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Heuristics in Systems Engineering

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- Have spent over 30 years at the company, in different roles including intelligence analyst, software developer, systems engineer, program manager and functional manager.
- Education includes a BS in Physics from Georgetown Univ., MSEE and MSCE degrees from Syracuse Univ., and an MA in Management from Fielding Graduate Univ.
- Currently the President of the Finger Lakes Chapter of INCOSE and is a Certified Systems Engineering Professional (CSEP).
- Have presented several papers at recent INCOSE IS, mostly related to the application of Integral Theory to SE.
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Agenda

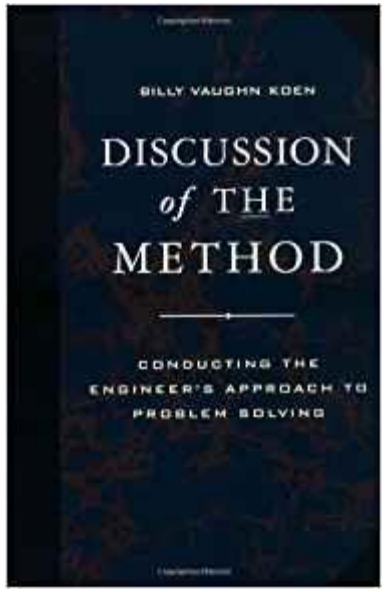
1. Introduction to Heuristics
2. Heuristics in SE
3. Some Recommendations

Introduction to Heuristics

Engineering Heuristics

- Koen's work on heuristics began in 1965
- Artificial intelligence class
  - Program a computer to demonstrate a portion of Godel's proof
  - Use heuristic programming
  - If arithmetic is a heuristic, maybe "all is heuristic"
- Koen taught engineering methods class
  - Developed his theory of heuristics

Billy Koen
M.E. Professor
University of Texas



Discussion of the Method (2003)

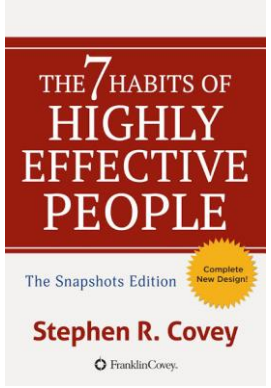
Heuristics and Chess

- Koen's roommate was a highly ranked chess player
- Chess defies analytical analysis
  - Large combination of positions
- Roommate taught Koen chess heuristics
  - Open with a center pawn
  - Move a piece only once in the opening
  - Develop the pieces quickly
  - Castle on the king's side as soon as possible
  - Develop the queen late

My Introductions to Heuristics

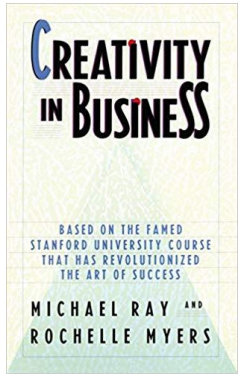
Stephen Covey – 7 Habits

1. Be proactive
2. Begin with the end in mind
3. Put first things first
4. Think win-win
5. Seek to understand first, then to be understood
6. Synergize
7. Sharpen the saw



Michael Ray – Creativity Course

- Have no expectations
- Absence of judgment
- Pay attention
- Ask penetrating questions



What is a Heuristic?

- A heuristic is anything that provides a plausible aid or some direction in the solution of a problem
  - Intended to be used as aids to make quick estimates and preliminary design decisions
- Experienced-based methods
  - Not scientifically derived or validated (like algorithms)
- Heuristics are frugal – they ignore part of the information
  - Used for finding a “good enough” solution (satisificing)
  - Contrast this with finding the “best” solution (optimizing)

Four Signatures of a Heuristic

- It reduces the search time for solving a problem
- Its applicability depends on the situation
- It does not guarantee a solution
- It may be contradicted by other heuristics

Two Types of Heuristics

- Numerical
  - Rules of thumb
  - Orders of magnitude
  - Factors of safety
- Non-numerical
  - General principles, best practices
  - Attitude determining heuristics
  - Design patterns, design heuristics

Numerical Heuristics

Rules of Thumb
The yield strength of a material is equal to 0.02 percent offset on the stress-strain curve
Air has an ambient temperature of 20º C and composition of 80% nitrogen and 20% oxygen
A properly designed bolt should have at least one and one-half turns in the threads

