27th annual INCOSE international symposium
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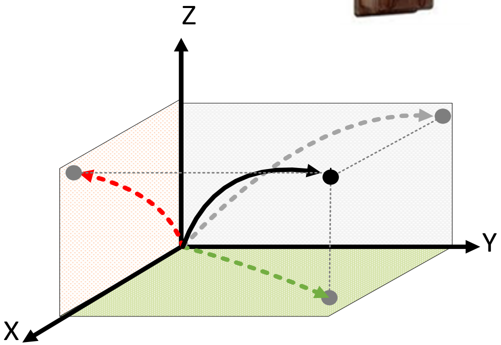
ENGINEERS AUSTRALIA SESA

# Innovation, Risk, and Agility, Viewed as Optimal Control & Estimation

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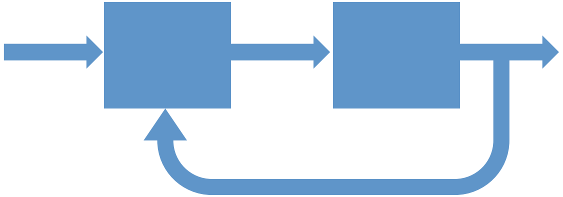



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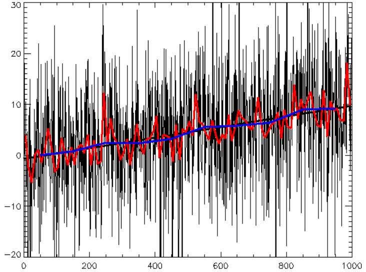
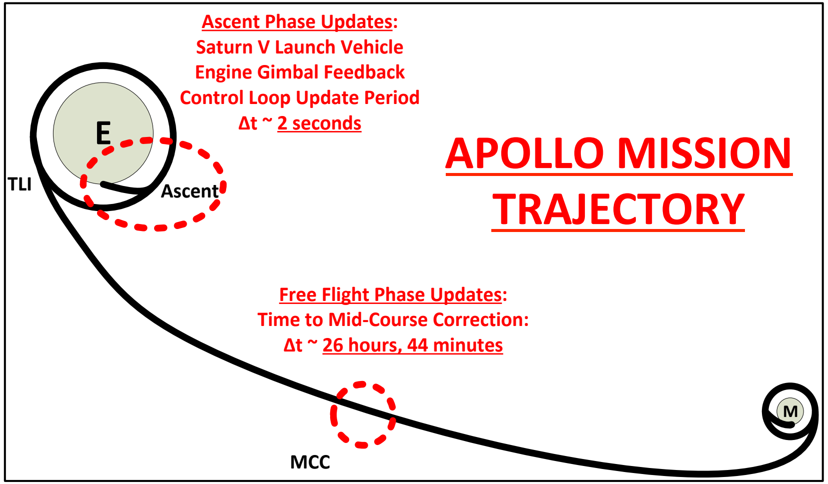
# Abstract


- This presentation will summarize how a *well-understood* problem—optimal control and estimation in a noisy environment—also provides a framework to advance understanding of a *well-known but less well-understood* problem—system innovation life cycles and the management of related risks and decision-making.
- A community perspective on system development and other life cycle processes is exemplified by the ISO15288 process framework and its exposition in the INCOSE SE Handbook. Concerns with improving the performance of the related processes in dynamic, uncertain, and changing environments are taken up by "agile" systems engineering approaches. All these are typically described in the languages of business processes, so it is not always clear whether the different approaches are fundamentally at odds, or really different sides of the same coin.
- However, describing the target developed system, its environment, and the life cycle management processes (including development) using models of dynamical systems allows us to apply earlier technical tools, such as the theory of optimal control in noisy environments.
- This approach is being applied in the INCOSE Agile Systems Engineering Life Cycle Model Discovery Project, as an input to a future update to ISO 15288. This presentation should be of interest to practicing engineers and process leaders.

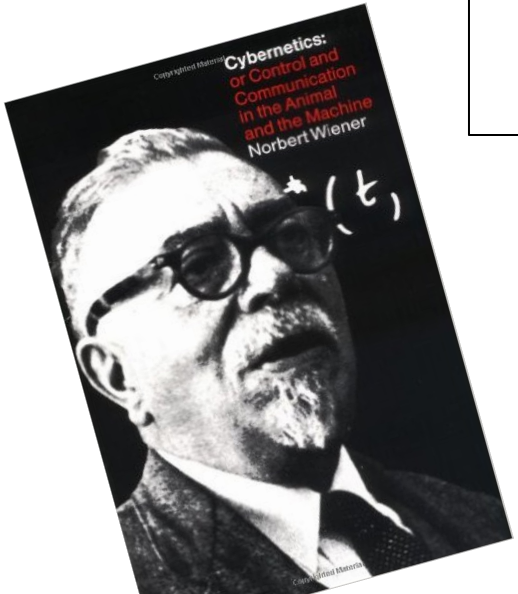
- The Idea in a Nutshell
- Innovation, Risk, and Agility: Traditional Perspectives
- How Models Change Our Perspective on Innovation
- The Guidance System: Including the System of Innovation
- What Optimal Control and Estimation Theory Tells Us
- Agility as Risk-Optimized Control of Trajectory in S*Space
- Examples of Applications
- Innovation in Populations: Markets, Segments, Ecosystems
- Conclusions, Future Work, Discussion
- References

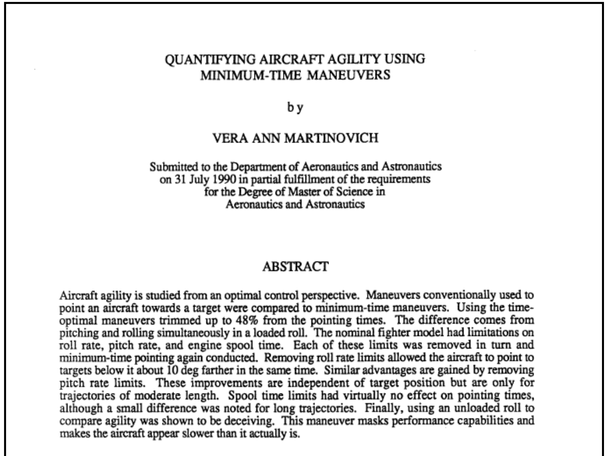
# In a Nutshell: Geometrization of Innovation Space







QUANTIFYING AIRCRAFT AGILITY USING MINIMUM-TIME MANEUVERS

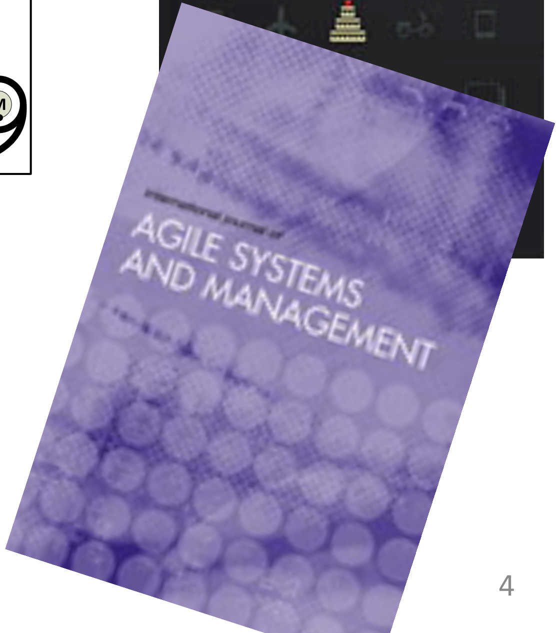
by

VERA ANN MARTINOVICH

Submitted to the Department of Aeronautics and Astronautics on 31 July 1990 in partial fulfillment of the requirements for the Degree of Master of Science in Aeronautics and Astronautics

ABSTRACT

Aircraft agility is studied from an optimal control perspective. Maneuvers conventionally used to point an aircraft towards a target were compared to minimum-time maneuvers. Using the time-optimal maneuvers trimmed up to 48% from the pointing times. The difference comes from pitching and rolling simultaneously in a loaded roll. The nominal fighter model had limitations on roll rate, pitch rate, and engine spool time. Each of these limits was removed in turn and minimum-time pointing again conducted. Removing roll rate limits allowed the aircraft to point to targets below it about 10 deg farther in the same time. Similar advantages are gained by removing pitch rate limits. These improvements are independent of target position but are only for trajectories of moderate length. Spool time limits had virtually no effect on pointing times, although a small difference was noted for long trajectories. Finally, using an unloaded roll to compare agility was shown to be deceiving. This maneuver masks performance capabilities and makes the aircraft appear slower than it actually is.



