Improving the capability to Engineer Complex Systems – Broadening the Conversation on the Art and Science of Systems Engineering

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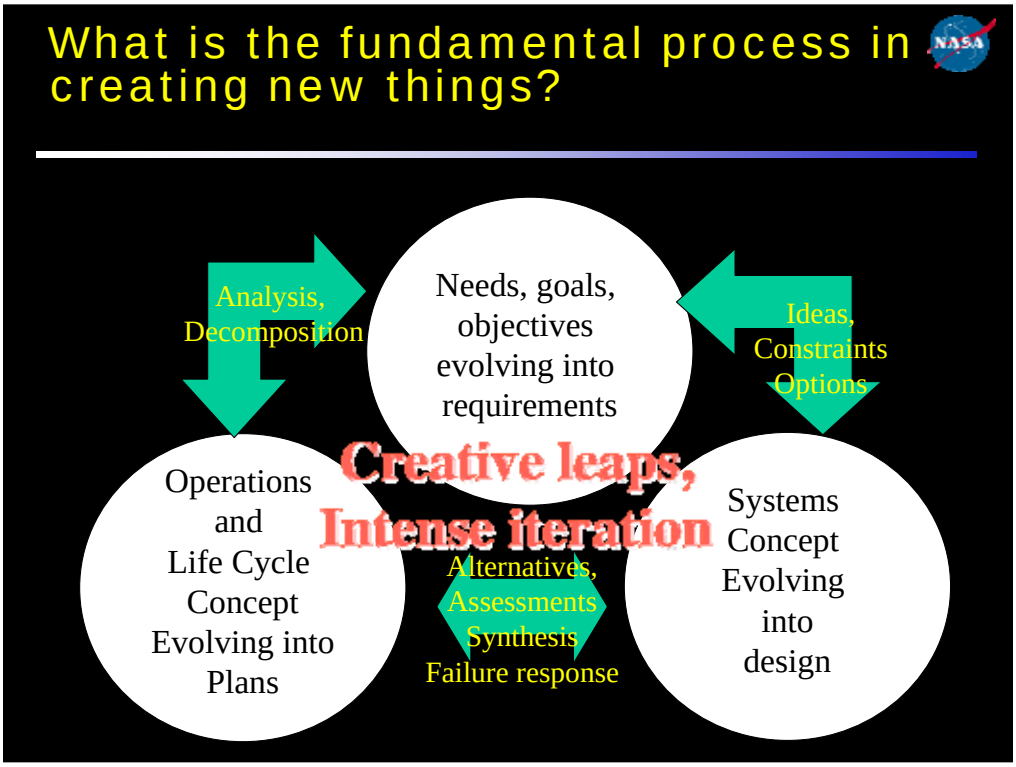
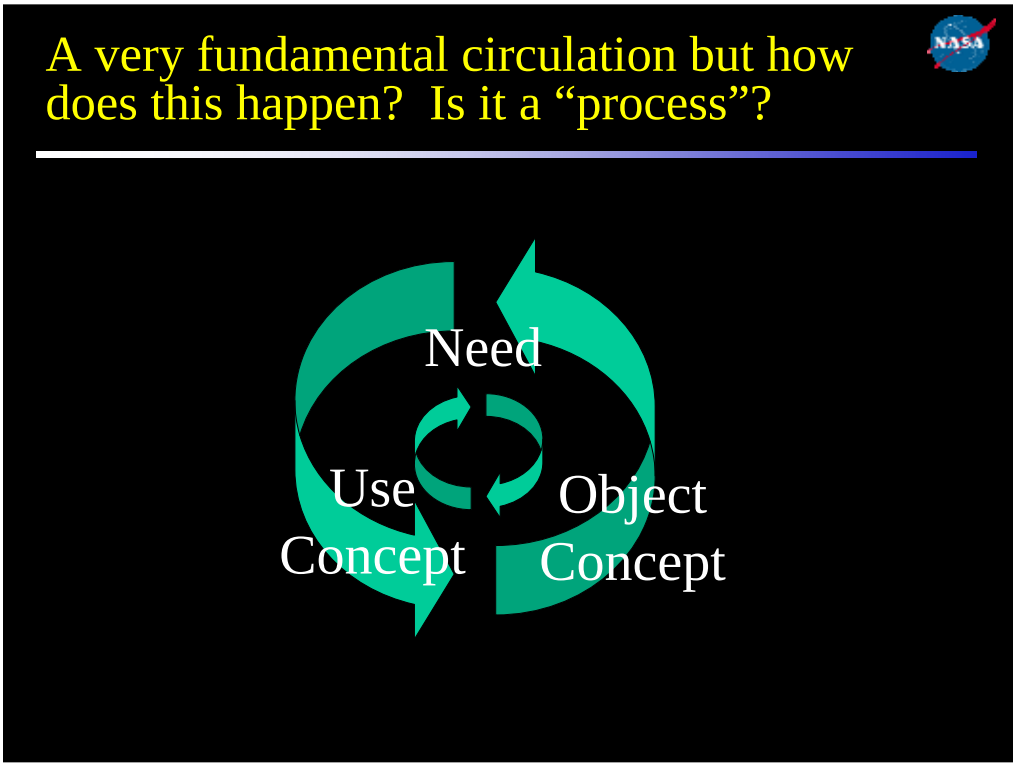
What is Systems Engineering?