Order of Magnitude
One gram of uranium gives one megawatt-day of energy
Cost of a highway - $2 million per mile (2-lane rural highway)
To estimate the cost of a building, estimate the amount of concrete, then multiply by the cost of hamburger meat
If a high-tech building, use sirloin instead of hamburger meat

Factors of Safety
Use a factor of safety of 1.2 for leaf springs
Use a factor of safety of 1.5 for commercial airplanes
Use a factor of safety of 2.0 for the bolts in an elevated walkway
Use a factor of 10-13 for flywheels

Non-numerical Heuristics

General principles
Always make the minimum decision
Break complex problems into smaller, more manageable pieces
Design for a specific time frame
Use feedback to stabilize engineering design

Attitude-Determining
Quantify or express all variables in number
Always give an answer
Work at the margin of solvable problems
Always give yourself a chance to retreat

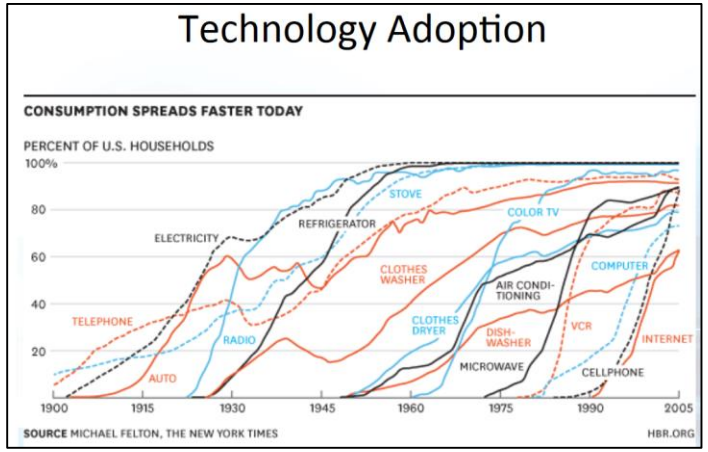
Design Patterns
Redundancy
Excess capacity
Layered defense
Graceful degradation
Loose coupling
Simplicity

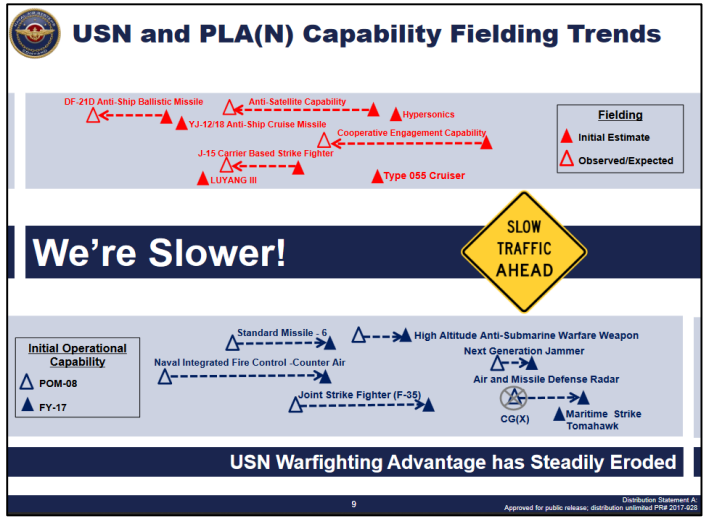
Heuristics as the State of the Art

- A group of heuristics is typically used to solve problems
  - Not used in isolation
  - The set of heuristics judged to represent the best engineering practice at the time is the “state of the art”
  - When a product or system is considered “state of the art,” that means it was built using the best set of heuristics available at the time
- State of the art changes with time
  - New heuristics added, obsolete ones deleted
- Each engineer has their own set of heuristics, personal state of the art
  - What are the heuristics that make up your own personal state of the art?

Why Heuristics Are Important – Speed!

- 2016 INCOSE IS
  - Jan Bosch (keynote)
  - The need for speed
  - Increasing speed trumps any other improvement R&D can provide to the company
- 2017 NDIA SE Conference
  - Admiral Paul Grosklags (keynote)
  - We need to develop systems faster
  - Adversaries are catching up to us



