

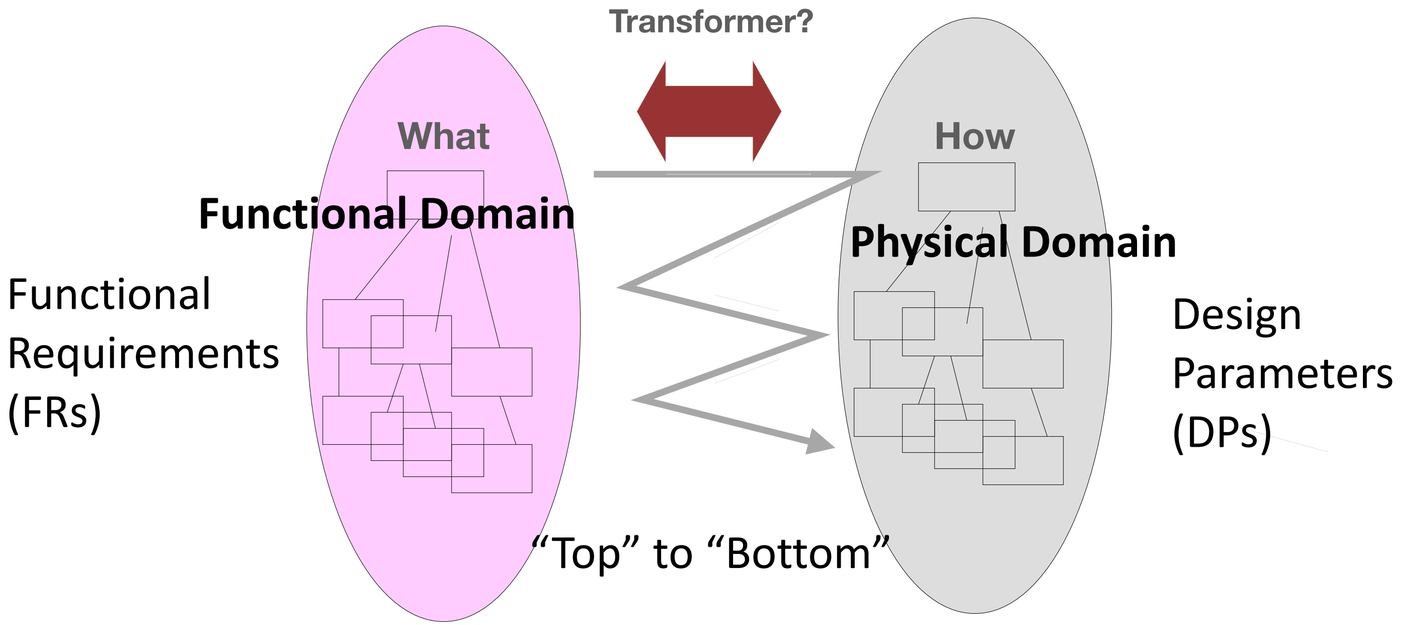
AI for Design and Manufacturing
Part 2: Thinking Design

Prof. Sang-Gook Kim
MIT

(Courtesy Relativity Space/photo Michael Baylor)

Design Principles

Search in the dark



Axiomatic Design

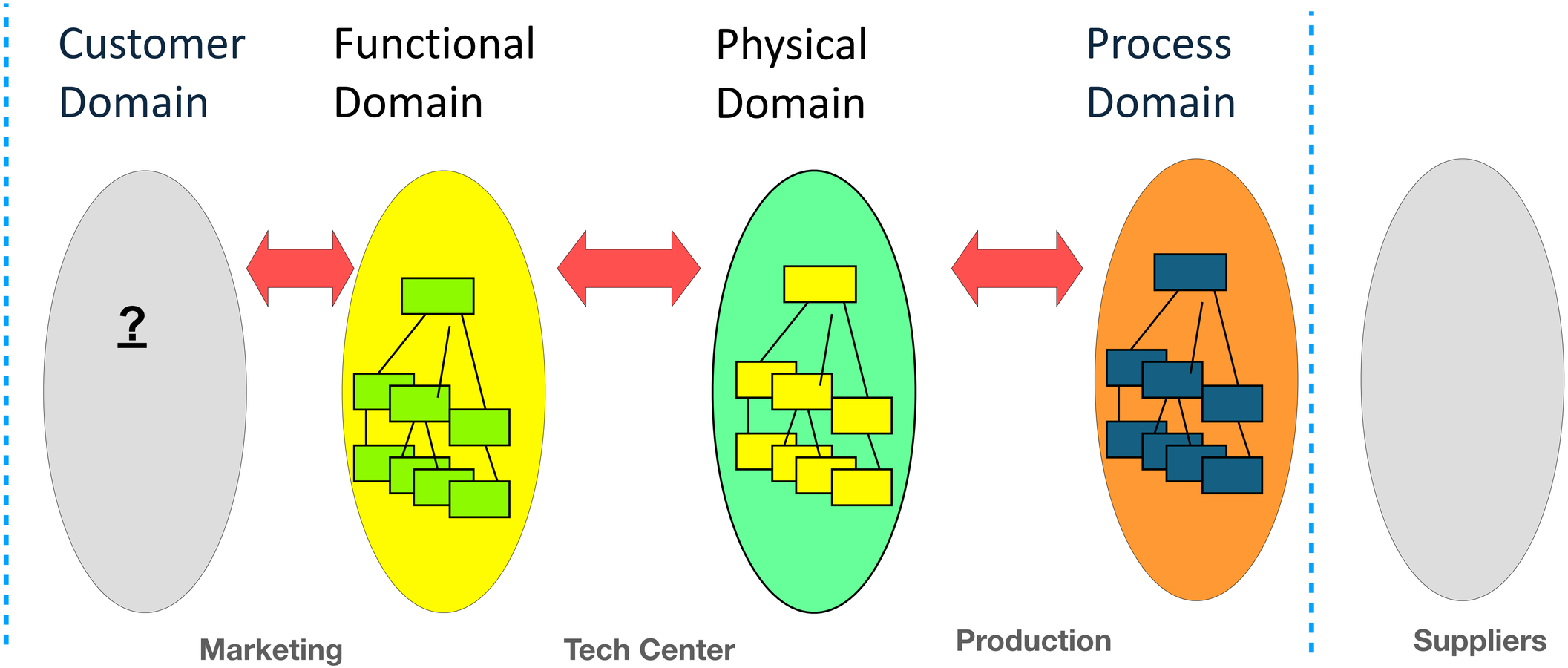
- What is a good design?
- Concept of Domains
- Functional thinking
- Top-down, zig-zagging decomposition
- Design axioms