# Innovation, Risk, and Agility: Perspectives from Several Communities

- Innovation, for purposes of this work:
  - Delivery of improved stakeholder outcome experience
  - Whether engineered or otherwise
  - Stakeholder outcome is not technology
- Life Cycles of Engineered Systems:
  - ISO 15288 and its expression in INCOSE SE Handbook
  - Development cycles: Waterfalls, Spirals, Waves, others
  - Other parts of the life cycle
- Risk Management:
  - Multiple types of risks, including arising from limited knowledge of changing environment, stakeholder situations and needs, as well as technical and other risks to performance, cost, schedule
  - Management of risks--Identify, Assess, Avoid, Transfer, Mitigate, Monitor

# Innovation, Risk, and Agility: Perspectives from Several Communities

- Agility as an approach to some risks, as seen by software, engineering, and business communities:
  - Agile Software Development
  - Agile Systems Engineering
  - Lean Start Up
  - Minimum Viable Product
  - Pivoting
  - Early feedback in presence of uncertainty and change

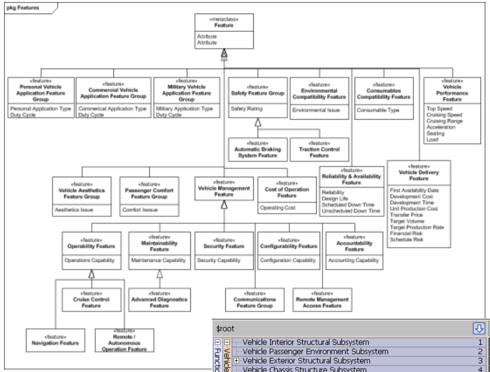
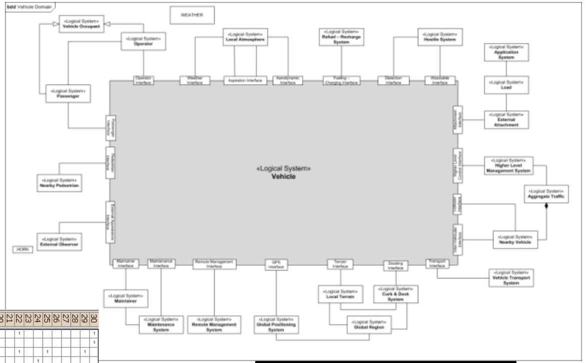
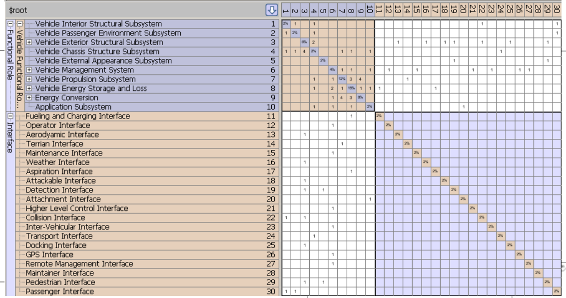
# Innovation, Risk, and Agility: Perspectives from Several Communities

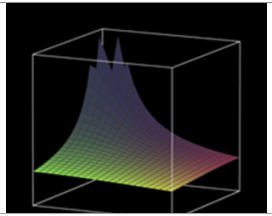
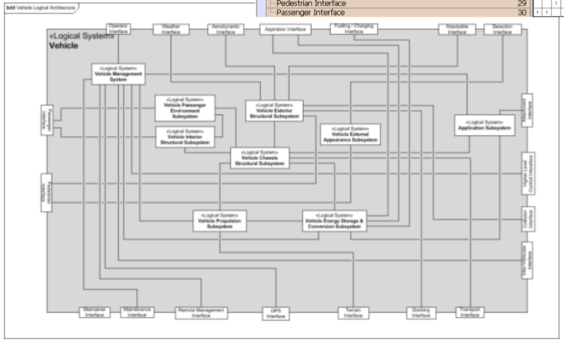
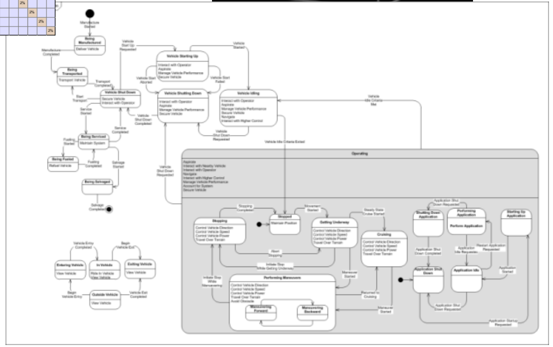
- Additional domains for innovation, risk, agility:
  - Biological natural selection
  - Epidemiology & other health care
  - Defense (conventional, guerrilla, asymmetric war)
  - Markets & ecologies
  - Resilient systems

# How Models Change our Perspective on Innovation





# Interactions and the Systems Phenomenon

Systems engineering has passed through a different path than the other engineering disciplines, which were better connected to underlying phenomena-based physical sciences . . .

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Edinburgh, Scotland, UK, July 18-21, 2016

## Got Phenomena? Science-Based Disciplines for Emerging Systems Challenges

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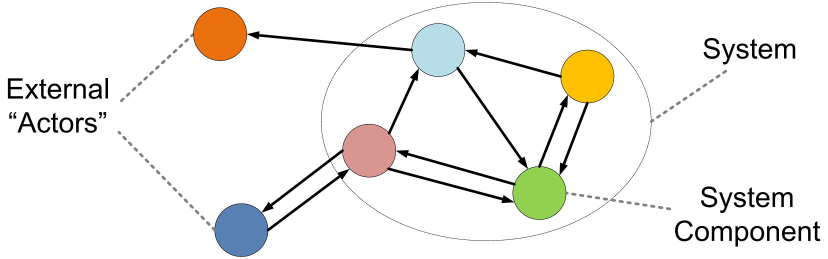
**Abstract.** Engineering disciplines (ME, EE, CE, ChE) sometimes argue their fields have "real physical phenomena", "hard science" based laws, and first principles, claiming Systems Engineering lacks equivalent phenomenological foundation. We argue the opposite, and how replanting systems engineering in MBSE/PBSE supports emergence of new hard sciences and phenomena-based domain disciplines.

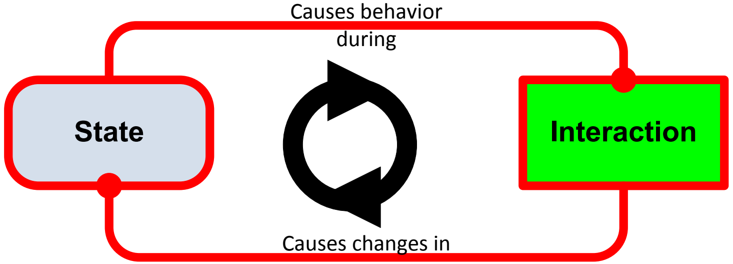
Supporting this perspective is the System Phenomenon, wellspring of engineering opportunities and challenges. Governed by Hamilton's Principle, it is a traditional path for derivation of equations of motion or physical laws of so-called "fundamental" physical phenomena of mechanics, electromagnetics, chemistry, and thermodynamics.

We argue that laws and phenomena of traditional disciplines are less fundamental than the System Phenomenon from which they spring. This is a practical reminder of emerging higher disciplines, with phenomena, first principles, and physical laws. Contemporary examples include ground vehicles, aircraft, marine vessels, and biochemical networks; ahead are health care, distribution networks, market systems, ecologies, and the IoT.

