change, evolution and destiny of things and their contexts)
Capability	1. What makes a system successful? 2. What recurring system patterns reinforce enduring operational capability and contextual suitability? 3. What principles and laws enable/constrain the emergence of new capability in nature and design?	Praxeology (about how best to achieve functions or purposes or pursue meanings)
Values	1. What makes a system or a design 'good'? 2. What mechanisms, laws and principles enable/constrain the viability of systems and the design of viable systems?	Axiology (about why and how things have value)
Learning	1. What does the systems perspective reveal that is otherwise hidden from view? 2. What mechanisms and methods enable the modelling or discovery of systems, system properties and systemic processes in natural and engineered systems? 3. What don't we know about systems and how can be gain that knowledge?	Epistemology (about the nature of and routes to knowledge about things)

Knowledge Classification Framework

			Disciplinary Matrix Elements							
			Data & Descriptions	Worldviews & Perspectives	Concepts	Principles	Laws	Theories & Models	Methods & Tools	Other: Exemplars, Case Studies & Evaluations
			1	2	3	4	5	6	7	8
Knowledge Categories	Identity	A								
	Character	B								
	Lifecycle	C								
	Capability	D								
	Value	E								
	Learning	F								

Research Agenda Development Examples

Research Agenda Proposals

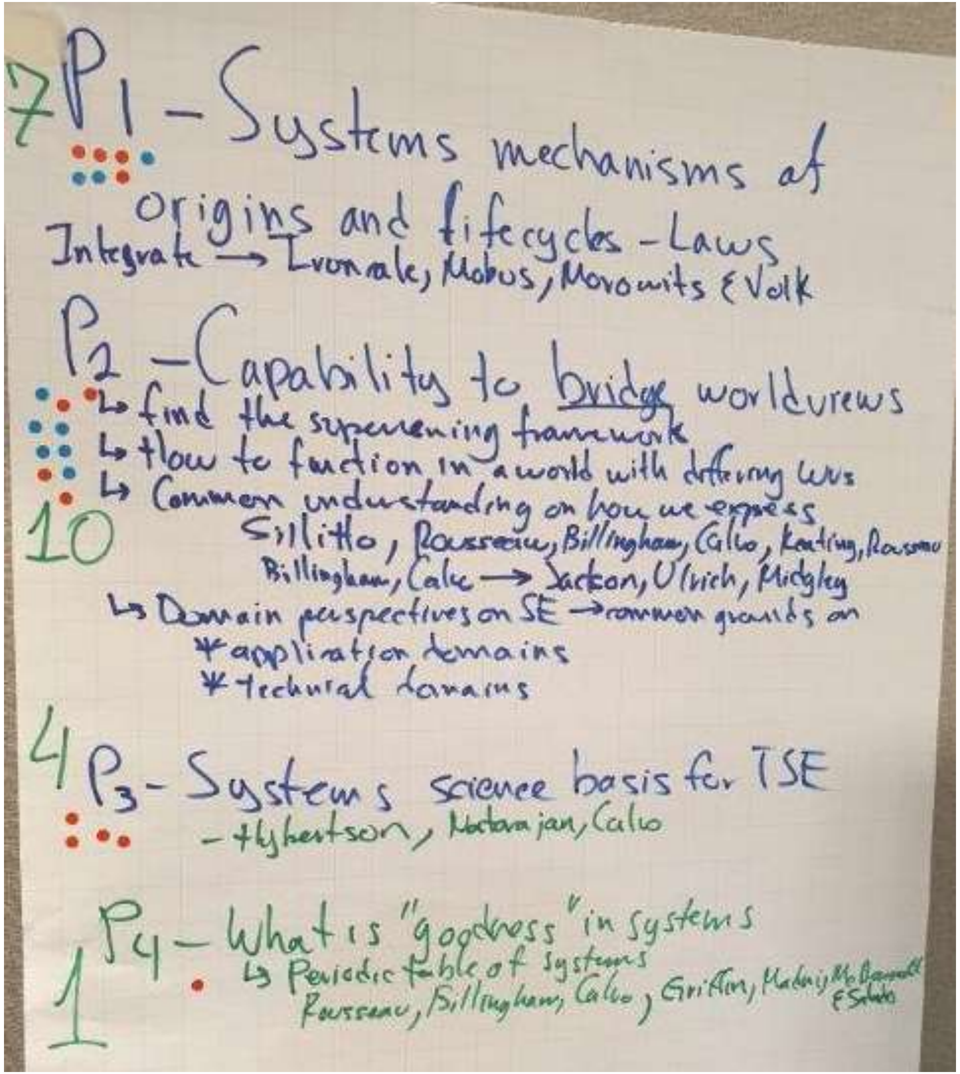
0 J 1) Literature review of work on worldviews