Nam Suh, MIT faculty (1970-2008), “Optimization of Manufacturing Systems through Axiomatics,” CIRP Annals 1978

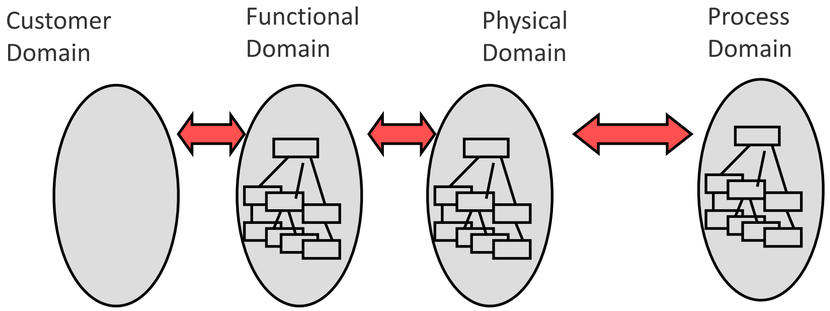
$$\overrightarrow{\mathbf{FR}} = [\mathbf{DM}]\,\overrightarrow{\mathbf{DP}} \qquad A_{ij} = \frac{\partial(FR_i)}{\partial(DP_j)}$$

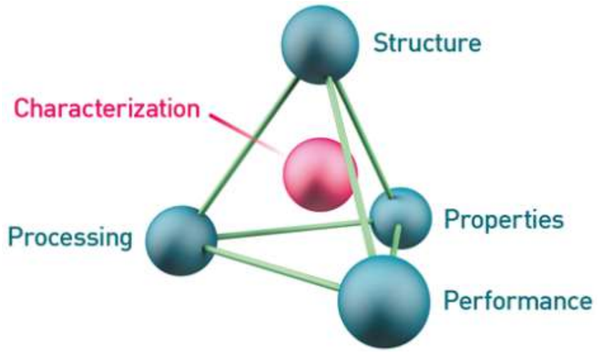
* S.G. Kim, et al. "Axiomatic design: Making the abstract concrete," 26th CIRP Design Conference, Procedia CIRP Volume 50, 2016
* S.G. Kim (EDs.), Advances in Multidisciplinary Engineering, ASME Press, NY, 2015
* S.G. Kim, Axiomatic Design, Encyclopedia of Production Engineering, DOI 10.1007/978-3-642-20617-7, # CIRP 2019, pp108

Four Design Domains



Four Domains of Systems





Material Science Tetrahedron

	Customer domain	Functional domain	Physical domain	Process domain
Manufacturing/ Engineering	Customers' attributes	Functional requirements	Design parameters	Process variables
Materials	Performance	Properties	Microstructure	Processes
Software	Attributes	Output	Input variables	Subroutines
Organization	Customer satisfaction	Functions of organization	Programs & Offices	Resources, people
Business	ROI	Business goals	Business structure	Resources, human, capital

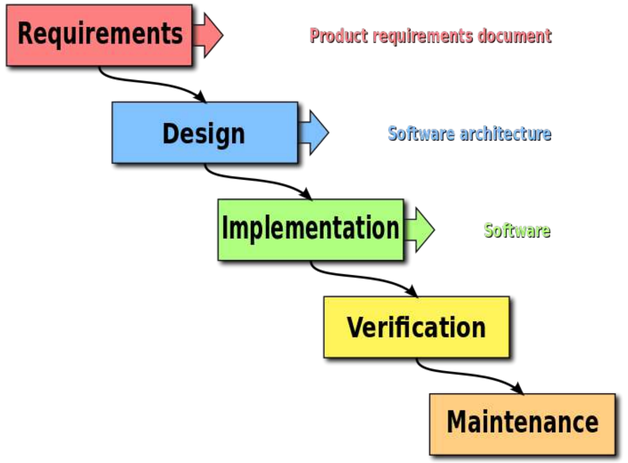
Designers' (Problem solvers’) common mistakes

1. Not to realize concept of design domains, “What” to “How”
2. Not to realize that design process involves mapping from “What” to “How”
3. Physical thinking (not **solution neutral**)
4. Decomposition without zig-zagging domains (concepts)
5. Trying to make functionally coupled designs work.

System Design of Software ?