# The System Phenomenon

- In the perspective described here, by system we mean a collection of interacting components:



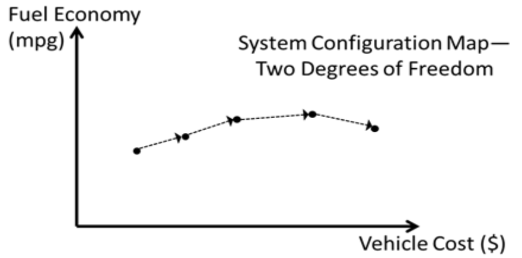




- Where interaction involves the exchange of energy, force, mass, or information, . . .
- Through which one component impacts the state of another component, . . .
- And in which the state of a component impacts its behavior in future interactions.

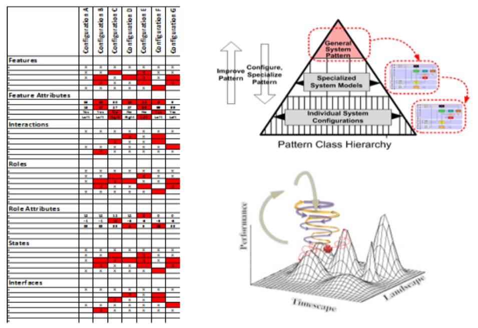
# Where Do Systems Come From and Go?
# System Life Cycle Trajectories in S*Space

- Configurations change over life cycles, during development and subsequently
- Trajectories (configuration paths) in S*Space
- Effective tracking of trajectories
- History of dynamical paths in science and math
- Differential path representation: compression, equations of motion

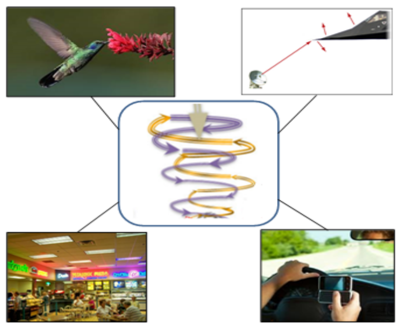
Evolving Systems Over Multiple Life Cycles




Path as a series of system configurations, through iterations of the SE process

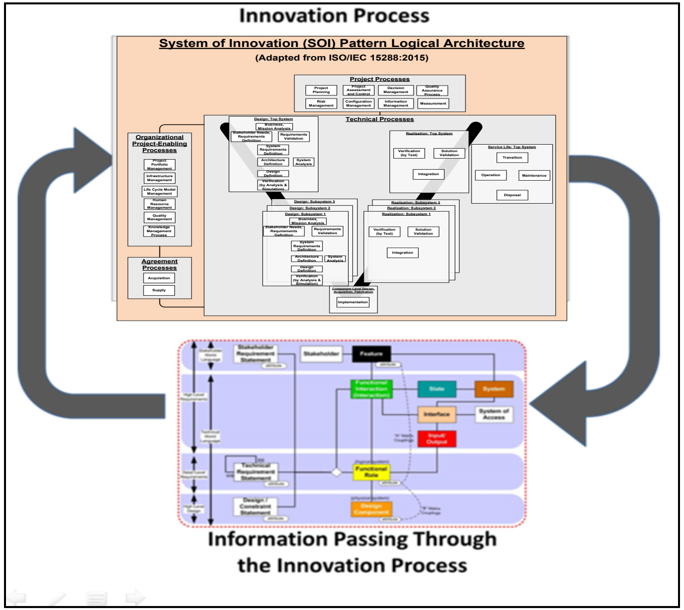



"Delta" Descriptions Further Compress Trajectory Representations

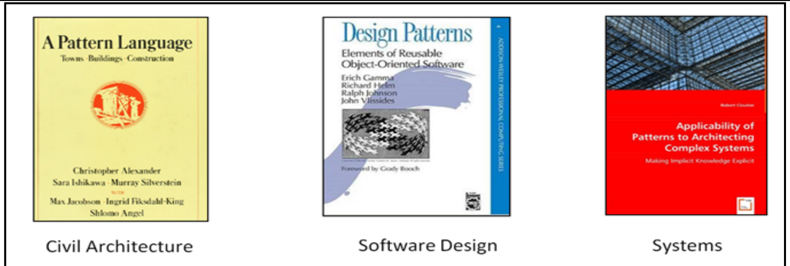


Co-Evolution of Interacting Systems

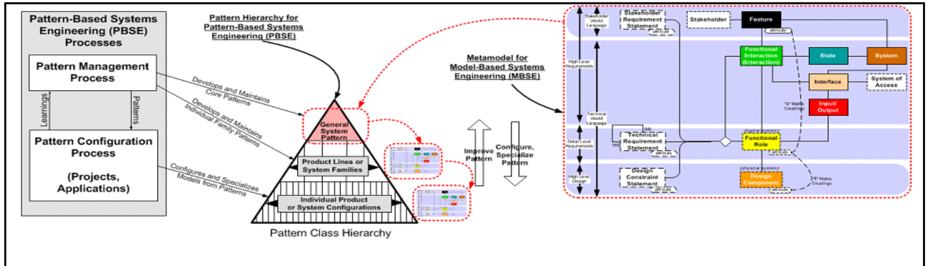
# Maps *vs.* Itineraries -- SE Information *vs.* SE Process



Information Passing Through the Innovation Process



Formal Patterns In Human-Performed Engineering Processes



Evolving Families of Systems, Pattern-Based Systems Engineering (PBSE)

- Model-based Patterns in S*Space.
- Interactions as the basis of all laws of physical sciences.
- Relationships, not procedures, are the fruits of science used by engineers: Newton's laws, Maxwell's Equations.
- Immediate connection to Agility: knowing where you are--starting with better definition of what "where" means. There is a minimal "genome" (S*Metamodel) that provides a practical way to capture, record, and understand—the "smallest model of a system".
- Not giving up process: MBSE/PBSE version of ISO/IEC 15288.

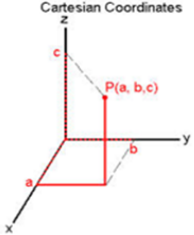
# Maps *vs*. Itineraries -- SE Information *vs*. SE Process

Itinerary ≠ Map!

*(What am I doing?)* *(Where am I?)*

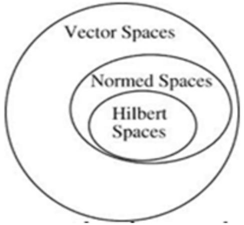
When they eventually did emerge, maps represented a newer idea of the nature of "where".

- The SE Process consumes and produces <u>information</u>.
- But, SE historically emphasizes <u>process</u> over <u>information</u>. (Evidence: Ink & effort spent describing standard process versus standard information.)
- Ever happen?-- Junior staff completes all the process steps, all the boxes are checked, but outcome is not okay.
- Recent discoveries about ancient navigators: Maps *<u>vs</u>*. Itineraries.
- The geometrization of Algebra and Function spaces (Descartes, Hilbert)
- Knowing where you "really" are, not just what "step" you are doing.
- Knowing where you are "really" going, not just what "step" you are doing next.
- Distance metrics, inner products, projections in system configuration S*Space.