Systems engineering is the art and science of developing an operable system that can meet requirements within imposed constraints. It is holistic and integrative and incorporates and balances the contributions of the "standard" engineering disciplines plus cross-cutting ones to produce a coherent whole that no single discipline dominates. Systems engineering is about tradeoffs and compromises, about generalists rather than specialists.



There have been many attempts to describe the logical process by which one proceeds from a need to create a system. Every description I have every seen, whether it is “V’s” or “W’s” or the SE engine or something else, understates how messy and non-linear the activity is or how important creativity isto both the “what” of the final system design but also the “how” of getting there. Creativity is every bit as important as knowledge but we don’t really understand it works or how to teach it. The willingness to try again and again until a good solution is critical as is knowing when to stop.



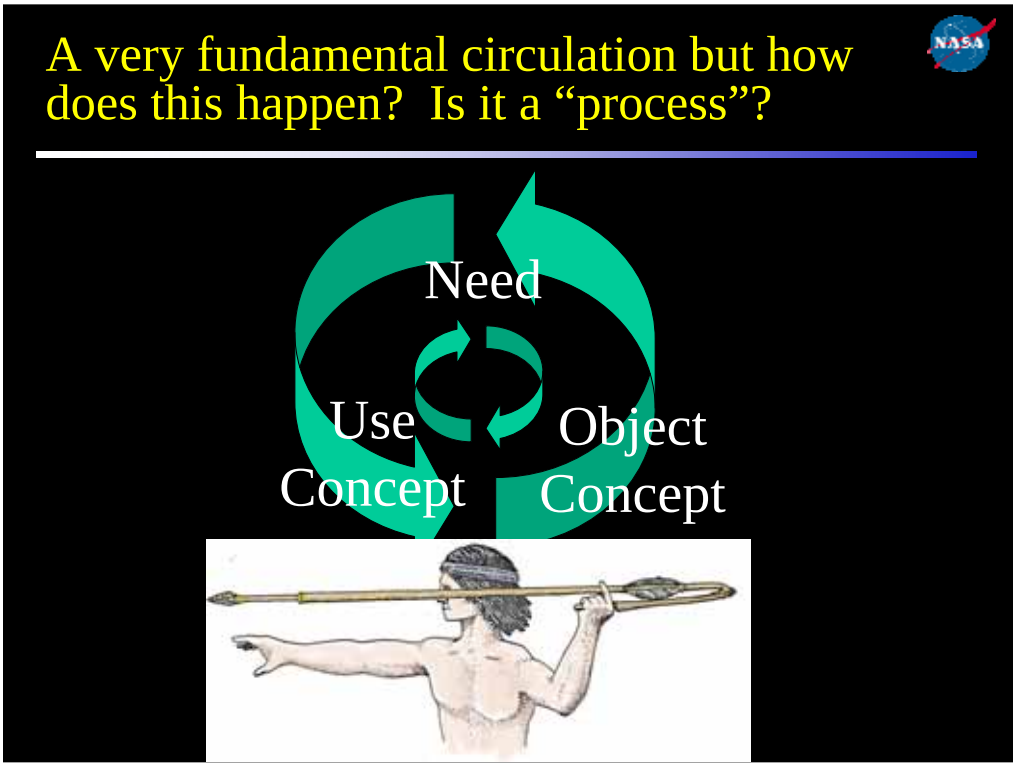
What triggers the leap from a need to either a object concept or a use concept?

Some humans have it, some animals have it.

What makes some people better at this than others? Experience? Ability to try a lot of things rapidly? Talent? All of the above?

While a great deal of effort has been invested in trying to figure out how "creation" works and how it can be taught, fundamentally, we do not yet know. Creative skills can be developed but not out of nothing. A photographer "sees" things others can't then "shows" them to others.