- Waterfall development
- Prototyping
- Incremental development
- Rapid Application Development
- Spiral Development
- Agile Development
- SADT

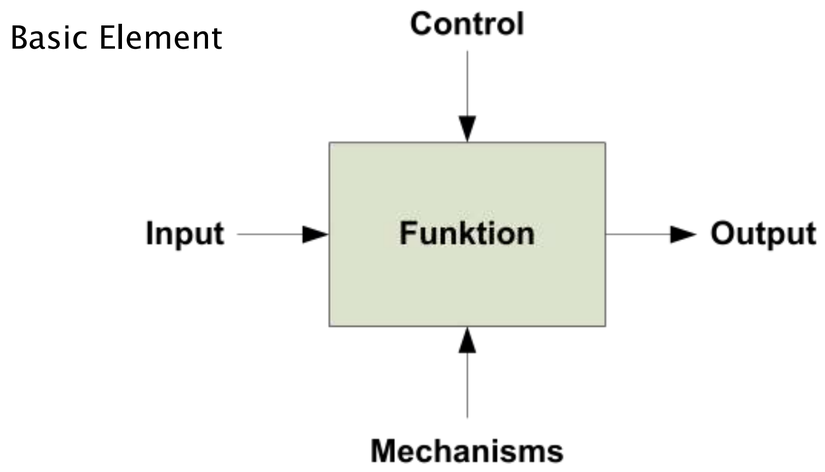
- Productivity: $/line, time to delivery, hard maintenance



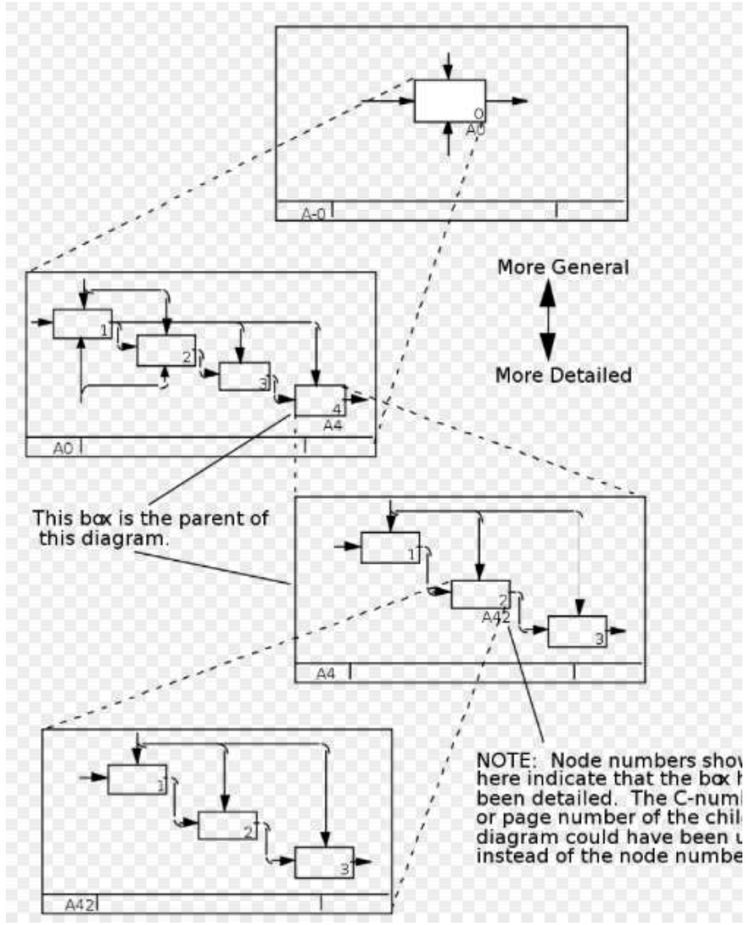


System Design of Software

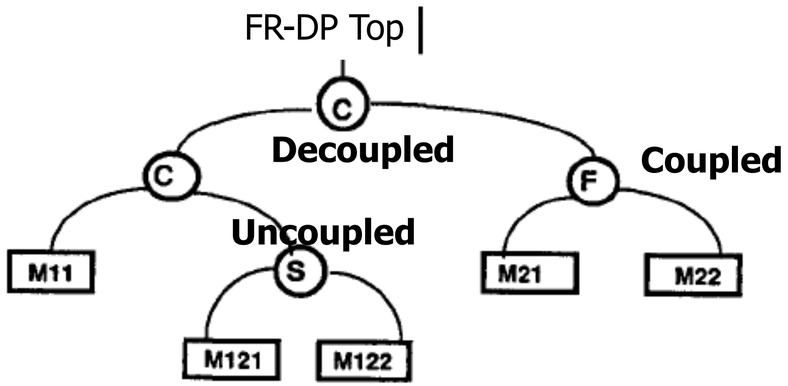
Structured Analysis and Design Technique (SADT)