9 J 2) a) What types of systems exist?
b) How can I identify what type I'm dealing with?
c) What assumptions & worldviews apply to diff't types of systems?

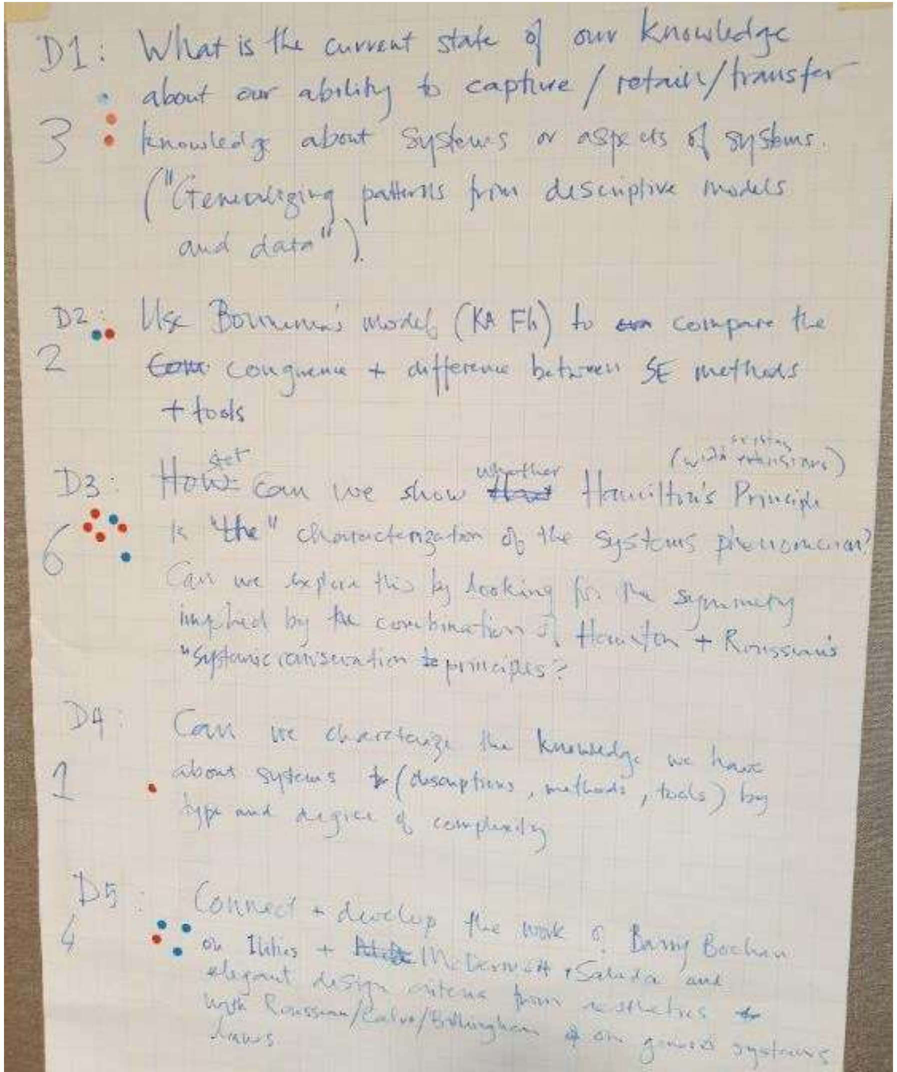
3 J 3) What types of problems exist?
(is this the same as 2?
↳ Compare/review methodologies and figure out what systems characteristic determined which is relevant. (SW)