This is inherent to engineering but it is not sufficient



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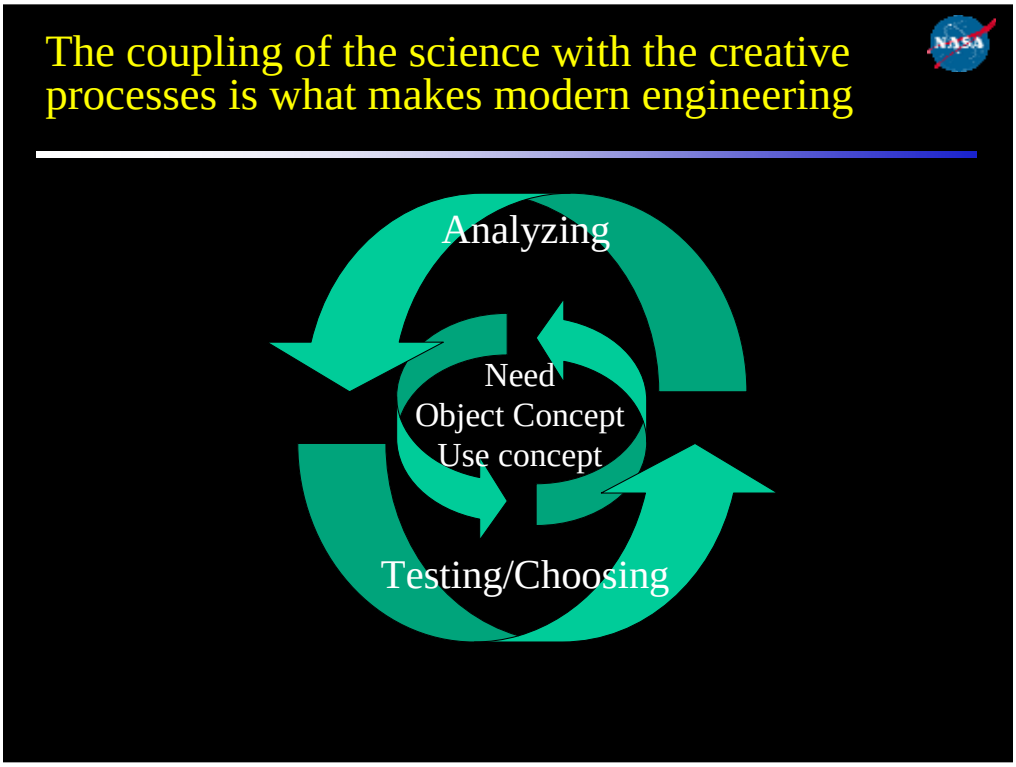
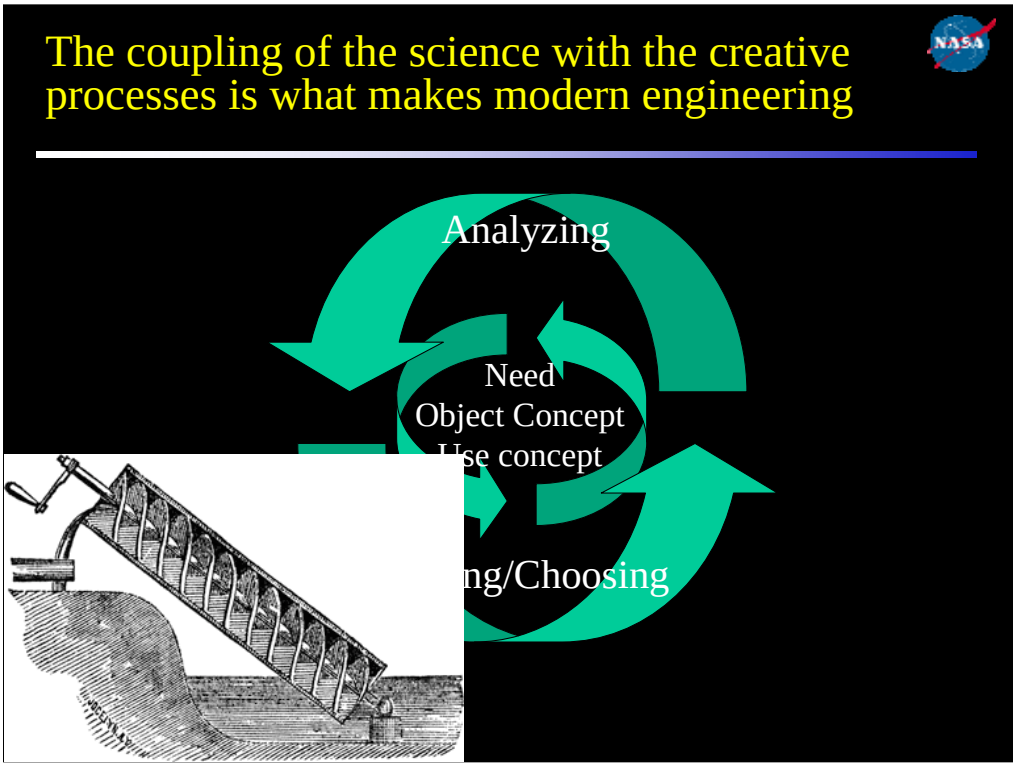
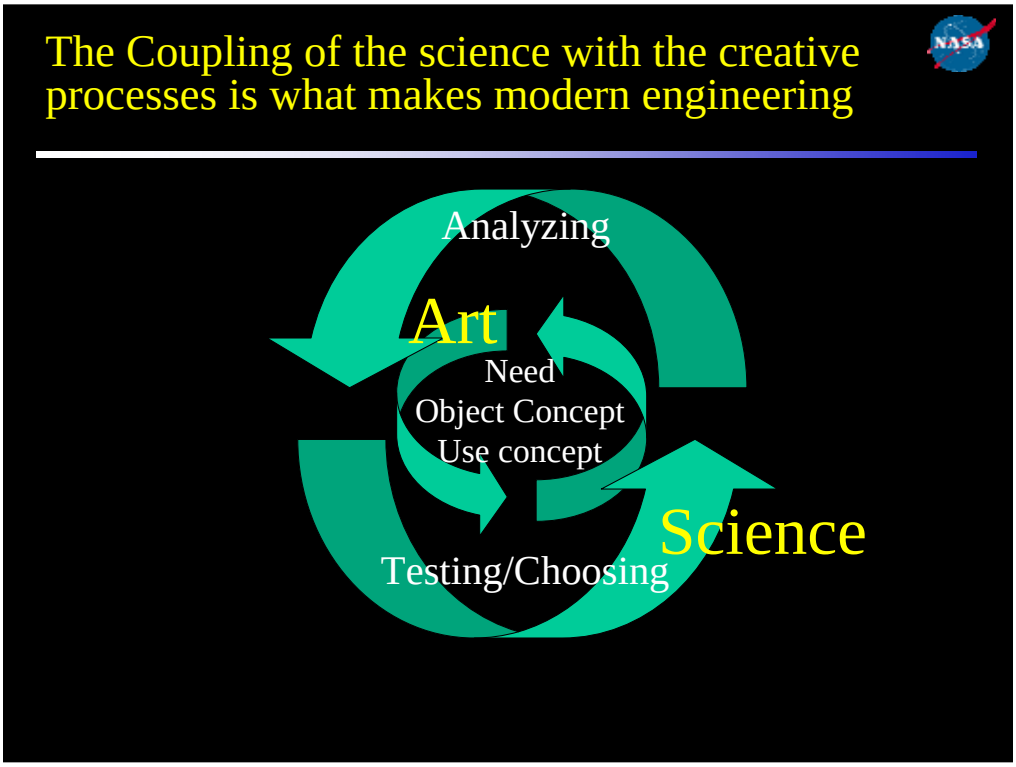