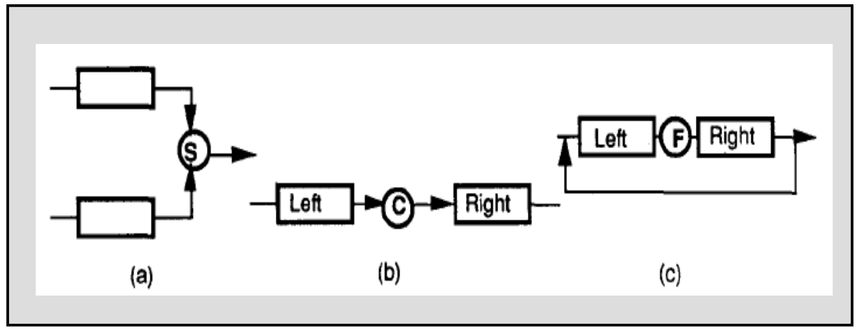


https://en.wikipedia.org/wiki/Structured_analysis_and_design_technique

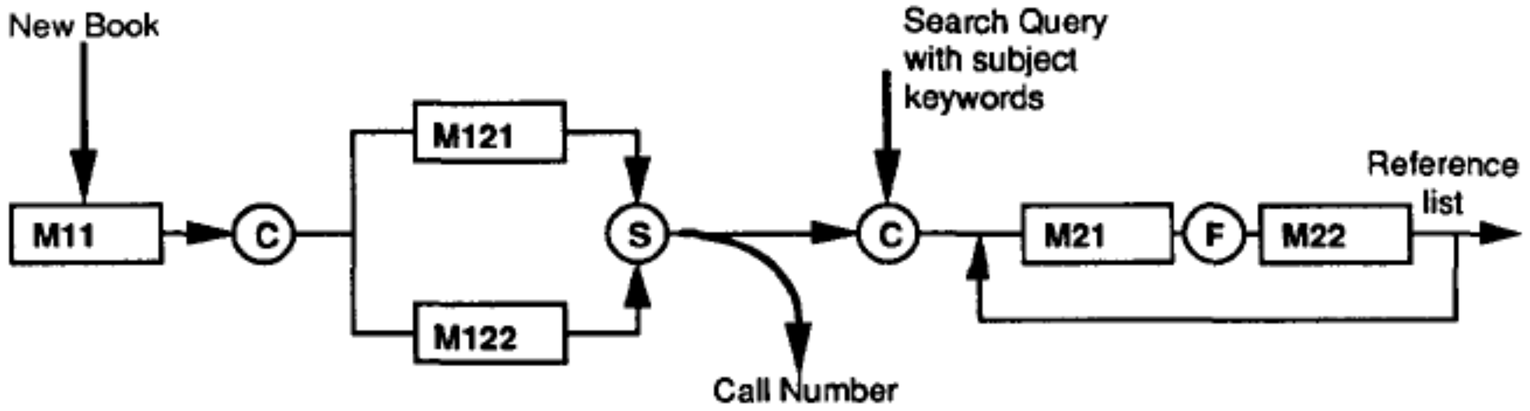


Module Junction Structure in Data Flow Domain





Uncoupled **Decoupled** **Coupled**



S.J. Kim, N.P.Suh, and S.G.Kim, "Design of Software System based on Axiomatic Design", Annals of the CIRP, Vol. 8,40/1,1991

Why do we teach/learn systems thinking? (2.778)

Functional Thinking

Why do we teach/learn systems thinking? (2.778)



The U.S. airport with the longest average wait time at security is more than double the shortest. Photo: Marius Dobilas / Shutterstock.com.

What would you do?

Could we improve the passengers experience through the airport security?





- **Bottle necks mitigation**
- Screening success rate

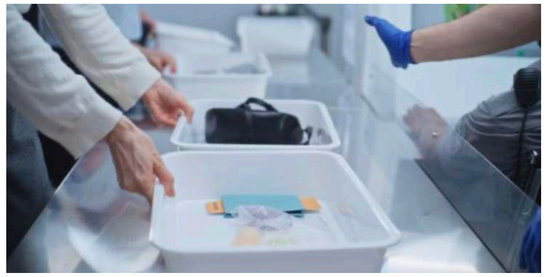
Could we improve the passengers experience through the airport security?

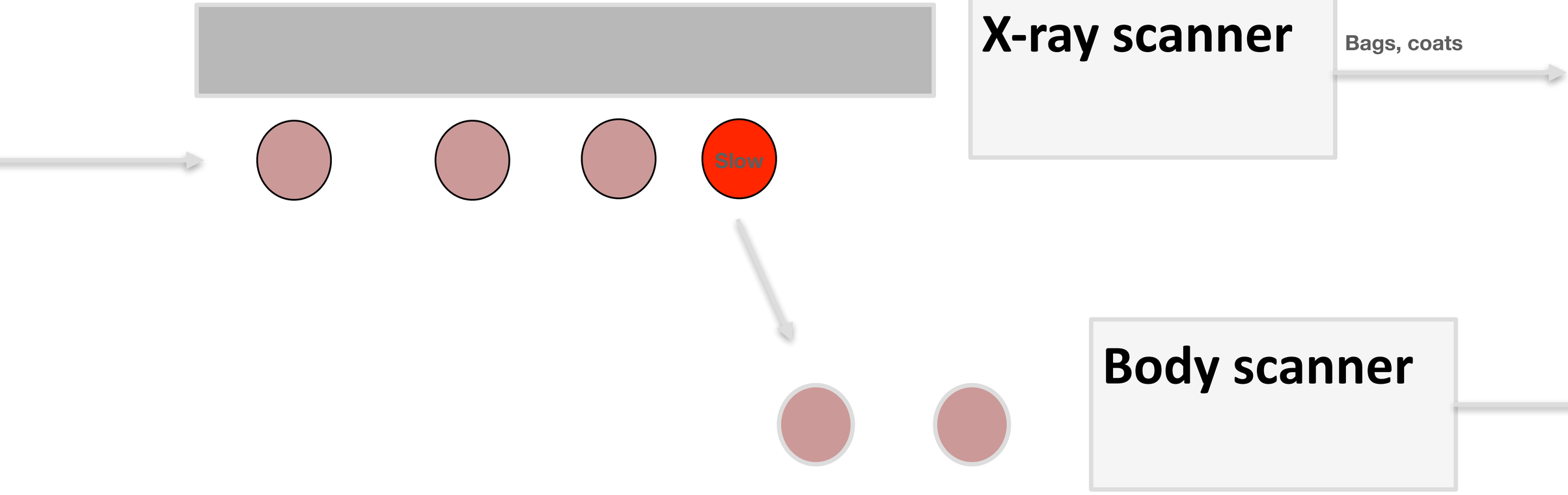
2 min thinking exercise

What are your suggestions for minimizing waiting time in the TSA line and significantly improve traveler experience at the airport?