2 J 4) Foundations for problem framing
a) Worldview classification/evaluation tool.
b) Develop Duncan's diagram.

Research Agenda Proposals



Research Agenda Proposals



D1: What is the current state of our knowledge about our ability to capture / retain / transfer knowledge about systems or aspects of systems. ("Generalizing patterns from descriptive models and data").

3

D2: Use Bowman's model (KA Fh) to ~~can~~ compare the ~~Con~~ congruence + difference between SE methods + tools

2

D3: ~~How~~ Can we show ~~that~~ whether Hamilton's Principle (w/ a system transitions) is "the" characterization of the systems phenomena? Can we explore this by looking for the symmetry implied by the combination of Hamilton + Rousseau's "systemic conservation ~~to~~ principles"?

6

D4: Can we characterize the knowledge we have about systems ~~to~~ (descriptions, methods, tools) by type and degree of complexity

1

D5: Connect + develop the work of Barry Boehm on Ilities + ~~Ahde~~ McDermott + Salado and elegant design criteria from aesthetics ~~+~~ with Rousseau/Calvo/Billingham ~~+~~ on general systems laws

4

Foundations for Systems Engineering (F4SE)

Execution Vision

Section Lead: Ron Luman

Options & Plans for Executing the Research Projects

- Envisioned future (What will good look like in 10 years?)
- Stakeholders and Needs (Who is impacted by the research?)
- Products and Sustained Activities (How do we show relevance and progress?)
- Options for an Entity or an Organized Movement
- Pros and Cons for Execution Options (What is best way forward?)
- Funding models and sources (How to get this funded?)
- Areas of consensus and issues to resolve

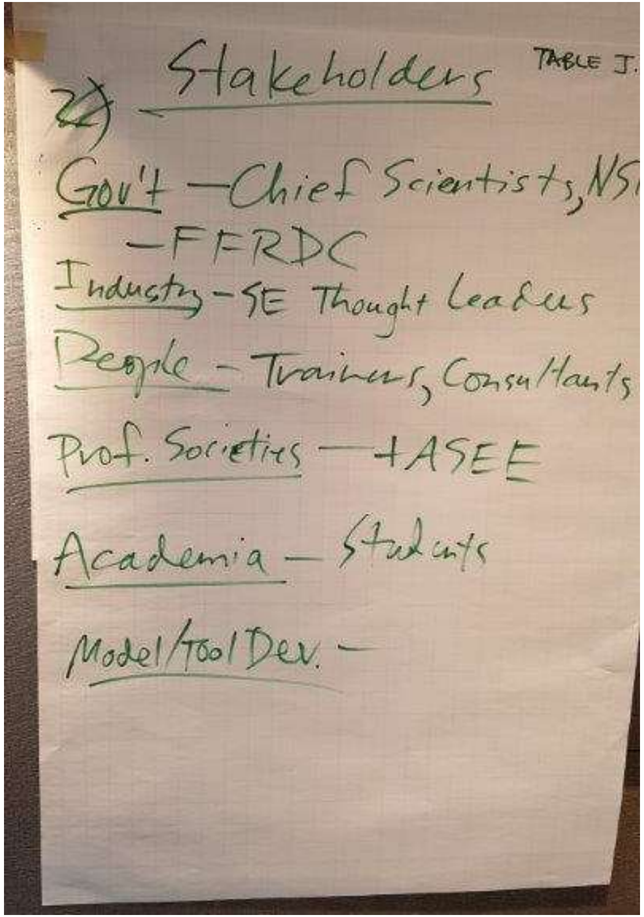
What will good look like in 10 years?