Clearly, engineering as we practice it relies on formal techniques, most of them mathematically based to allow for rapid generation and testing of designs and concepts. The tools and methods have evolved dramatically over time but fundamentally, we make a mathematical abstraction of a concept and test it via deterministic or probabilistic methods against some kind of objective criteria to determine "goodness"



The picture is of Archimedes screw and was chosen because while Archimedes was clearly a pioneering mathematician and disdained anything “useful”, one can make the argument that Archimedes was the first (or at least the forerunner of the modern engineer). Although it took most of another two millennia for the rest of the world to catch up, he clearly used mathematical analysis as a tool to solve problems. This was a sea change since others though of complex mathematics as as topic to be studied for its own sake and NOT as a tool with which to understand and do virtual manipulations of the rest of the world. Although is is hard to discern fact from amplified legend, even with near contemporaneus history it is clear that he designed an built a great many war machines which King Heiro of Syrcuse used in an extended defense of the city against the Roman General Marcellus. If you want proof that Archimedes was an engineer, you only need to consider how he died. Archimedes apparently paid no attention to the siege and battle and after the fall of the city, Marcellus send soldiers to bring Archimedes to him. When the soldiers accosted him at work, Archimedes reported told them to “stand away frm my diagram” whereby one of the soldiers stabbed him. There are many deans and project managers who can sympathize.



Seems simple, so why is this so hard? I submit that this is rooted in what Mike Griffin identified in his Boeing Lecture at Purdue in 2007 as the "two cultures of engineering". Building on C.P. Snow's description of the cultural divide between those knowledgeable in the humanities and those knowledgeable of the sciences, Griffin described a similar divide between the "art" and the "science" of engineering. He described "*engineering* science as the study of that part of the world which has been created by man" primarily using processes and formalisms which can be written down and taught and heavily rooted in mathematics and the hard sciences. Theodore von Karman observed that, "Scientists study the world as it is; engineers create the world that has never been." The "art" of engineering is that creation and while there are techniques which can aid and abet, fundamentally the "art of creation" is tends to build on "talent" and is learned in the school of hard knocks. Engineering is just like almost everything else we do as humans. predispostion ("talent" plus training plus sweat can take you to the highest echelons of any endeavor. If any of these are missing, you won't go nearly as far. We see it in almost everything we do –"you can't coach height", " the girl has a photographers eye".

