Paul B. Martin

The Science of Systems Engineering

January 12, 2017 • 37 Likes • 11 Comments

[This was originally published at my SE-Scholar blog.]

I have a standard rant that I give to my students during my graduate SE course at UMBC. It goes something like this:

"Every engineering discipline has its science — Electrical Engineering has its Ohm's law — Mechanical Engineering has all of Newtonian Physics — Civil Engineering has Material Science — Chemical Engineering has its periodic table of elements — and so on and so forth. But what about Systems Engineering? Where is our science?"

Then I go on to explain how science can investigate and explain the parts of a system but not the emergent properties of a completed system. Emergence is a mystery to scientists. How do systems exhibit properties that will only manifest when components interact with one another? System level properties that are different than the individual component level properties? These system level properties can not be predicted.

Prediction is the main concern of Science. It is all about discovering laws of the universe that can predicted. These laws are then applied by Engineers so that a new technology can be created to meet mankind's needs. Scientists find knowledge, Engineers uses that knowledge to create or change the world we live in.

But here's the thing. There is no science to explain 'emergence'. It just is. And yet 'emergence' is a chief concern for a Systems Engineer. Even the INCOSE Systems Engineering Handbook Version 4.0 states:

"4.4.2.3 Emergent Properties — Emergence is the principle that whole entities exhibit properties, which are meaningful only when attributed to the whole, not to its parts. ... System elements interact between themselves and can create desirable or undesirable phenomena called "emergent properties," such as inhibition, interference, resonance, or reinforcement of any property. Definition of the architecture of the system includes an analysis of interactions between system elements in order to prevent undesirable properties and reinforce desirable ones. The notion of emergent property is used during architecture and design to highlight necessary derived functions and internal physical or environmental constraints."

But how can this "analysis of interactions between system elements" occur when you have no science to back you up. But you may ask — Don't we have "Systems Science?" Sure but "Systems Science" can not help us when it comes to 'emergence'. Again a quote from the INCOSE Systems Engineering Handbook:

"Research in systems science attempts to compensate for the inherent limitations of classical science, most notably the lack of ways to deal with emergence. Systems science has developed — and continues to develop — hand in hand with practice, each maturing and learning from the other."

So if we don't have a science, what do we do then? Well, we model. And that's why Model Based Systems Engineering is a critical concern within our profession. That's why the INCOSE SE Vision document, A World in Motion, Systems Engineering Vision 2025, states that:

- Model-based approaches will enable understanding of complex system behavior much earlier in the product life cycle.
- Model-based visualization will allow seamless navigation among related viewpoints such as system, subsystem, component, as well as production and logistics.
- Models will be used not only to capture design but to embody design rationale by linking design to top level customer and programmatic concerns
- On so on and so forth

So Systems Engineering lacks a science. It's OK, we have our best practices and it works. That why, when you look at the definition of Systems Engineering from the INCOSE Systems Engineering Handbook:

"Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems."

— notice that word: successful. Rest assured, we are in a profession that produces successful systems.

Written by

Paul B. Martin

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37 likes 11 comments

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Dave Robinson

Explictly focused on solving complex Aeronautical design problems for the Aerospace & Defense Industry

Is it really that emergent properties cannot be predicted or is it that we do not yet have the ability to look at and consider when bringing together the many diverse elements of a system, including those of sub-systems, every possible combination, permutation and associated outcome, in a timely manner and within budgeted limits for effort expended ?

Like(2) Reply(5) 1 day ago

Edouard Kujawski and Rafael Azevedo

Dave Robinson

Explictly focused on solving complex Aeronautical design problems for the Aerospace & Defense Industry

In the end it comes down to observing behaviours, recording those observations, analyzing the recorded data yielded through the observations, making inferences based on the analysis, predicting future outcomes based on the inferences, devising experiments to test those predictions, etc., i.e., the "Scientific Method" ...

Like 6 hours ago

Dave Robinson

Explictly focused on solving complex Aeronautical design problems for the Aerospace & Defense Industry

Paul, as I understand it (and I probably or most likely do not really), Analytics applied to Big Data (Data of huge Volume, Velocity, Variety: structured & un-

structured) constitutes a special framework for carrying out analysis and giving rise to algorithms which can be used for making predictions, useful in yielding insights subsequently to be employed in decision making.

Statistics can then facilitate the assignment of probabilities to go along with the results offered up through predictive analytics.

I hope, I'm sure actually, someone more knowledgeable than I on this will jump in and correct my misinterpretation if I've got it wrong.

Needless to say, Big Data Predictive Analytics may allow for the advanced discovery of Emergent Properties one day, ... perhaps not in the too distant future ?

Like 6 hours ago

Paul B. Martin

INCOSE ESEP; CompTIA CTT+

I've done some in-depth studying on Systems Science and Systems Thinking and I've never run across Data Science as a discipline to consider. Isn't Data Science a new label for the statistical mathematics crowd?