Rene Descartes
1596 - 1650

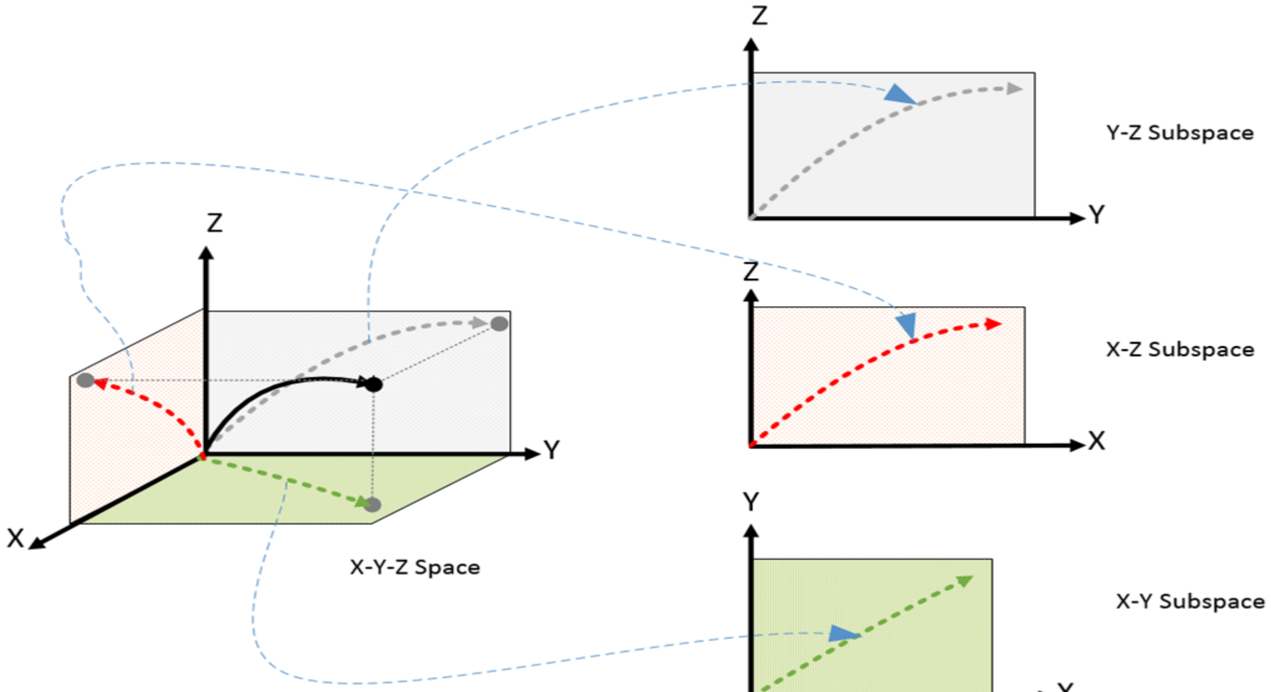
Geometrization of Algebra, by Rene Descartes