Envisioned Future: Foundations of Systems Engineering

1. There will be a generally accepted and applied theory of system complexity, design elegance, and system potential.
2. Engineering systems and engineered systems are able to adapt to change in a timely manner, including context of use/mission.
3. We will have operationalized our ethical and humanistic commitment as part of our SE process and practice. That is, SE will have moved beyond purely technical decisions in a value-adding way.
4. SE is applied in many areas that ignore it today, because the general systems theory is transdisciplinary and hence SE will have compelling value across application domains and market sectors.

Potential Stakeholders vis a vis the Research Agenda

- Government: Advocates and sponsors of large-scale complex systems
- Industry: Developers of large-scale complex systems
- Systems engineering and systems thinking practitioners
- Professional societies: INCOSE, IEEE (EMS), IEEE (ETEMS), ASEM, SEMS, etc.
- Academia (esp. universities with SE doctoral programs)
- Commercial SE model and tool developers



Products and Sustained Activities

Necessary to demonstrate relevance and progress

- Journal(s)
- Newsletters via email and social media
- Dedicated F4SE conferences
- Keynote speeches and technical panels at global SE conferences
- Academic degree programs
- Certificate programs
- New departments in prominent universities
- Consulting services to large-scale, complex systems developers

Options for an Organized Movement or Entity

1. Leap-ahead cells of practitioners (e.g., Silicon Valley ICs and AI)
2. Distributed movement among academia
3. A professional society adopts the vision as a core objective
4. An existing institution expands with a focused F4SE division
5. A new institution (or consortium) dedicated to the F4SE vision and mission

Issues abound. For example, if an institution:

- Physical or virtual institute?
- Level of commitment of researchers
- Independent or affiliated with a university or professional society?
- Funding requirements and sources

Pros and Cons for Execution Options

Option	Pros	Cons
Cells of practitioners	• Close to application challenges • Innovative and agile; team-oriented • Access to problem-driven investment	• Opportunistic, short-term results oriented • Not mission-driven • Little incentive for theoretical foundations
Academia	• Incentivized towards theoretical foundations • Free to pursue the hardest problems	• Principal investigator orientation • Challenging to find research grants • Not close to application challenges
Professional society	• Can engage practitioners and academia • Controls publications and symposia • Provides creative outlet with status/cache	• Resource poor • Part-time participants
Expand existing institution	• Organizational stability • Augmentation of existing sponsor base • Capitalize on existing business model • Attractive to prospective researchers	• New areas compete with established areas • Re-chartering the institute to include new vision/mission
New institution	• Fresh vision and mission yields excitement • No competition for vision/mission	• Challenging to become established • Developing new business model • Appears risky to prospective researchers

Funding Models and Sources

Aligned with the stakeholder list

Option	Funding Models	Potential Sources/Stakeholders
Cells of practitioners	Contracts on large-scale complex systems Consulting contracts	Industry or government Industry or government
Academia	Grants Philanthropic grants/endowments Tuition support	Government Individuals or foundations Specialized MS or PhD programs
Professional society	Grants Tax on dues	Government or industry Membership
New or expanded institution	Grants Endowment Tuition (if university-affilitated) Contracts on large-scale complex systems Consulting contracts	Government Individuals or foundations Specialized MS or PhD programs Industry or government Industry or government

Vision for Impact

Section Lead: Paul Schreinemakers

Impact Options and Proposals

- What should be our objectives to ensure impact?
  - Build public and professional understanding and embracement of our mission and vision
  - Build collateral to help us get started (website, walking deck, 1-pager, value proposition…)
  - Develop routes to adoption of the outputs (teaching, consulting, showcase events, publications, pilots, case studies…)
  - Build a knowledge base to aggregate results and make them accessible
  - Promote Systems Science as a new scientific discipline
  - Build credibility of F4SE organization
- What have we missed?
- How should we prioritise the development of our impact projects?
- Where are the leverage points and the hazards?
- In what sequence should we leverage the channels available to us? (e.g. teach ourselves or via universities, industry communities of practice, professional societies…)
- Which organizations should we target to help us with the above? What networks should we build?
- What collateral do we need to pursue above objectives?
- How can we fund the activities that build our impact?