Like(1) 15 hours ago

Dave Robinson

Dave Robinson

Explictly focused on solving complex Aeronautical design problems for the Aerospace & Defense Industry

.
Paul, I just had a 'Eureka' type moment.

Seems that Big Data & Analytics (or "Big Data Analytics") and Systems Engineering or more aptly, 'System of Systems' Engineering, are due for a melding of minds in order to better tackle the issue of emergent properties.

That will, dare I say it, constitute the application of Data Science to the realm of Systems Engineeing.

Like 17 hours ago

Paul B. Martin

INCOSE ESEP; CompTIA CTT+

Good point Dave. I see both issues in a simultaneous conflagration of concerns that need to be managed during the design process. Thanks for sharing.

Like 22 hours ago

Mark Powell

Rescuer of Doomed Projects; Solver of Impossible Problems; Inspired by Sharing How to Do It All

Paul,

You said, "So Systems Engineering lacks a science."

I have to disagree with this rather strongly. SE actually employs and has all the "sciences" behind all the traditional engineering disciplines, else it won't work.

Also, emergence appears in most of the sciences as well, and is very normal. Think of all the concepts that emerged when the Hubble telescope went active. Think about CERN and all the concepts that emerged from that instrument.

The really big difference between SE and the traditional engineering disciplines is that SE actually must employ scientific thinking (not the scientific method) and approaches rather than look up and plug and chug formulas from a book without full understanding. SE has to understand or it won't even observe most emergences in systems.

Mark Powell

Like(1) Reply(2) 21 hours ago

Edward Davis

Mark Powell

Rescuer of Doomed Projects; Solver of Impossible Problems; Inspired by Sharing How to Do It All

Paul B. Martin,

Well, you are quoting the INCOSE handbook, which was generated by folks who seem strongly desirous of reducing the SE discipline to a set of procedures that can be executed by a less civilized tribe of bonobos.

That quote from the handbook (sic) is I think you will agree is not really complete, nor comprehensive, or won't be to anyone who has actually applied SE and made it work.

SE of course does not employ the scientific method, any more than any of the traditional engineering disciplines. There really is no place for the scientific method in any engineering traditional discipline or the supra-discipline of SE. That said, unlike the traditional engineering disciplines, a lot of scientific inquiry and approach must be applied to make SE work.

My point (one that seems to be ignored by those folks who generated and support the INCOSE handbook) is that a good SE practitioner who can actually be effective will be very experienced if not an expert in multiple traditional engineering disciplines, and any CSE worth their salt will be very experienced in most if not all traditional engineering disciplines. Now if you are talking about the SE clerks for which the handbook seems to be designed, you certainly do not need the science based expertise to do the job.

I don't know about you, but I have always hired folks with AA degrees to do the clerical SE jobs. They are cheap, usually very enthusiastic about the job, and do very well. Don't have a lot of technical chops to do a practitioner's job, but some build them with experience as clerks.

I hope I am amplifying your points.

Mark Powell

Like(2) 14 hours ago

Irfan Khan and Edouard Kujawski

Paul B. Martin

INCOSE ESEP; CompTIA CTT+

Mark, Actually it sounds like we do agree. My point was to explain that the more domain oriented engineering specialties (Electrical, Chemical, Mechanical, ...) all have a knowledge base that is based on the "scientific method." In other words, scientific principles that are found via a pattern of scientific activities of reductionism, repeatability, and refutation. (see Checkland, Peter. Systems Thinking, Systems Practice. Chichester: J. Wiley, 1981. page 51)

But when you look at the second part of the Systems Engineering definition from the INCOSE Handbook, "[Systems Engineering] focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. 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."

What part of any of these activities in this definition requires a principle discovered by the scientific method? Sure there is the fact we "integrate all the disciplines and specialty groups" who use their own scientific principles doesn't mean we have our own. Which is why "systems thinking" becomes critical to the SEs tool kit.

Does that clear up what I was saying? let me know. ~~Paul

Like 17 hours ago

Mikael Seppälä

Design for Data and Enterprise Architecture

Enterprise Architecture (EA), which, if I understand SE correctly, seeks to apply Systems Engineering to (ICT) systems development. EA is heavily model-based but not necessarily always successful in dealing with emergence. We need both approaches: modeling for causalities (the traditional science) and creating systems conditions (still marginal in sci-

ence) that might give rise to desired outcomes. In addition to modeling systems, principles/high level guidelines are an approach that is being applied for emergence. The GDS Service Manual is a great example of this that seeks to create desired emergence in a highly complex context (government): https://www.gov.uk/service-manual/service-standard

Like Reply(1) 1 day ago

Paul B. Martin

INCOSE ESEP; CompTIA CTT+

Very astute observation Mikael. The more I study 'emergence' and its effect on systems studies, the more I'm convinced that effective modeling is the key. Thanks for sharing your thoughts.