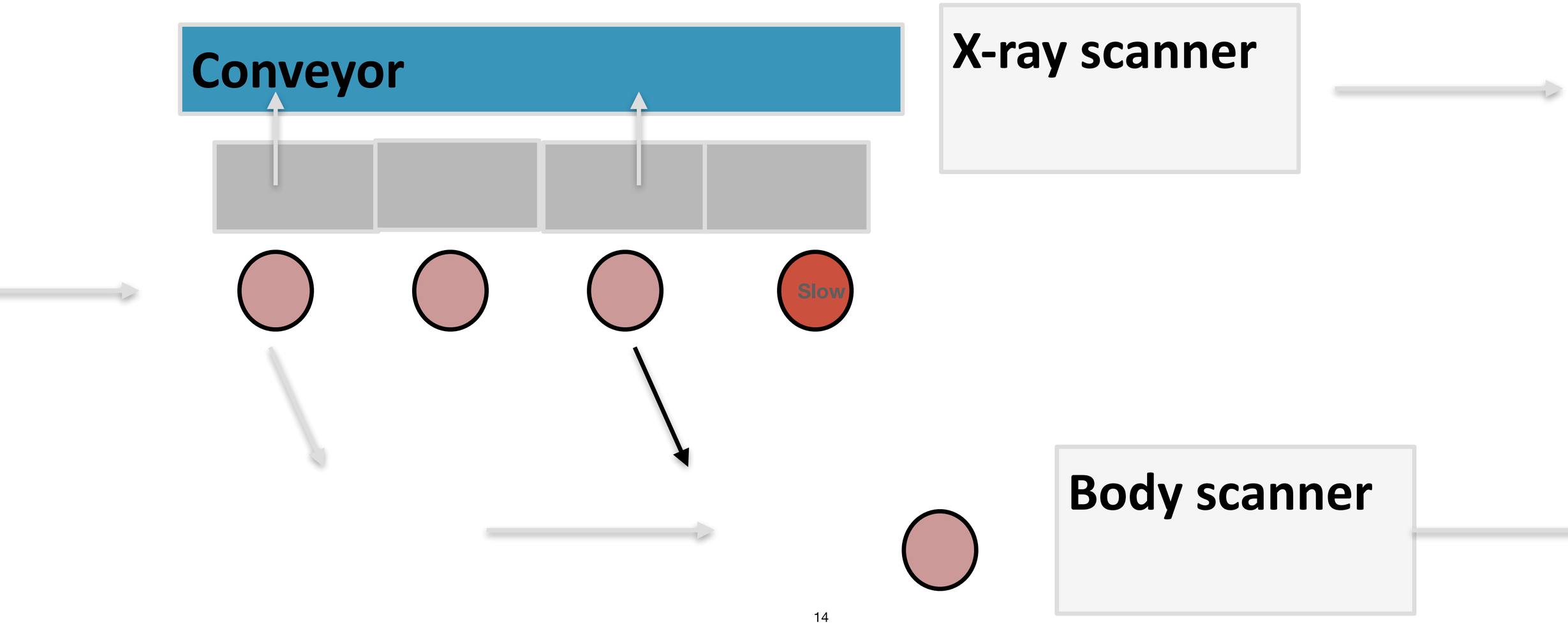
Assume TSA has enough number of fast 3D scanners.

At most Airports





Good Design Solution



Enhanced security prep lanes (2020)





- Atlanta International Airport by Delta
- 30% higher throughput

- Gatwick Airport
- 30% higher throughput

MIT's 2.777, Large and Complex Systems (since 2016)

When you face a complex problem,

Where to begin?

What kind of learning do you need to solve the problem?



Principles and Disciplines

Modelling and Optimization

Heuristics and Insights

College education

Principles of Design

- Axiomatic Design
- Systems Architecture

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

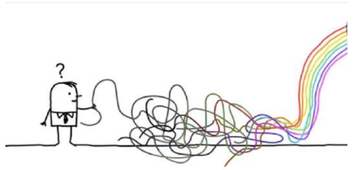
Big national project experience

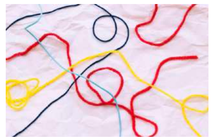
Systems Analysis

- Tenets
- Guides
- Elements

System Architecting and System Analysis (2.778)







Understand the problem — Structure the problem — Generate Concepts

Lectures

Identify stake holders
Functional thinking
Solution agnostic
Find their requirements
Mind complexity

Extract/Abstract requirements
Concept of Domains
Design Axioms
Uncouple the couplings

Try a few concepts
Test them with Axioms
Reduce complexity

Test with Rigor
Story telling/Blue Team approach

Detailed Solution Steps

Projects

Findings at a glance (charts, etc.)
Think one up and one down levels
Structured Thinking