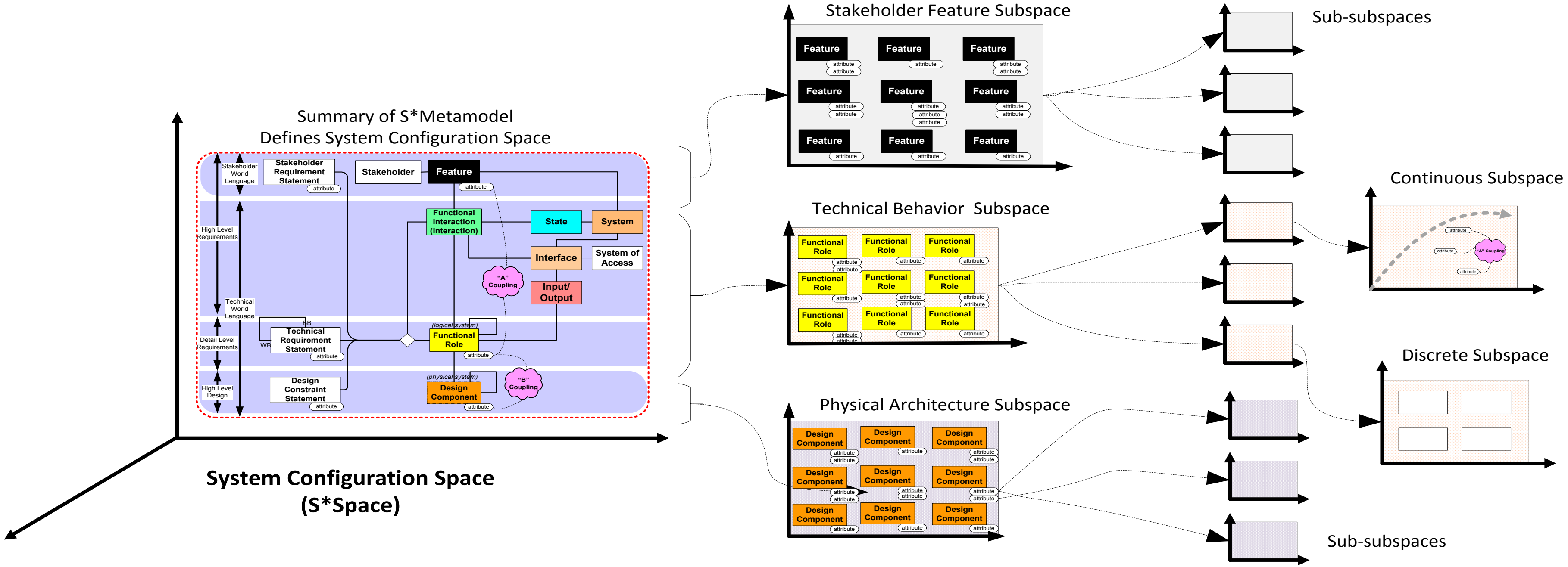

David Hilbert
1862 - 1943

Geometrization of Function Space, by David Hilbert

# Simple Geometric/Mathematical Idea: Subspace Projections

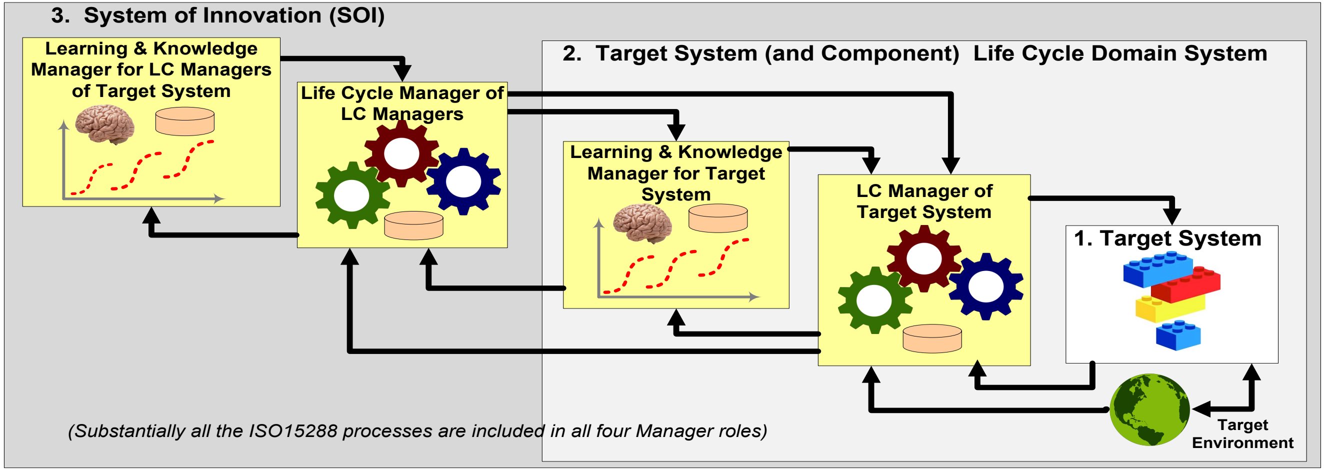


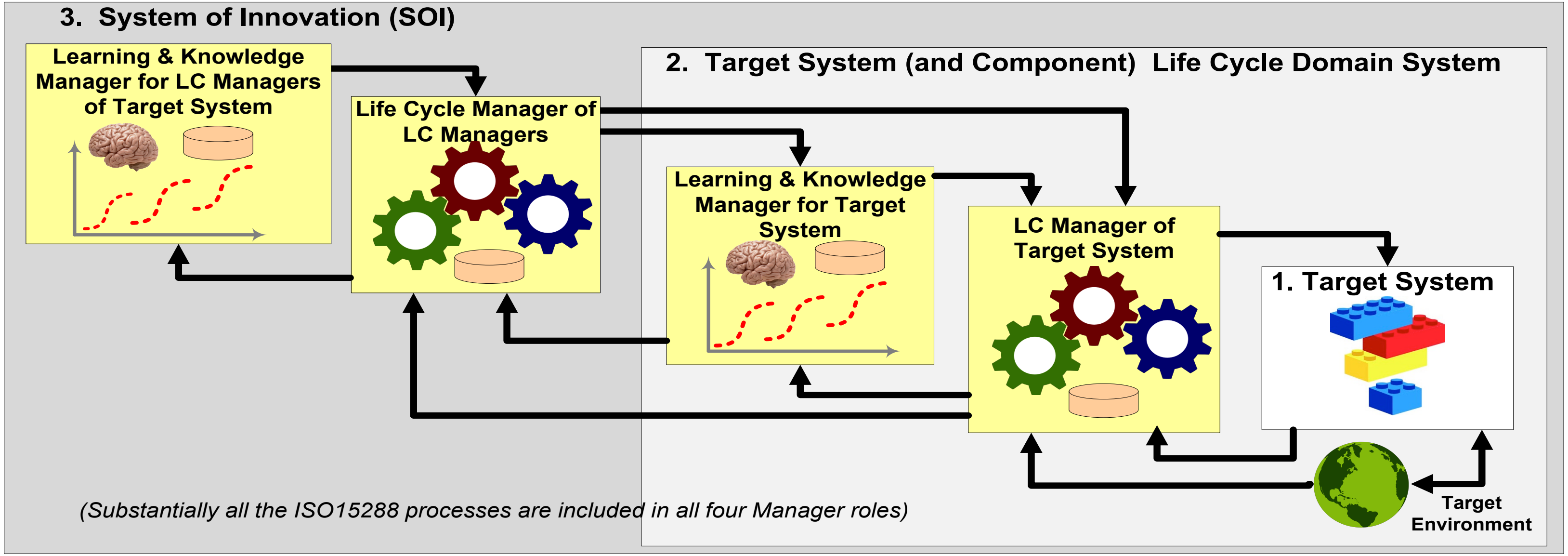
# System Life Cycle Trajectories in S*Space, and S*Subspaces



# The Guidance System: Including the System of Innovation In the Model

- A complex adaptive system reference model for system innovation, adaptation, operation/use/metabolism, sustainment, retirement.
- Whether 100% human-performed or automation-aided, various hybrids.
- Whether performed with agility or not, 15288 compliant or not, informal, scrum…
- Whether performed well or poorly.
- Includes representation of pro-active, anticipatory systems.





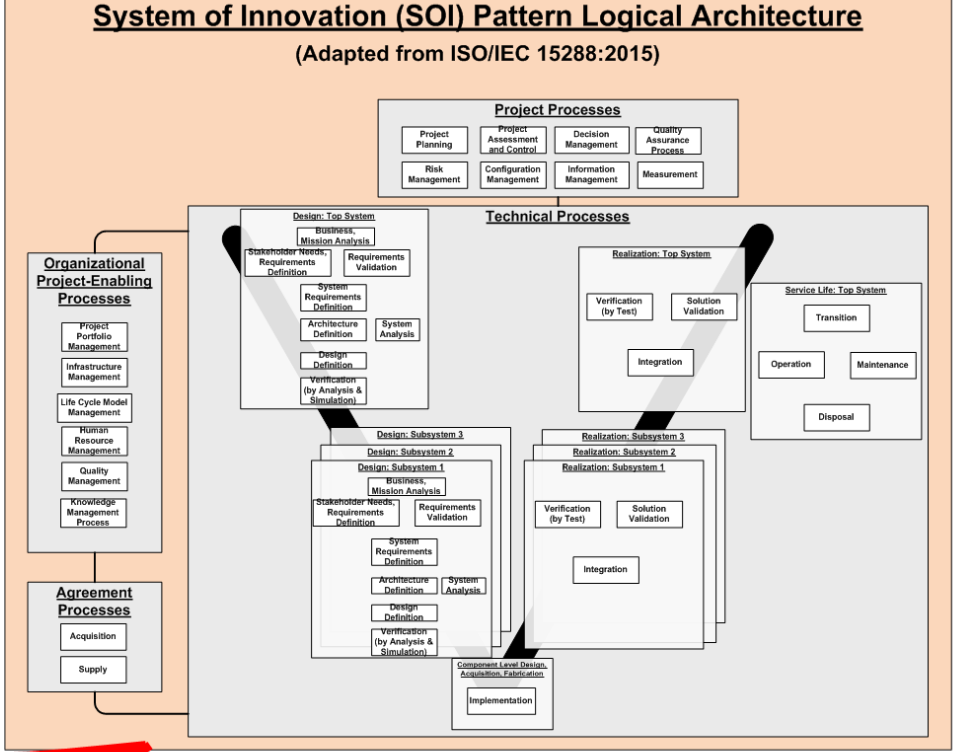

S1: Target system of interest, to be engineered or improved.

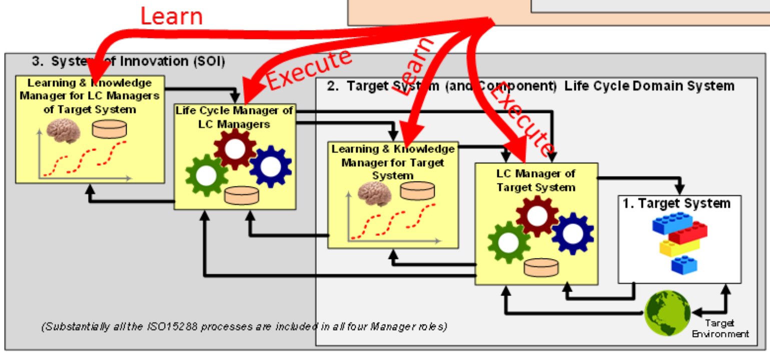
S2: The environment of (interacting with) S1, including all the life cycle management systems of S1, and including learning about S1.

S3: The life cycle management systems for S2, including learning about S2.

*Many of the toughest challenges of agility, and systems engineering in general, are S2 and S3 problems, not S1 problems.*

ISO15288 and INCOSE SE Handbook describe a framework of ~32 roles of system Life Cycle (LC) Management.

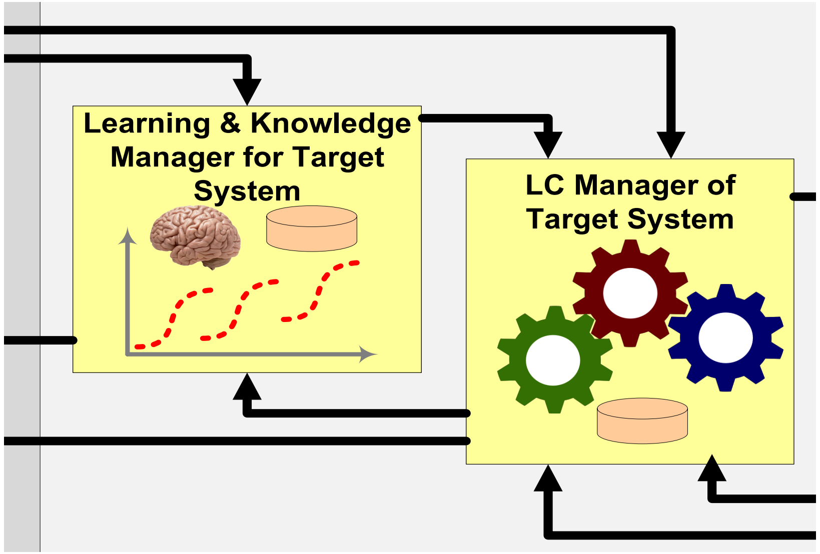


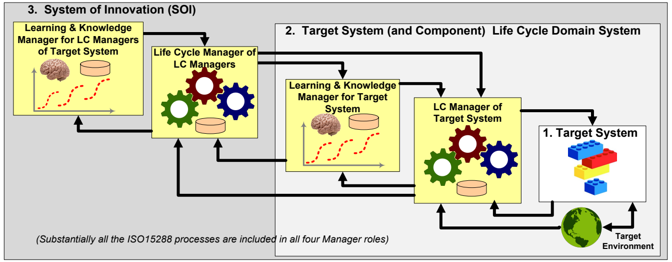

They appear repeatedly, in different ways in the SOI & ASELCM Patterns . . . . . .