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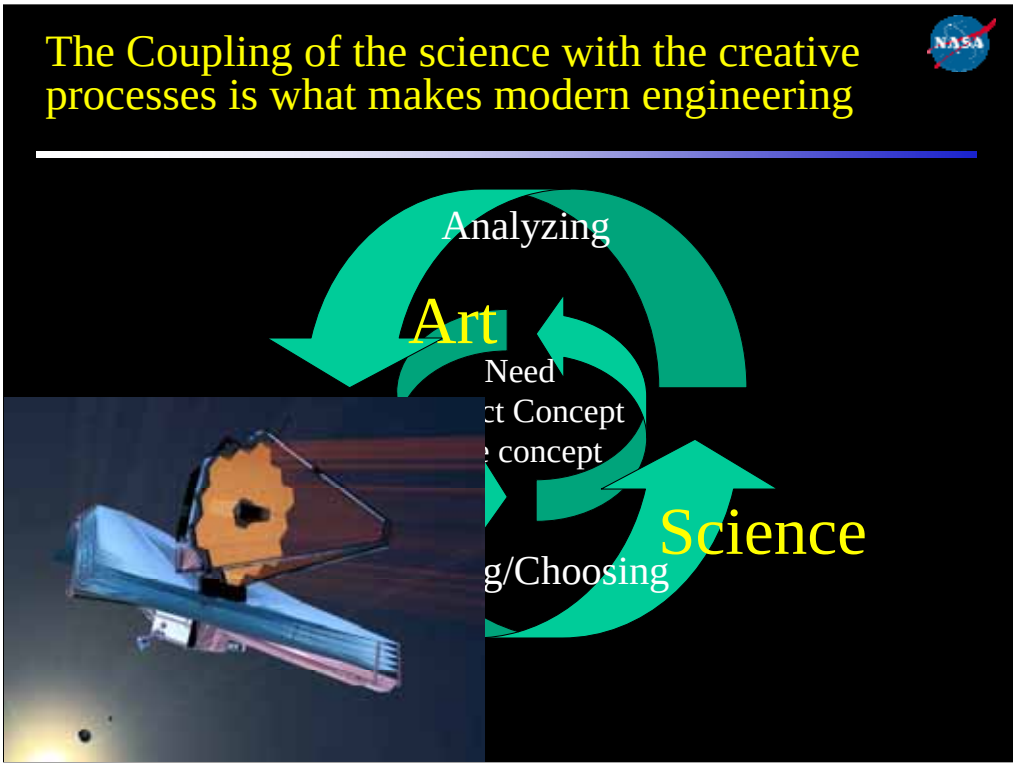

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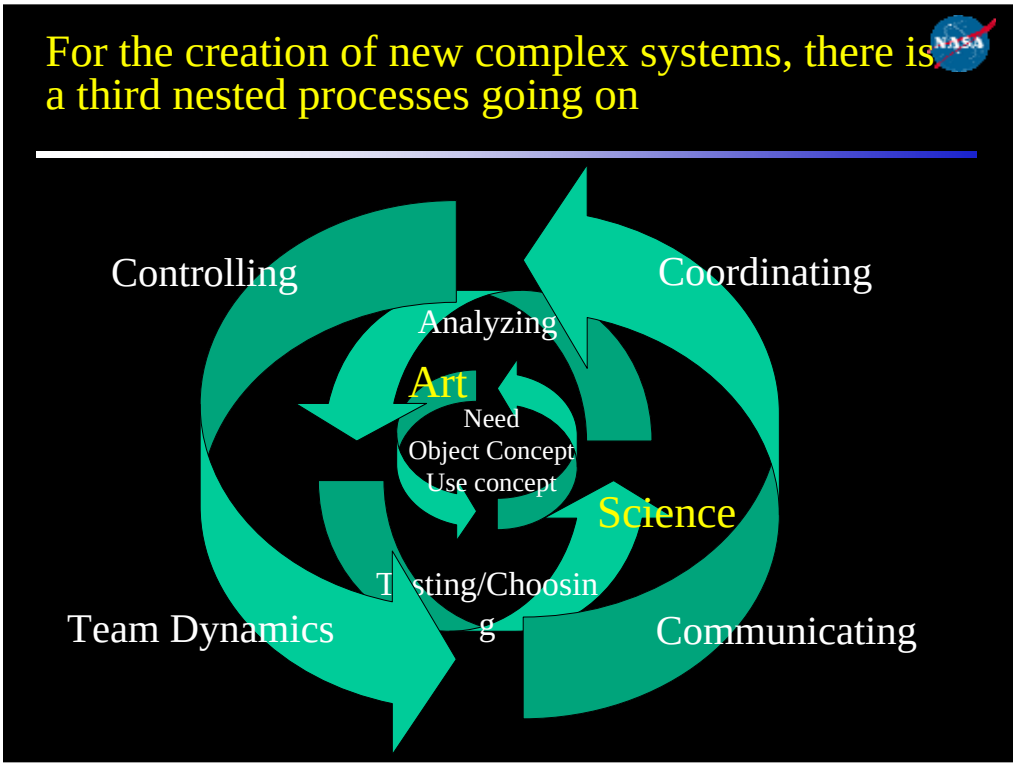
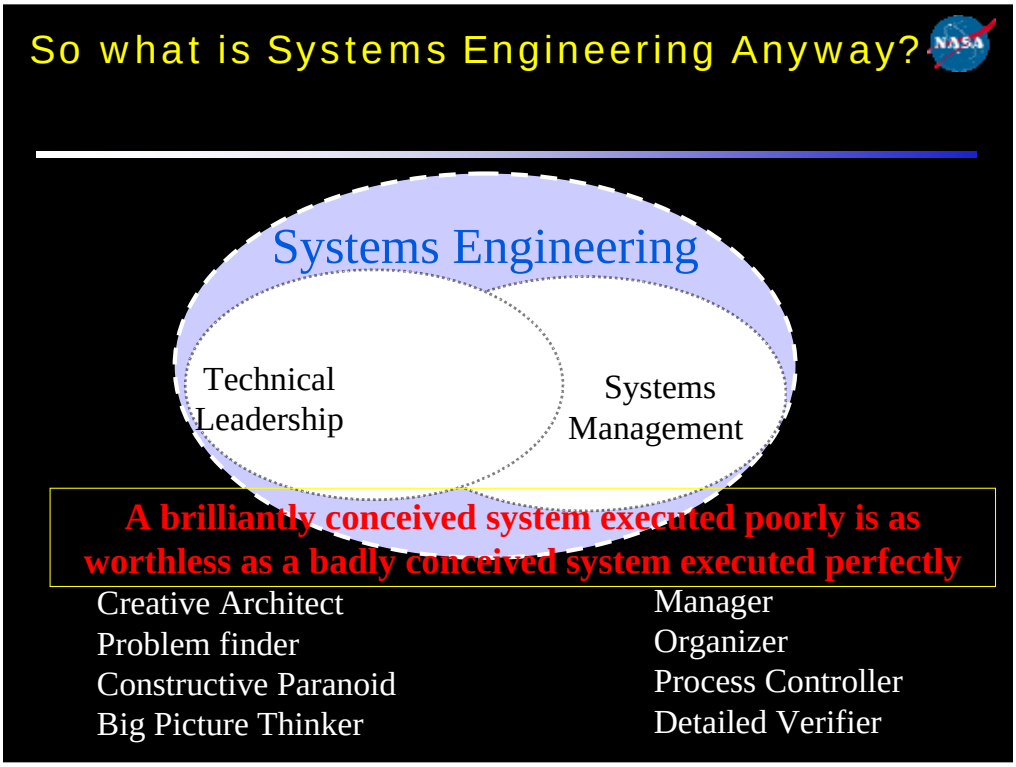