Findings at a glance (charts, etc.)
Systems Analysis

MS1 MS2 MS3 MS4 MS5

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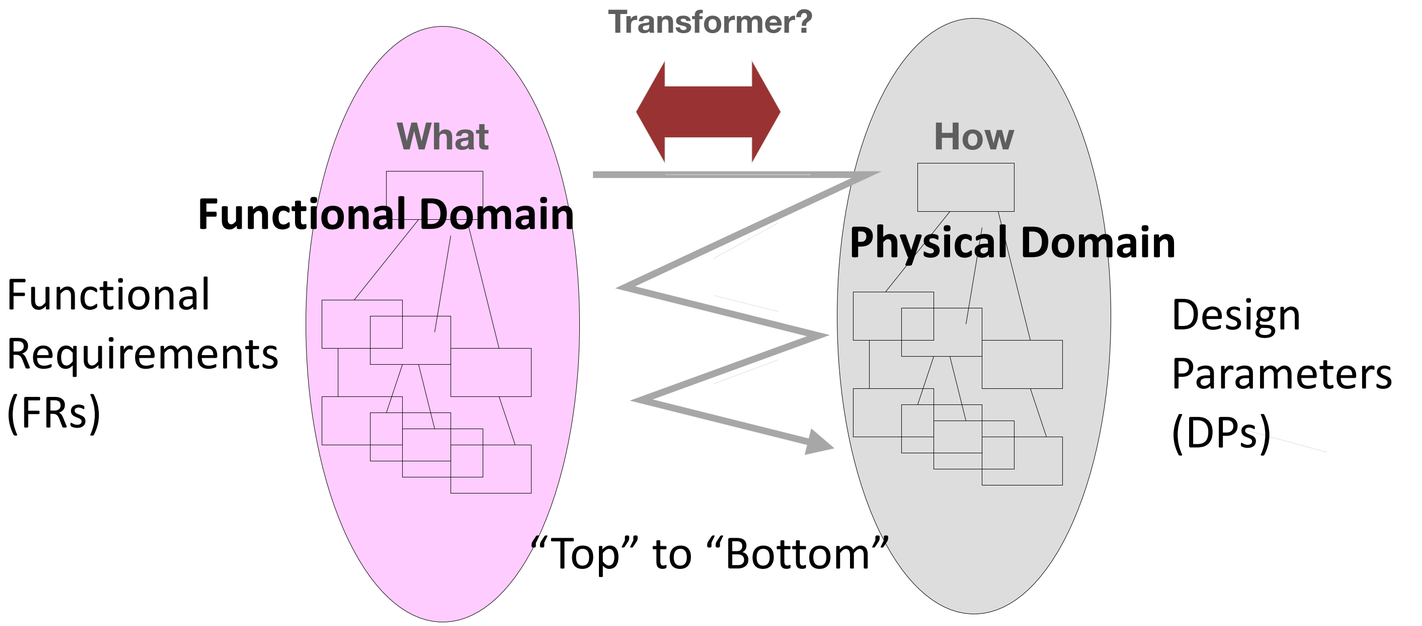
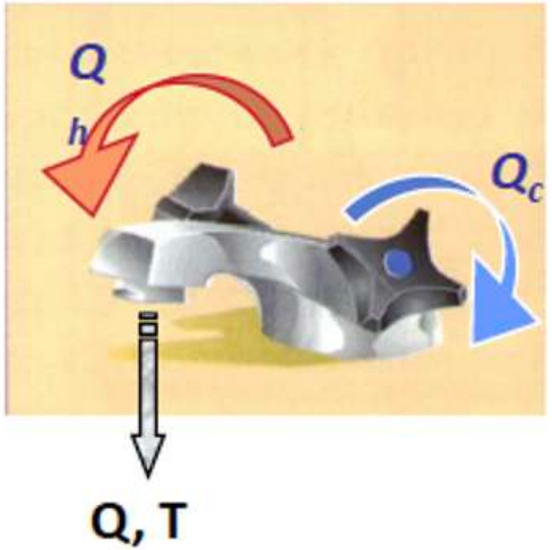
Aximmatic Design



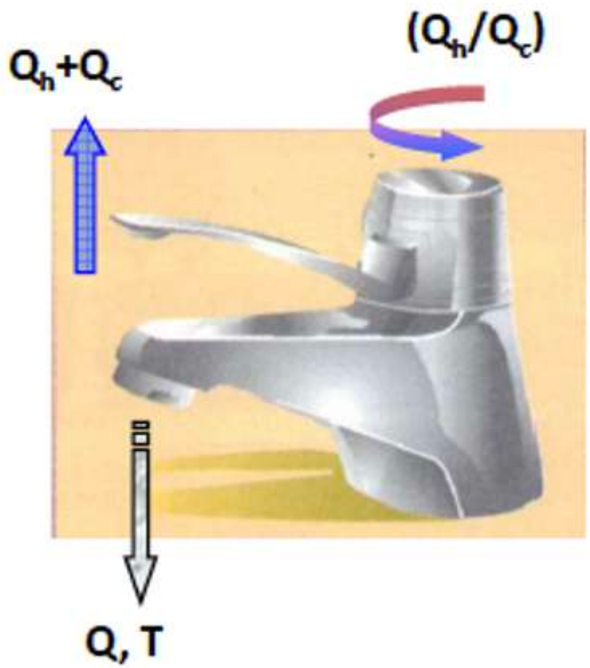
Observation #1: Functional Couplings are bad.

Fully coupled design



FR \ DP	Hot water flow (Q_{hot})	Cold water flow (Q_{cold})
Control the flow (Q)		
Control temperature (T)		

Uncoupled Design



	Flow control V-level, $Q_{hot}+Q_{cold}$ ($Q_{hot}/Q_{cold}=C$)	Temp control by rotation, Q_{hot}/Q_{cold} ($Q_{hot}+Q_{cold}=C$)
Control the flow (Q)		
Control temperature (T)		

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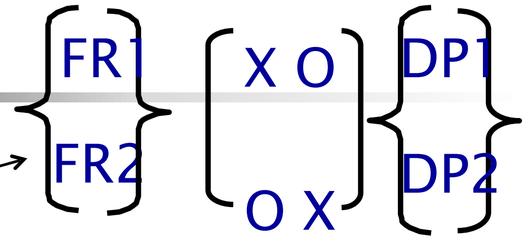
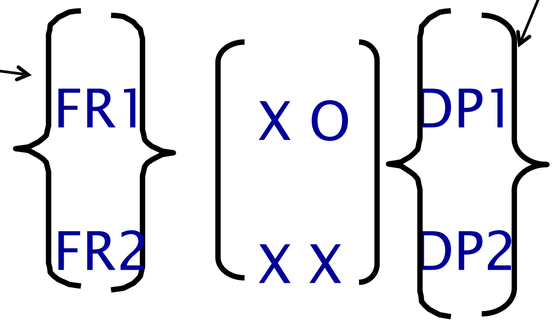
Functional Couplings

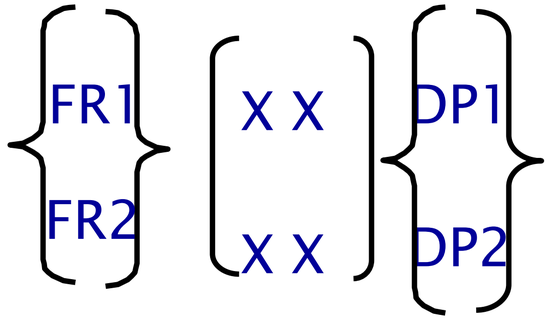


- Uncoupled

Good Design



- Decoupled
- Coupled



Bad Design

Observation #2: If you see functional coupling early stage of your design, big big savings of resources.