Like(1) 22 hours ago

Mikael Seppälä

Eero Hollming

..worth widening into “Systemic Systems[-of-Systems] ‘engineering’ is an interdisciplinary full-spectrum-response-approach and means to enable and deliver the focal-to-systemic-viable and lateral-longitudinal-embedded through-life-response of successful/surviving/viable-value-delivering co-evolutionary [eco]systems" [..into increasingly complex-emergent systemic wickedness]. The very emphasis on the emergence-vs-design[ed/-able]-interference-intensive focal-to-systemic through-life-spanning viably-surviving-response orchestration [across full-spectrum-disciplinary domains on platforms/capabilities/operations/systemic-viable-ambidexterity-response/etc]..

Like Reply(2) 1 day ago

Eero Hollming

..we had already since early 2000's (especially in 2005-2007, 2008-2009) quite extensive efforts (involving e.g. local INCOSE here in Finland) on such Network-Centric-Innovation-response into complex-emergent and systemic-wicked fusion-landscape of (a) strategic-growth-outcomes-driven business-ecosystems [spanning related joint open-strategizing to operations and respective ambidexrous-growth-requirements-driven responses], (b) respective complex-emergent through-life-spanning systems-of-systems [as such platforms/capabilities/operations etc, and related full-spectrum wickednesses], and (c) related dynamic-mission intervention-vehicles [i.e. complex programmes/projects and increasingly towards viable-value-delivering mission-responses]. Since then, quite an extensive journey with such apparatuses and responses on various scales, and quite recently, e.g. last year and ongoing, some extensive elaborations with continuous strategic-growth-outcomes-driven open-strategizing across such systemic-wicked dynamic-co-evolutionary mission ecosystems, and respective strategic spearheading..

Like 19 hours ago

Paul B. Martin

INCOSE ESEP; CompTIA CTT+

Eero, Nice steam of conscious. I think your saying that approaching design in a "system-of-systems" manner can try to anticipate any unintended consequences [which I define as undesirable emergent properties]. If your concerns can be captured into a model, then we'll definitely be closer to a proper design solution. Thanks for sharing your thoughts.

Like(1) 22 hours ago

Eero Hollming

Poliñho Katina., BSc MEng PhD

Good read. You might want to get in touch with Kevin Adams

Like Reply 1 day ago

Rafael Azevedo

Customer Business and Support Manager for South America at Honeywell Aerospace

Nice article! Thank you for sharing.

Like Reply 1 day ago

Bjorn Cole

Project Systems Engineering Analysis Lead at JPL (NASA's Jet Propulsion Laboratory)

Paul thank you for the post. I have been thinking a lot along these lines as well, but upside down. Emergence is a bottoms-up way of getting to complex behavior that is hard to find a (understandable) model to. Deep learning is now fitting models to complex behavior but if you tried to read them you'd be just as baffled as with the original behavior.

My own thinking is that our goal as systems engineers is to decompose a system or problem with complexity in such a way that minimizes an aggregate of the complexity of all individual models in the explanation combined with complexity of the network.

I don't quite have a polished set of slides in the idea but wanted to get some on slideshare. I'd greatly appreciate your thoughts when that happens.

Like Reply(1) 21 hours ago

Paul B. Martin

INCOSE ESEP; CompTIA CTT+

Yes, Bjorn, please keep in mind if you want someone to review your ruminations on the subject. I may do the same to you. ~~Paul

Like 16 hours ago

Michael Fox

Emergent function in the context of replicated systems, which exceeds mere multiplicity pro-

vides a more distinct case where SE makes invention/innovation to achieve an appropriate level of complexity. Only in SE does one apply the scientific method since decisions are primarily focused on ruling out those system designs which are infeasible by finding no more than one proposition per concept to reject, justifying culing the list of alternatives. Physical science, on the other hand, has generally provided sufficient understanding for design to proceed in the context of a closed set of rules. If your SE practice doesn't operate based on these fundamentals, you may expect to find unexpected outcomes.

Like Reply 10 hours ago

Qaswar Abbas B.Eng,MBA,PMP, ITIL

Avionics / Electrical /Fly By Wire Sr. Project Engg Specialist - Global 7000 Program

Science of systems engineering is prediction of systems performance. This science is also in the emerging phase, shall mature in future.

Like Reply 2 hours ago

Tim Manning MBA

Freelance Business Architect

Systems Engineering does not lack a science. Systems Thinking is the science of systems. Systems Engineering is applied Systems Thinking in the field of engineering. ST as a science, applies the scientific method, i.e. the systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses. It does this principally through the creation of models, e.g. climatic change modelling.

Like Reply 1 hour ago

Geoff Elliott

Owner, Elliott Partnership - Management Consultancy

.....ST as a science, applies the scientific method, i.e. the systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses. It does this principally through the creation of models, e.g. climatic change modelling..... But is doesn't. ST is about thinking including systemic thinking and not about applying systematic observation,measurement and the analytical reductionist paradigm. Modelling, eg SD is only one part.

Like Reply 1 hour ago