# Effective Learning:
# More than "Lessons Learned" Reports

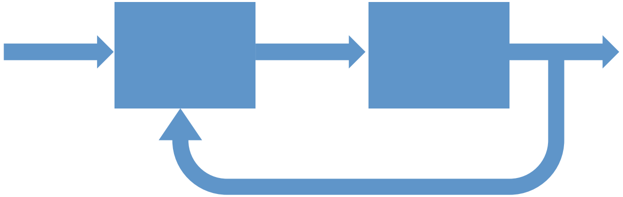
Learn




Execute



# What Optimal Control and Estimation Theory Tells Us



- 50+ years of successfully applied math, used in other domains:
  - Norbert Wiener (time series, fire control systems, feedback control, cybernetics), Rudolph Kalman (filtering theory, optimal Bayesian estimation), Lev Pontryagin (optimal control, maximum principle), Richard Bellman (dynamic programming), others.
  - Applied with great success to fire control systems, inertial navigation systems, all manner of subsequent domain-specific feedback control systems.
- Model-Based Filtering Theory and Optimal Estimation in Noisy Environment:
  - Estimation, from noisy observations, of current state of a modeled system that is partly driven by random processes, optimized as to uncertainty.
  - Control of a managed system's trajectory, optimized as to time of travel, destination reached, stochastic outcomes.

# Is it Plausible to Apply Optimal Control to the Innovation Process?

| Aspect of Common Theoretical Framework | Application to a Vehicle Guidance System | Application to a System of Innovation |
|---|---|---|
| Overall domain system | Propelled airborne vehicle guidance to moving airborne target | Development of new system configuration for a system of interest |
| The controlled system | Airborne Pursuit Vehicle | The development process |
| Control system | Flight control system and pilot sometimes | Development management & decision-making process |
| Other actors | Target, atmosphere | Stakeholders, operating environment of system of interest, suppliers |
| State space in which controlled performance occurs | Vehicle position in 3-D geometric space | Configuration space of system of interest, including its features, technical requirements, and physical architecture |
| Driving processes | Target dynamics, pursuit thrust, flight control surface movements | Stakeholder interest, supply chain |
| Random aspects of driving processes | Buffeting winds | Stakeholder preferences, competition, technologies |
| Observation process model | Radar tracking of moving target, sensor characterization | Status reporting, market feedback, development status report process |
| Random disturbances of observation processes | Sensor errors | Inaccuracies or unknowables in development status; sampling errors |
| Environmental Conditions | Target maneuvers; atmospheric effects | Market or other environmental conditions; |
| Control input | Flight control surface orientation | Management direction; resources |
| Objective function to optimize | Time to target | Time to market; Competitive Response Time; Innovated System Performance; Innovation Risk vs. Reward |
| Dynamical model | Ballistic Flight, Atmospheric Effects, Thrust | Coupled development processes |
| Outcome risk | Risk of missing airborne target | Risk of innovation outcomes across stakeholders |

# Optimal Control and Estimation Problem Frameworks

- Optimal control problem, in continuous deterministic form:

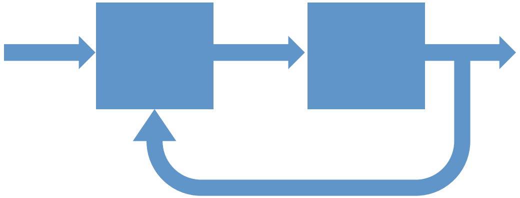
*System defined by:*

$$X = f(X,U) , \quad X \in R^n$$

*system state X(t) and control U(t);*

*Find an optimal control U(t) that minimizes:*

$$\int_0^T g(X(t),U(t))dt$$



# Optimal Control and Estimation Problem Frameworks

- Optimal estimation/filtering problem, in discrete time form:

*System state $X_n$, driven by random process $W_n$ :*

$$X_{n+1} = \Phi_n X_n + \Gamma_n W_n$$

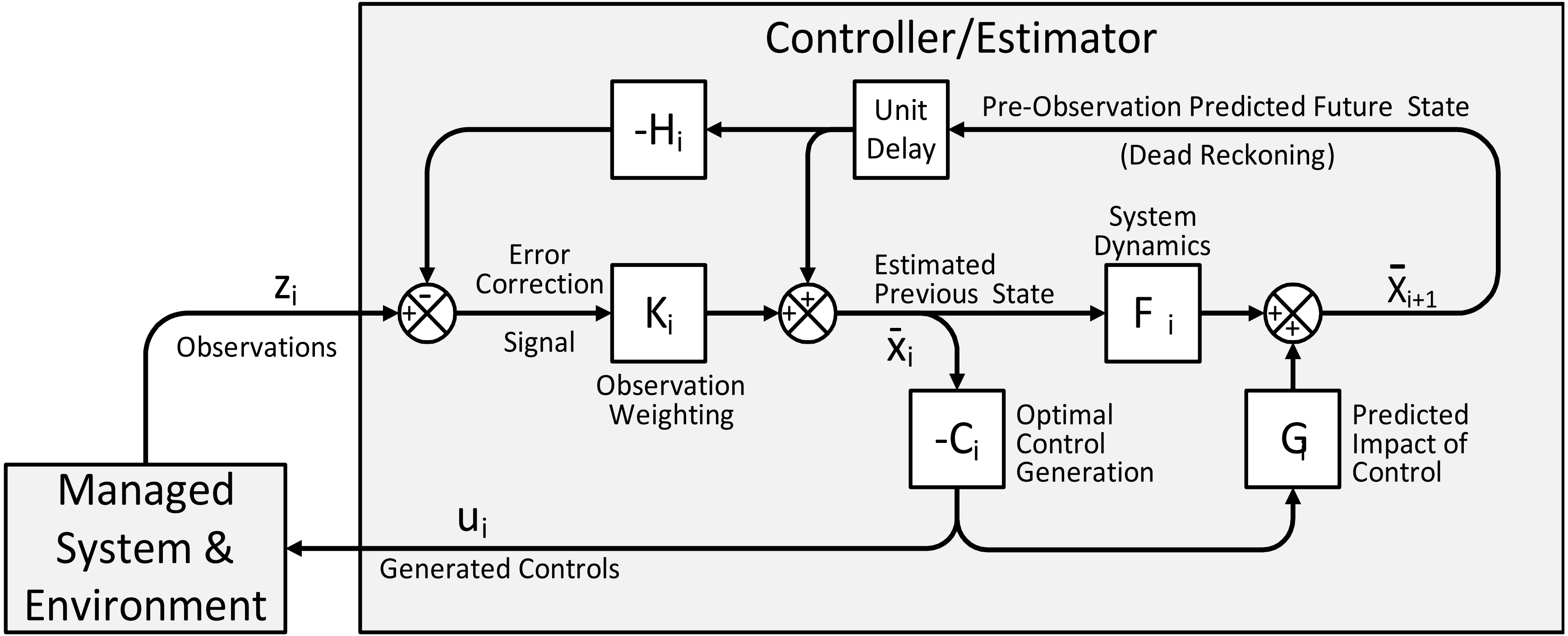
*and monitored through observable $Z_n$ , with that observation corrupted by random process $V_n$:*