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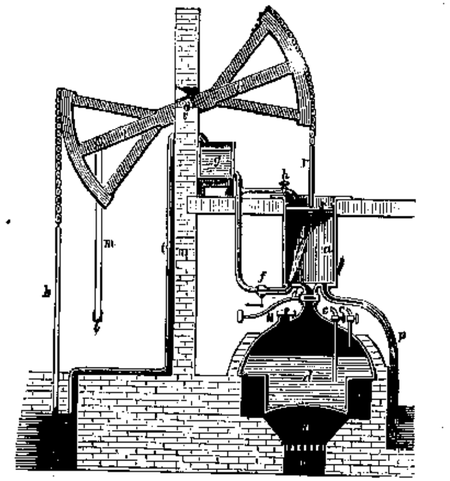
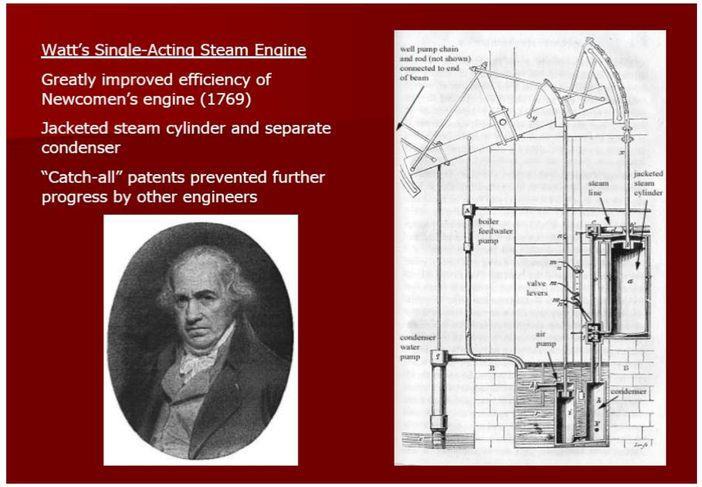
Axiomatic View of Watt's Steam Engine Design



Newcomen's Engine, A. D. 1705.



Watt''s Engine, A. D. 1769.

- First Law of Thermodynamics, 1850
- Second Law of Thermodynamics, 1824-1860, Carnot, Clausius

$$\eta = \frac{\Delta W}{\Delta Q_H} = 1 - \frac{T_C}{T_H}$$

Carnot Theorem

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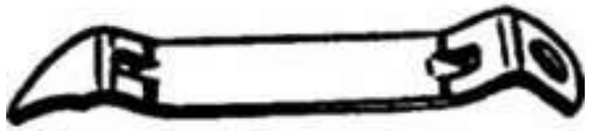
Coupled design or not?

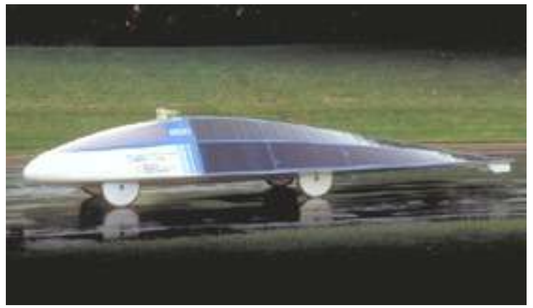
Can and bottle opener





Observation #3: Physical coupling is good in most cases. Functional coupling is bad.

Case: Solar Car Race 1987



Sunraycer (1987)



Gossamer Albatross

1979



Courtesy AeroVironment

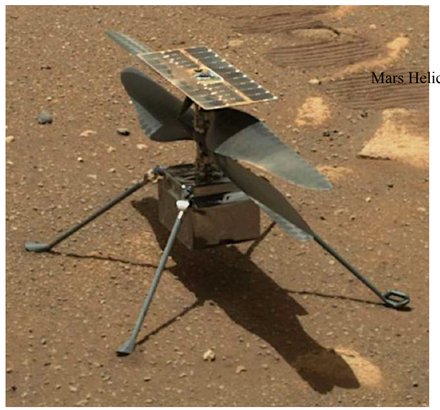
Future versions of the unmanned, solar-powered Helios will fly above 50,000 feet for six months at a time, serving many purposes, such as telecommunications and weather watching.

Pathfinder
Helios

1982



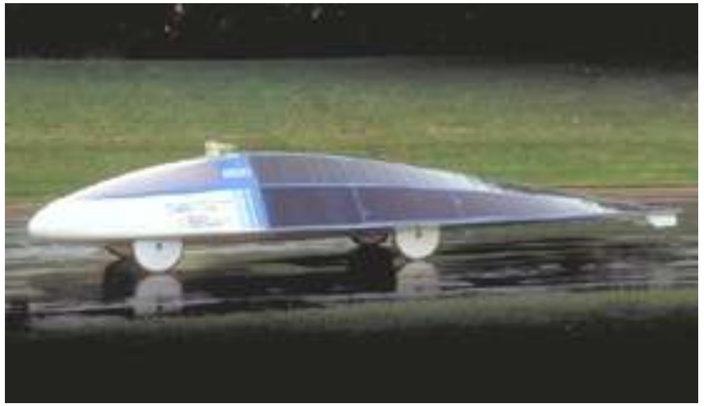
Paul MacCready, Aerovironment
(1925-2007)



Mars Helicopter, Ingenuity

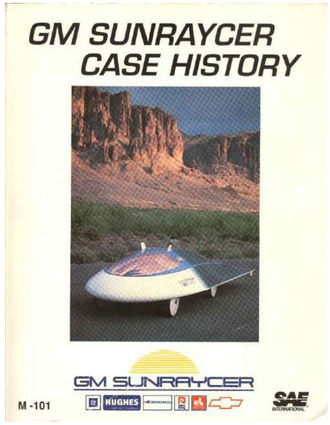
http://www.progressiveengineer.com/PEWebBackissues2003/PEWeb%2042%20Sep%2003-2/MacC.htm

Sunraycer





GM Impact



Paul MacCready, 1987, Aerovironment Co.