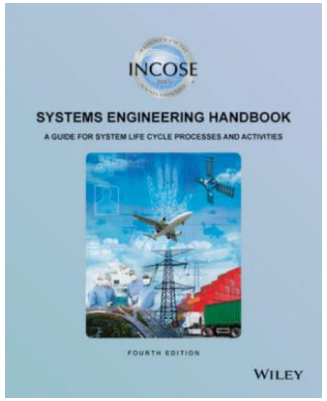


Heuristics in SE

SE Heuristics – Rules of Thumb

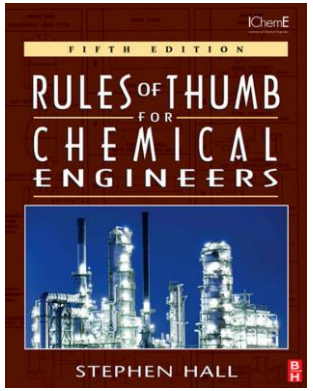
Hard to Find SE Rules of Thumb

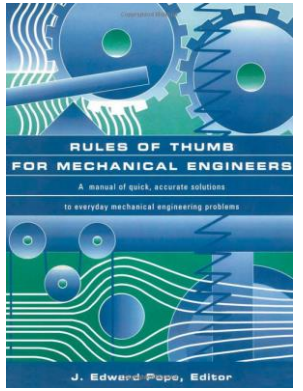
- INCOSE handbook has 3
  - System architecting – for each level in a hierarchy, there should be no more than 7 +/- 2 elements subordinate to it
  - Life cycle cost – when 20% of the actual system cost has been accrued, 80% of the total LCC has already been committed
  - SE planning – the optimum level of SE effort is 14% of the total program cost



Other Disciplines Use Them

- Chemical, mechanical engineering have books full of rules of thumb
- Over 400 pages
- “Hundreds” of rules of thumb





Why So Few Rules of Thumb for SE?

- Systems engineering prefers algorithms to heuristics
  - Cultural preference for optimizing over satisficing
  - SE roots in operations research and optimization
  - Resistance to settling for “good enough”
- Heuristics tend to be domain-specific
  - Systems engineering is domain agnostic
  - SE domain areas may be more fertile ground for rules of thumb and shortcuts
  - Aerospace, automotive, healthcare, infrastructure, transportation, energy, etc.

Example - Radar SE Rules of Thumb

- To double detection range, add 12 dB more power
- Every 1 dB of extended range costs $1M
- Radar horizon (nm) = $1.23\sqrt{Height(feet)}$
- For array antennas, space elements half-wavelength apart
- Good estimate of angular accuracy is 1/20 beamwidth
- Antenna gain is roughly 32,000 / ($beamwidth_{az}$ * $beamwidth_{el}$)
- For every pound of electronics, estimate two pounds of mechanical structure
- Clutter canceling – 60 dB easy, 80 dB hard, 100 dB pushing it
- It takes 3 years to develop a radar prototype
- It takes 5-6 years to develop a radar product
- Have at least 3 dB performance margin at Preliminary Design Review

Lightweight Counter Mortar Radar

SE Heuristics – General Principles

Systems Architecting

- The Art of Systems Architecting
  - By Mark Maier, Eberhardt Rechtin
  - 180 heuristics
- Architecting Resilient Systems
  - By Scott Jackson
  - 40 heuristics

Lean Systems Engineering

- Lean for Systems Engineering
  - By Bodhan Oppenheimer
  - 180 heuristics

Cost Estimation

- Heuristics for Systems Engineering Cost Estimation
  - By Ricardo Valerdi
  - 31 heuristics

System Modeling

- Operations Research: Principles and Practice
  - By A. Ravindran, Don Phillips, James Solberg
  - 10 heuristics

Top Level SE Principles – No Consensus

Several papers on heuristics written in early 2000's

Year	Main Author	Title	Count
1993	J. DaFoe	An Identification of Pragmatic Principles	8
2001	B. Mar	Systems Engineering Heuristics	44
2002	R. Halligan	Systems Engineering Principles	20
2004	M. Han	Systems Engineering Principles Revisited	8

- Can we come up a canonical list of SE guiding principles?
  - A 7 Habits of Highly Successful SE's?
  - Or 10 or 12?
- Seems like this falls under INCOSE mission
  - "INCOSE produces state-of-the-art work products that further the discipline, leading to improvements in productivity and effectiveness"

Core Principles vs. Guiding Principles

Core Principles (Han, 2004)
SE keeps the systems perspective
SE transforms big complex problems into many small solvable problems
SE reduces the risk of failure and development costs
SE considers the full life cycle of the system
The core of SE is the SE process
SE emphasizes scientific measurement, V&V
SE provides information and facilitates communication among developers, customers and users
SE makes a plan and manages against it