$$Z_n = H_n X_n + V_n$$

*and having* var($W_n$ ) = $Q_n$ *and* var($V_n$) = $R_n$

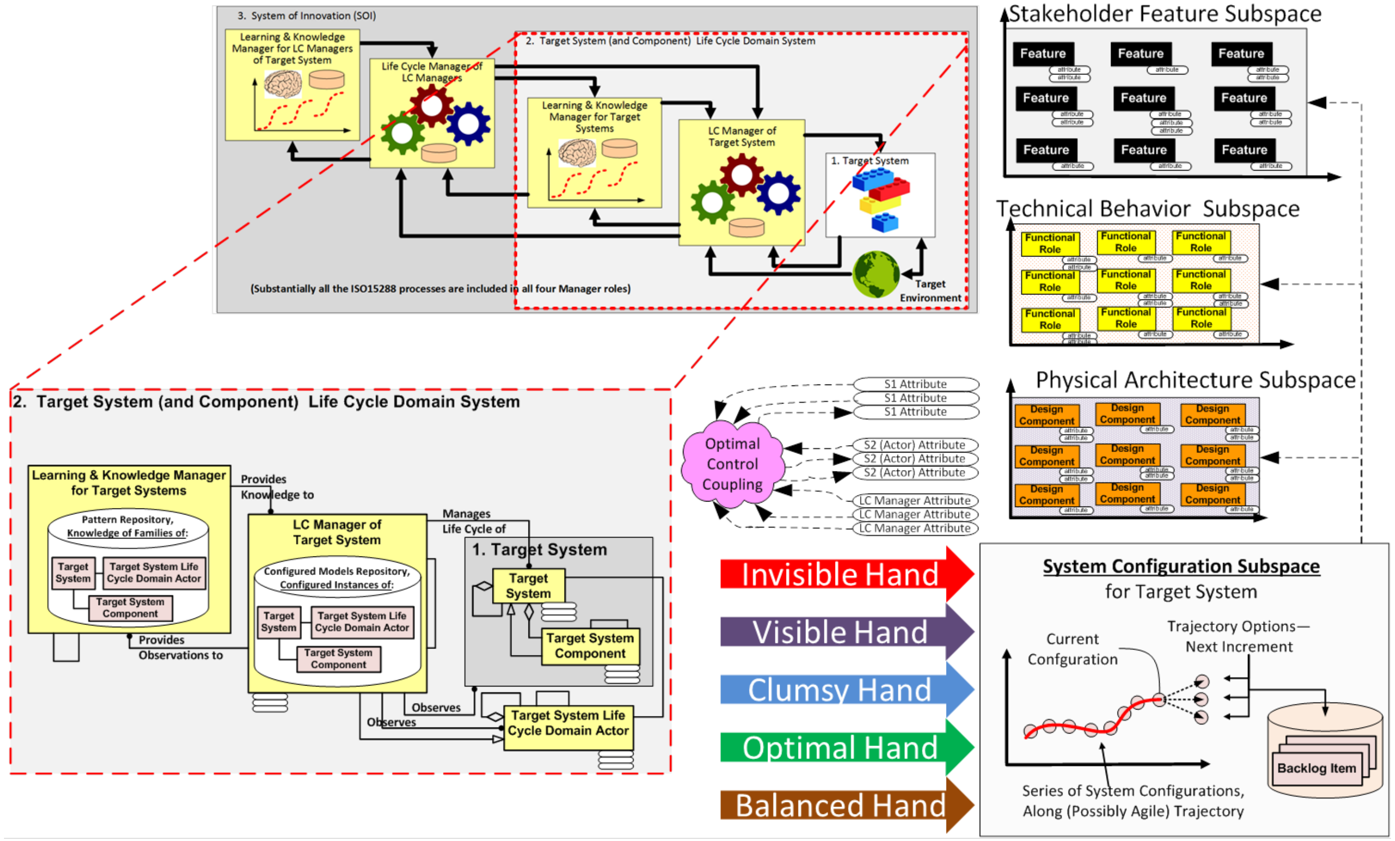
*Assuming a previous estimated system state $X_n$ , find an optimal next estimate $X_{n+1}$* minimizing $P_{n+1}$ = var($X_{n+1}$ - $X_{n+1}$)

# Form of typical optimal stochastic estimator/controller, in linearized discrete time form

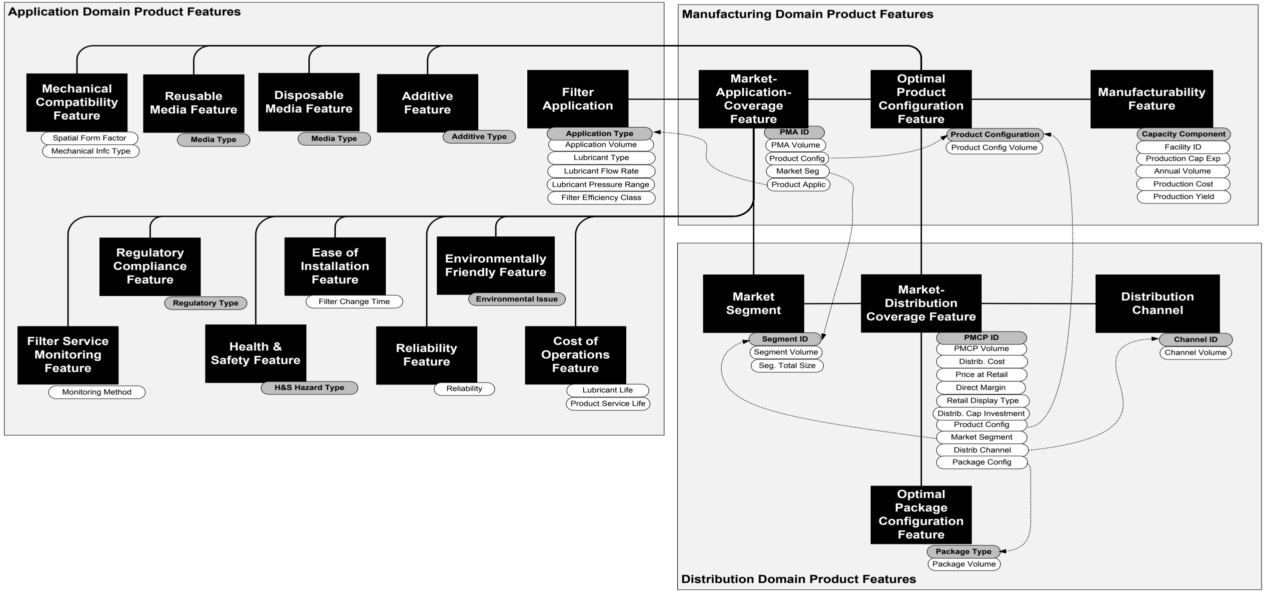



(adapted from (Bryson and Ho 1967) and (Schindel 1972))

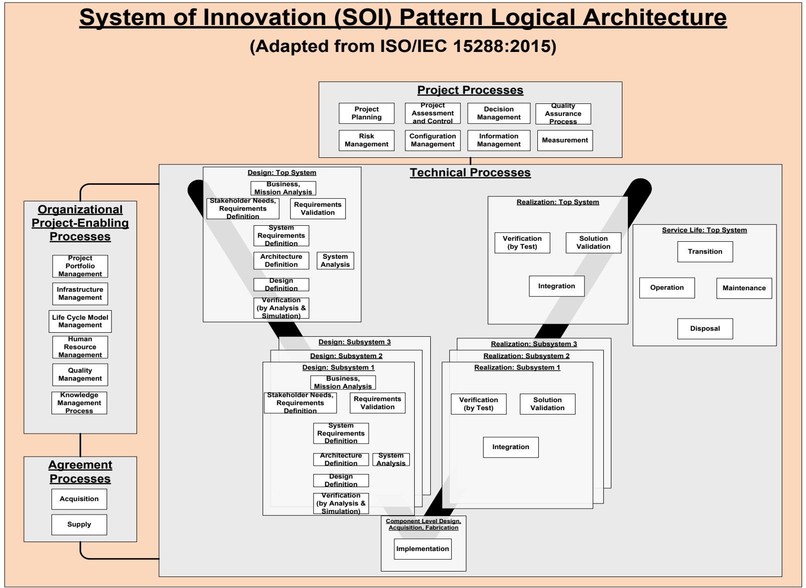
# Agility as Optimal Trajectory Control in S*Space: Finding the Best Next "Direction" & Increments