Impact drivers per lifecycle stage (straw man)

	Getting started	Doing research	Disseminating results	Applying results
Activities	• Set up exec team • Publicise mission & vision • Raise funding	• Build research network • Raise funding	• Publicity • Teaching	• Consultancy
Collateral needed	• Website, 1-pager, walking deck, funding docs	• Collaborator model & guidelines	• Knowledge base • White papers	• Value propositions
Network & partners	• Infrastructure partners	• Research partners • Funding partners	• PR routes • Publication channels • Teaching channels	• Community of practice
Metrics & proof points	• Funding • Awareness • Advocacy	• Peer review • Follow-on projects	• Uptake of related courses • Citations	• Pilots & case studies • Value delivered

Output consolidation and next steps

Strength	**Weakness**
Opportunity	Threat


BILL

Wrap-up

Next steps

- Summit outcomes will be processed and formally reported on at IW2020

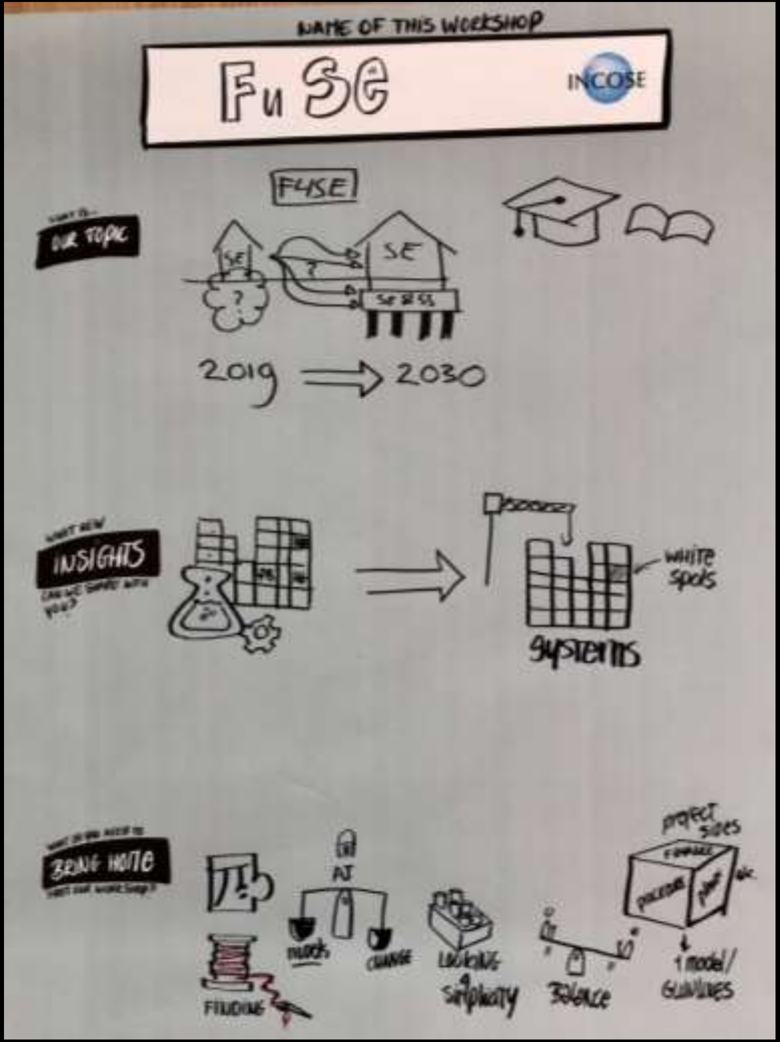
- Follow-on summits and workshops will be planned to take place from next year drawing in wider participation

- If you would like to contribute/participate in F4SE, please email:

  david.rousseau@systemsphilosophy.org

‘Marketplace’ Poster

(drawn by facilitation artists)



Thank you!

Suggestions?