Guiding Principles (Mar, 2001)
Don’t assume the original problem statement is right
Be the voice of the customer during development
Plan for changing requirements
Quantify as much as possible
Identify and check all model assumptions
Have a contingency plan for each risk
Work the critical issues first
Prioritize performance, cost, schedule and risk

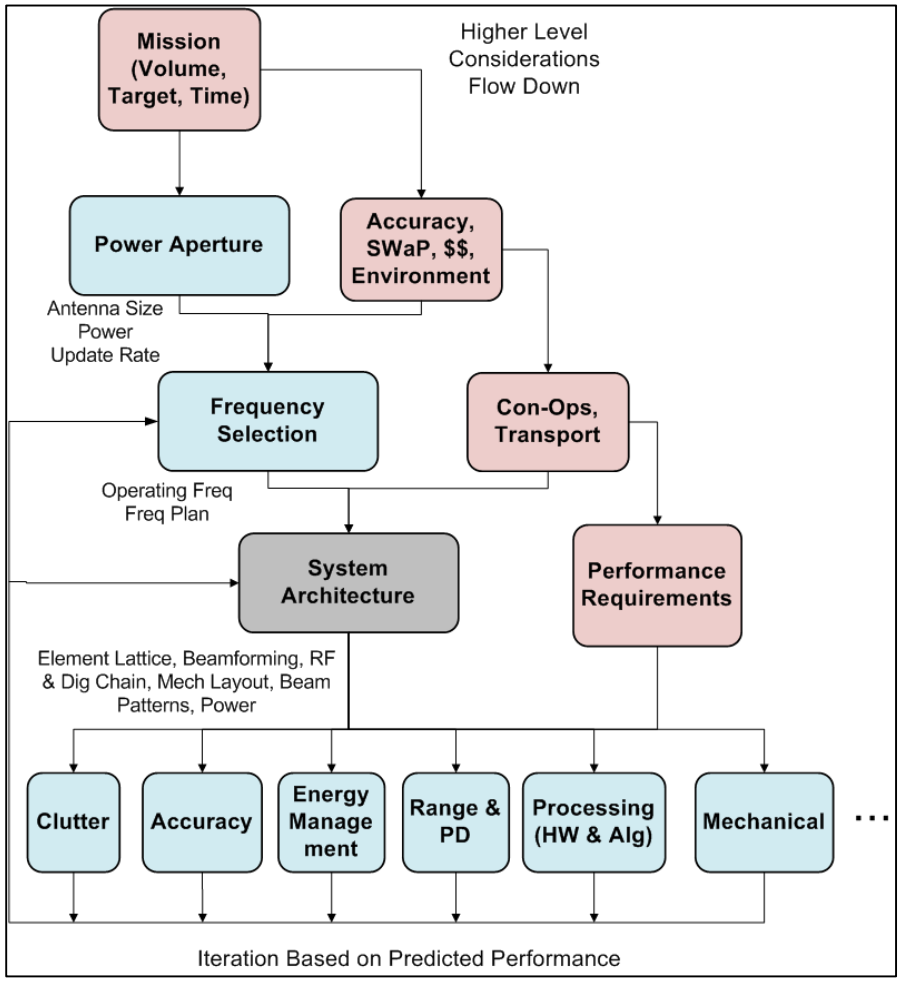
Some Recommendations

SE Heuristics - INCOSE

- Start a SE Heuristics Working Group
  - INCOSE facilitate collection and dissemination of useful heuristics
- SE rules of thumb
  - Gather rules of thumb from different SE domains
  - Look for commonalities across domains for general SE rules of thumb
- Framework of general principles
  - Boil down to most important principles (e.g. top ten)
  - Aim for “completeness”
- Activities
  - Organize heuristics sessions at IW and IS
  - Publish handbooks of heuristics and rules of thumb

Heuristics at SRC

- Develop a Radar Engineering Handbook
- Capture the particulars of the radar development process
  - Tim Graham's radar architecture process more defined than generic SE process
  - Identify the tools (e.g. Blake chart) commonly used
- Capture the heuristics we use
  - General principles
  - Rules of thumb
  - Not just systems, also other functional areas
  - Heuristics may be useful to help cross functional divide
    Systems to other functions (e.g. systems to RF)



Radar Architecture Process
(from Tim Graham, SRC)

Summary

- Heuristics are useful tools
  - Rules of thumb
  - General principles
- State of the art
  - Best set of heuristics in use at the time
- SE field can make better use of heuristics
- Maybe your company can too

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