- ***Example 1****: Value gradient in Product Line Feature Sub-space, for Oil Filter Product Line:*
  - *Adding new feature configurations over time*
- *Trajectory direction selection for Agile Sprints:*
  - *Feature-modeled market uptake, investment, uncertainties*
  - *Optimal trajectory, orthogonal to wave front.*



- ***Example 2***: *Introduction of SE, or MBSE, PBSE, or Agile SE:*
  - *Changing how people think, communicate, perform work*
  - *Organizational change, including information systems*
- *What changes and capabilities to "bite off" next:*
  - *Feature-modeled capabilities, resistance, investment, risks*
  - *Optimal trajectory, orthogonal to wave front.*



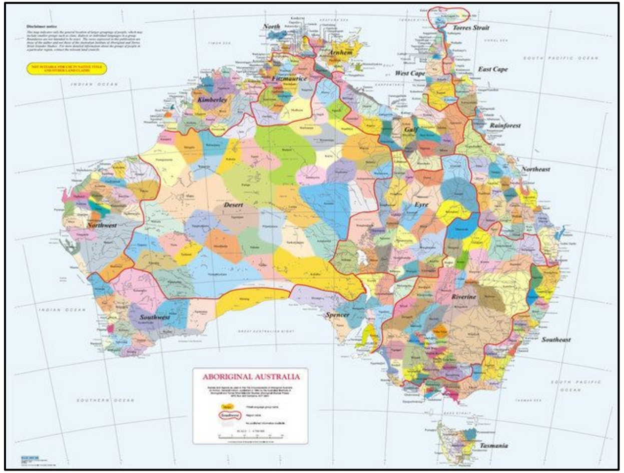
# Implications for Agile Innovation to Product or Process: Execution as Well As Strategy

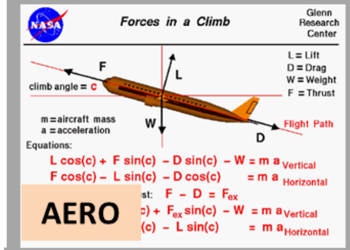
- <u>Existing</u> Pattern Configuration Envelopes:
  - Discovering and representing explicit System Patterns (S*Patterns), to increase agility of innovation: Leveraging what we know to lower risk, improve cost, speed of response, time to market, competitiveness;
  - These gains are available within the configurable space (envelopes) of those S*Patterns, by exploiting what "we" already "know";
- <u>Expanding</u> Pattern Configuration Envelopes:
  - Patterns are initially discovered and later expanded in envelope size by the exploratory learning part of the configuration trajectories;
  - Creating new higher level domain specific sciences by agile pattern extraction—the process of science, great success of the last 300 yrs.
  - Underlying patterns as Accelerators; Fields and Attractors.
- Improved intuition, as well as discipline, about direction and decision.
- Potential for automated support of direction analysis decisions.
- Environmental & opponent trajectories; game theory, differential games.
- Applies to innovations in the SOI itself, not just in the Target System

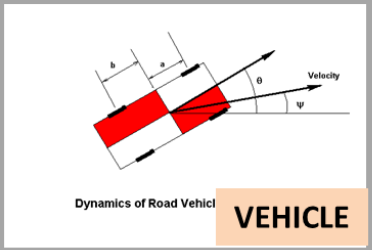
# Extension to Innovation Populations: Markets, Segments, and Ecosystems

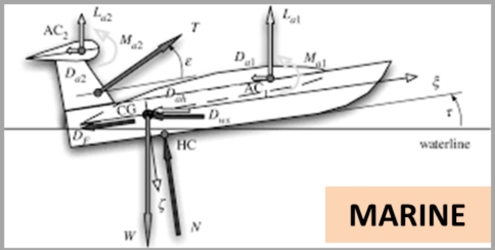
- We are also interested in more than the life cycle trajectory of a single system instance alone:
  - Dynamics of size of <u>populations</u> of innovated system instances
  - Markets, ecosystems
  - The diffusion of innovation
  - Directly tied to strategies of production, distribution, marketing.
- Diffusion of innovated system types through:
  - Commercial markets for products and technologies
  - Biological and other natural ecosystems
  - Military systems
- As studied at length in technology (Everett Rogers) and biological populations (E. O. Wilson, R. MacArthur):
  - Niches, Environmental Potentials, and Organizing Forces
  - Niche Organization and Entropy

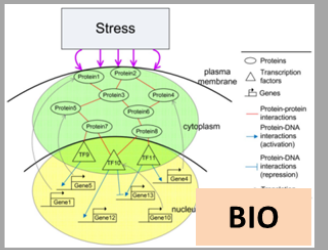
# Innovation in Populations: Markets, Segments, and Ecosystems



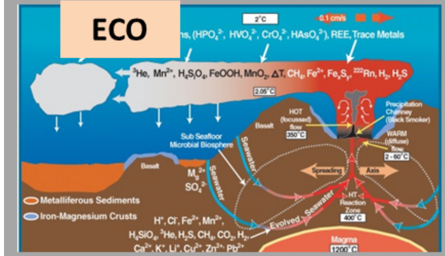




## ⬆ Recent Generations of Science / Engineering Patterns ⬆

As engineered systems become increasingly complex and human-critical, the challenge of innovation direction-setting needs to be more disciplined, objective, and transparent.

The theory of optimal control and estimation can help in this new environment.

## ⬇ Current Challenges Inviting Future Science & Engineering ⬇



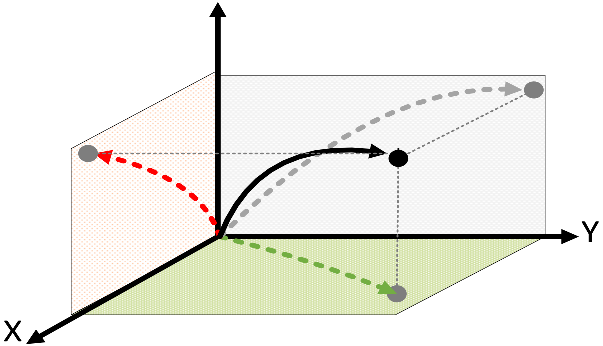


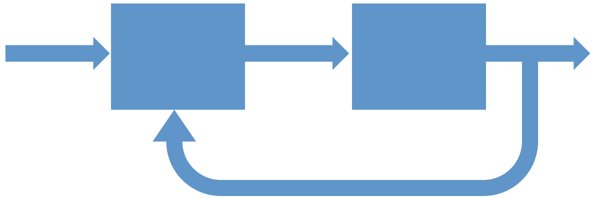

# Conclusions

1. Theories of optimal control and optimal estimation are based in state space, and become more applicable to innovation strategy when explicit system models are used to express system configuration.
2. Geometrization of formal spaces, already a source of major insights in the history of STEM, when applied to the innovation domain brings insight and understanding to planning and executing system innovation.
3. Heuristic practices for innovation strategy, agility, risk management, and learning may be enhanced by the use of mathematical system models of life cycle trajectories over innovation cycles.
4. For learning to be effective, the products of learning must be built into the roles that will perform future tasks to be informed by that learning—"lessons learned" filed in reports or searchable databases are not really learned in an effective sense.
5. Use of models does not replace human judgment, but enhances it in much the same way that STEM has advanced other human-managed activities, adding science and math-based foundations to previously intuitive practices.
6. Quantitative understanding of agile, fail-fast and recover early, lean, and experiment-based innovation methods is enhanced by viewing these through the lens of trajectory in configuration space.

# Future Steps, Discussion

7. How automated engineering tooling can be enabled to assist innovation teams by improving their decision-making around selection of activities;
8. Further exploitation of the historical work of (Pontryagin et al 1962), (Bellman 1957, 1959), and (Kalman 1960);
9. Extension of the mathematical theory by moving to populations, applicable to markets and other ecologies;
10. Incorporation of model verification, validation, and uncertainty quantification (VVUQ), and related application of learned system patterns (PBSE);
11. Enhanced visualization of product life cycle trajectories;
12. Simulation of innovation as a dynamical system.



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