As Stephen Johnson has laid out so well in the "Secrets of Apollo", starting in the fifties to deal with very complex and "unforgiving" systems, the aerospace industry has evolved the techniques of systems management but by focusing on them, we have a tendency to lose sight of the complete picture.

When talking about what we can do to make our complex developments "go better" we tend to quickly focus on policy, process, databases, tools and techniques. Partly because these ARE necessary to support completeness and consistency, partly because it is straightforward to come up with an action plan and make metrics.

We tend to pay less attention to the things which affect creativity, innovation and team performance in part because it is hard to come up with a deterministic improvement plan and in part be cause we are part of a scientific and engineering culture which tends to undervalue the "soft" skills. Even more importantly and perhaps because it is so difficult, we tend



Technical leadership focuses on a system's technical design and technical integrity throughout its lifecycle. **Technical leadership, the *art of systems engineering, balances broad technical***

domain knowledge, engineering instinct, creativity, leadership, and communication to

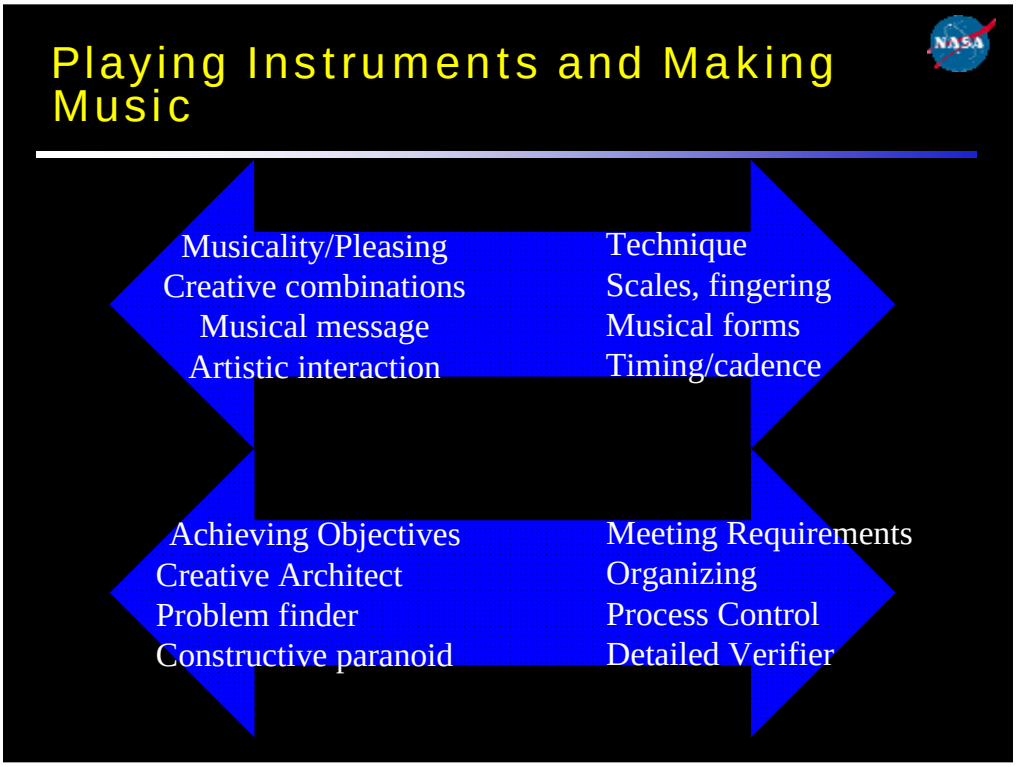
develop new missions and systems.

• Systems management focuses on managing the complexity associated with having many technical disciplines, multiple organizations, and hundreds or thousands of people engaged in a highly technical activity. **Systems management's focus is on rigorously and efficiently managing the development and operation of complex systems.**

The Mentioned and the Unmentioned

- The things we talk about
  - Analyzing
  - Documenting
  - Controlling
  - Coordinating
  - Decomposing
  - Verifying
- The things we don't
  - Creating
  - Communicating
  - Team Dynamics
  - Challenging
  - Problem hunting
  - Gaps
  - Situational awareness

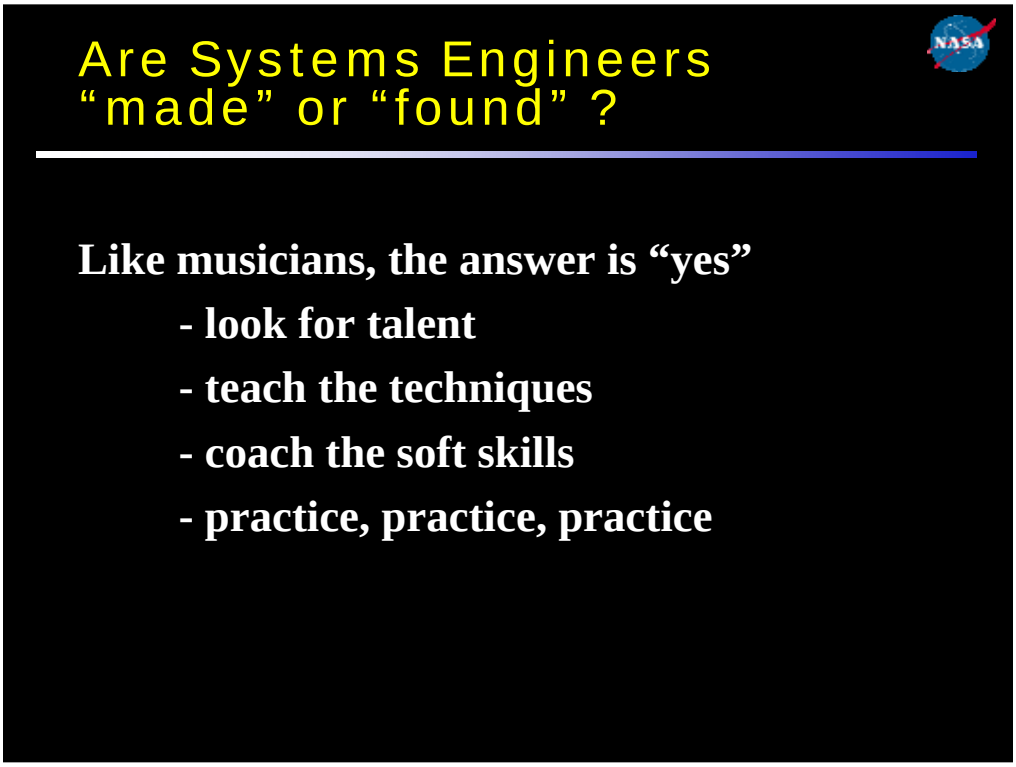
"The prescription of technique cannot be a substitute for talent and capability, but that is precisely how we have tried to use technique." – *Robert Frosch, 1969*



One way to describe the art and science of systems engineering is by comparing it to an orchestra and its ability to perform a symphony. Though most people understand what music is, not everyone can play an instrument. Each instrument requires different levels of expertise and skill (a technical discipline). Some musicians spend their entire careers mastering one instrument, which is good because every instrument needs to be played well. But more sophisticated music needs many different instruments, played in unison. They may produce beautiful music or a terrible cacaphony, depending on how well they come together. Think of the symphony musicians attempt to play as the system. Musicians apply the science of music: they follow the process of translating notes on a page to play their instruments. But a conductor must lead them to connect the process of playing music with the art of creating great music. The conductor is the systems engineer, who knows what the music should sound like (the look and function of a design) and has the skills to lead a team in achieving the desired "sound." Orchestra conductors do a lot more than just keep time! An orchestra conductor: • knows music and understands issues like pitch, rhythm, dynamics, sonic qualities—as well as capabilities of various instruments and musicians • is necessary once the orchestra reaches a certain size and complexity • typically has mastered one or more musical instruments • may be a composer • selects and shapes the music an orchestra plays • interprets a composer's music in light of the audience • often strives to maintain the integrity of the composer's intentions • organizes and leads musicians playing different musical instruments • is responsible for the performance's success Similarly, a systems engineer: • understands fundamentals of mathematics, science and physics, as well as capabilities of various people and disciplines • is necessary once a project reaches a certain level of complexity The Art and Science of Systems Engineering • has mastered a technical discipline and learned multiple disciplines • must understand the endeavor's end game and overall

The Mentioned and the Unmentioned

- The things we talk about
  - Easy to write down
  - Easy to measure
  - Can be learned in classroom
  - Amenable to “guidelines”
- The things we don’t
  - Hard to write down
  - Hard to measure
  - Mostly learned by doing
  - Noticed only when absent
  - Commonly absent from training and development programs



We all know the stories of the jazz musician who went started playing with the "greats" as a young person. He had to have enough talent and capability to get "in" and then learned by doing.

For systems engineers the time honored tradition is to let them grow via a similar apprenticeship process

- start in a discipline and master it
- take on more and more complex problems, bigger teams
- join a systems team under a "guru" and become a "guru"

The flow is sound but we can and must accelerate and go for greater consistency and completeness

- teach the science

A NASA-centric Study - What makes a great systems engineer

- The NASA Chief Engineer commissioned a study to interview "go to" systems engineers to identify common characteristics and behaviors
  - Social scientists interviewed subjects and then observed them at work
  - Results were remarkably similar across NASA
  - Used to formalize the basis for identifying high potential candidates
  - Used to update curricula, training programs, etc

This was done to put the work on a firm basis, both for the hard science non-believers and for the human resources people so we can formally make these part of evaluation and selection processes. Everyone believes that an systems engineer ought to have a technical degree and demonstrated technical acomplishments, not everyone wants to believe that leadership is important for a "Technical" position

A NASA-centric Study - What makes a great systems engineer

- **Technical Acumen** -- **Possesses Technical Competence and Has Comprehensive Previous Experience**
- **Problem Solving & Systems Thinking** -- **Has the Ability to Find Connections and Patterns Across the System; Identifies the Real Problem**
- **Attitudes & Attributes** -- **Has a Comprehensive View, Possesses a Positive Attitude and Dedication to Mission Success; Is Aware of Personal Limitations; Adapts to Change and Uncertainty; Uses Intuition/ Sensing**
- **Communication** -- **Listens Effectively and Translates Information; Facilitates an Environment of Open and Honest Communication; Communicates Through Story Telling and Analogies**
- **Leadership** -- **Creates Vision and Direction; Appreciates/ Recognizes Others; Understands the Human Dynamics of a Team; Coaches and Mentors; Delegates**

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Leadership

"A **team** is **made up of many individuals. The more individualistic, the better. When putting a team together, the director should not** try **to find people whom he can outsmart, but people who are smarter than he is.."**

Then comes a test of leadership. All **the people around the table are experts in their own field. Each one should be a strong individual, with strong feelings, capable of thinking problems through on his own -- or he should not be there. When a conflict arises, the director must be able to find a compromise solution that is best for the satisfactory accomplishment of the mission, and get willing agreement from the dissenters."**

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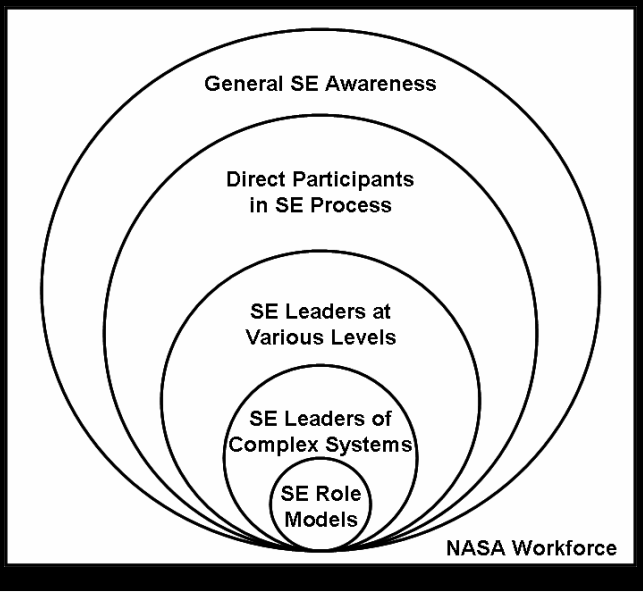
Werner von Braun

We need to be aware to whom we are talking



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Suggested reading

----Mike Griffin, speech on the two cultures of engineering at Purdue University, March 28, 2007
http://www.nasa.gov/news/speeches/admin/mg_speech_collection_archive_2.html

---- http://www.nasa.gov/news/reports/NASA_SE_Behavior_Study.html
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The easiest way is to just go to: http://appel.nasa., which redirects to the OCE site and then they can look for SELDP.