4 Top Winning Strategies:

- Light weight
- Efficiency
- Reliability
- Simplicity



Observation #3: Design is Top-Down. North star of design goals

Design Principles of Axiomatic Design Thinking

Observation # 1: Functional Couplings are bad.

Observation # 2: Uncoupling the function coupling often results in drastic improvements under time pressure. A way to handle system complexity.

Observation # 3: Physical coupling is good in most cases unless functionally coupled..

Observation # 4: Design is Top-Down. Find **north star** of design goals.

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Case: Social system design — Health Care





Partners Healthcare (now Mass General Brigham), ~75,000 staffs

Can we apply the Toyota Manufacturing System to Hospitals?

ER crowdedness (Newton Wellesley Hospital)

MAXWELL BLUM EMERGENCY PAVILION

- Background
  - Over the past six years, ED visits at NWH have soared from about 30,000 to just under 50,000
  - Long waits into a treatment room: avg 55 min on weekdays, avg 90 min on weekend; national overall average is 56 min (as of 2004)
    - 45 minutes weekdays and 55 minutes on weekends (on NWH web page)

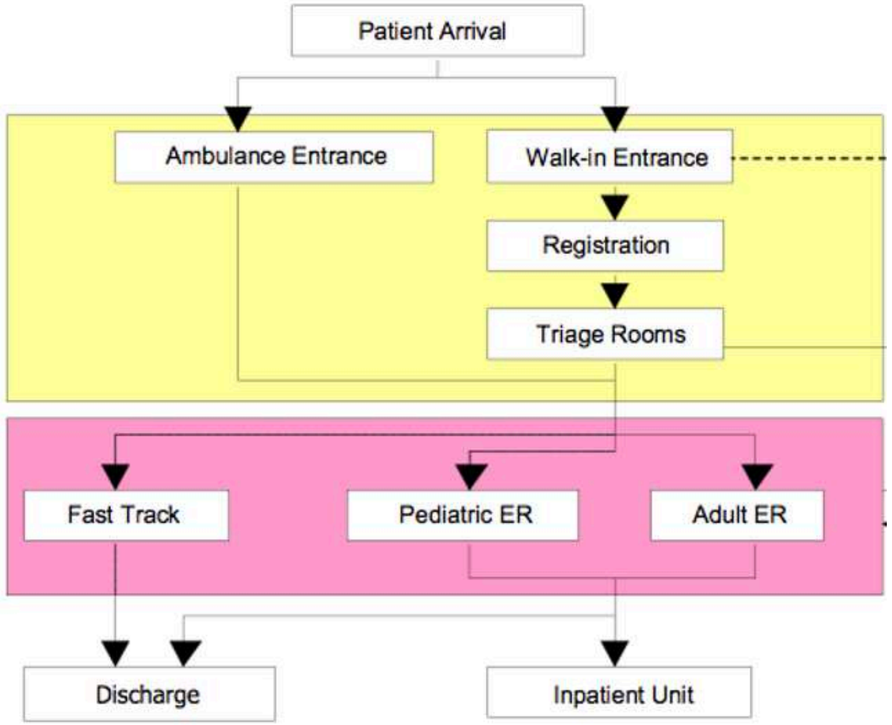


	Old ED	Maxwell Blum EP
Target volume	28,000/yr	55,000/yr
Footprint	~12,000 sq. ft	35,000 sq. ft
Private rooms	19	36
Pediatric section		8 beds
Adult section		24 beds
Fast-track	3 beds	4 beds
Fast-track op hr	? Hrs	8 hrs(wk) /10 hrs(wknd)
Employees	X	X + 47
Triage room	Y	Y + 1
Test equipment	?	Two X-ray rms, a CT scanner, ultrasound scanning

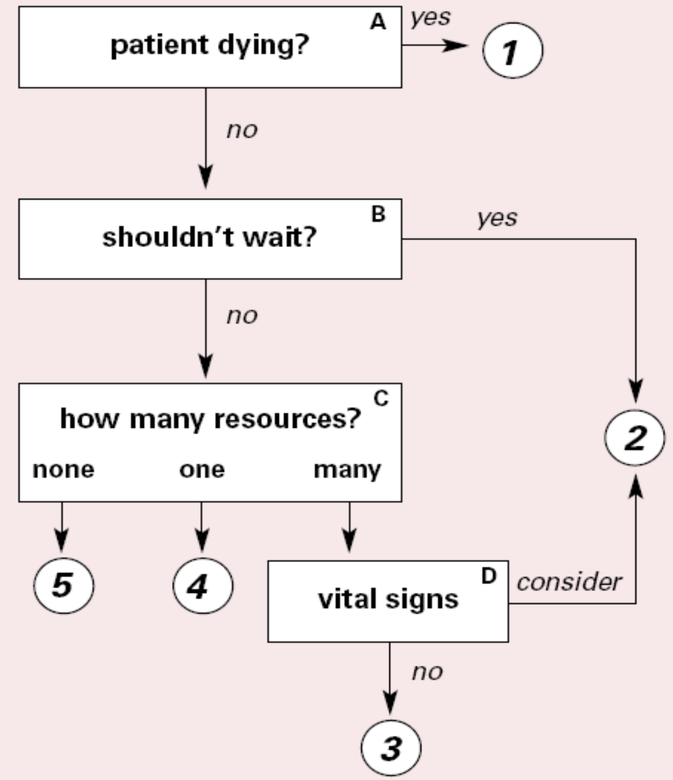
© Sang-Gook Kim, MIT

Fast Track Problem

- FT serves the purpose of increasing ED Capacity and if it is not used to its maximum then resources are being wasted.
- FT is used to decrease the waiting time of low acuity patients, yet despite the existence of FT the ESI 4 and 5 TTB remains the highest.

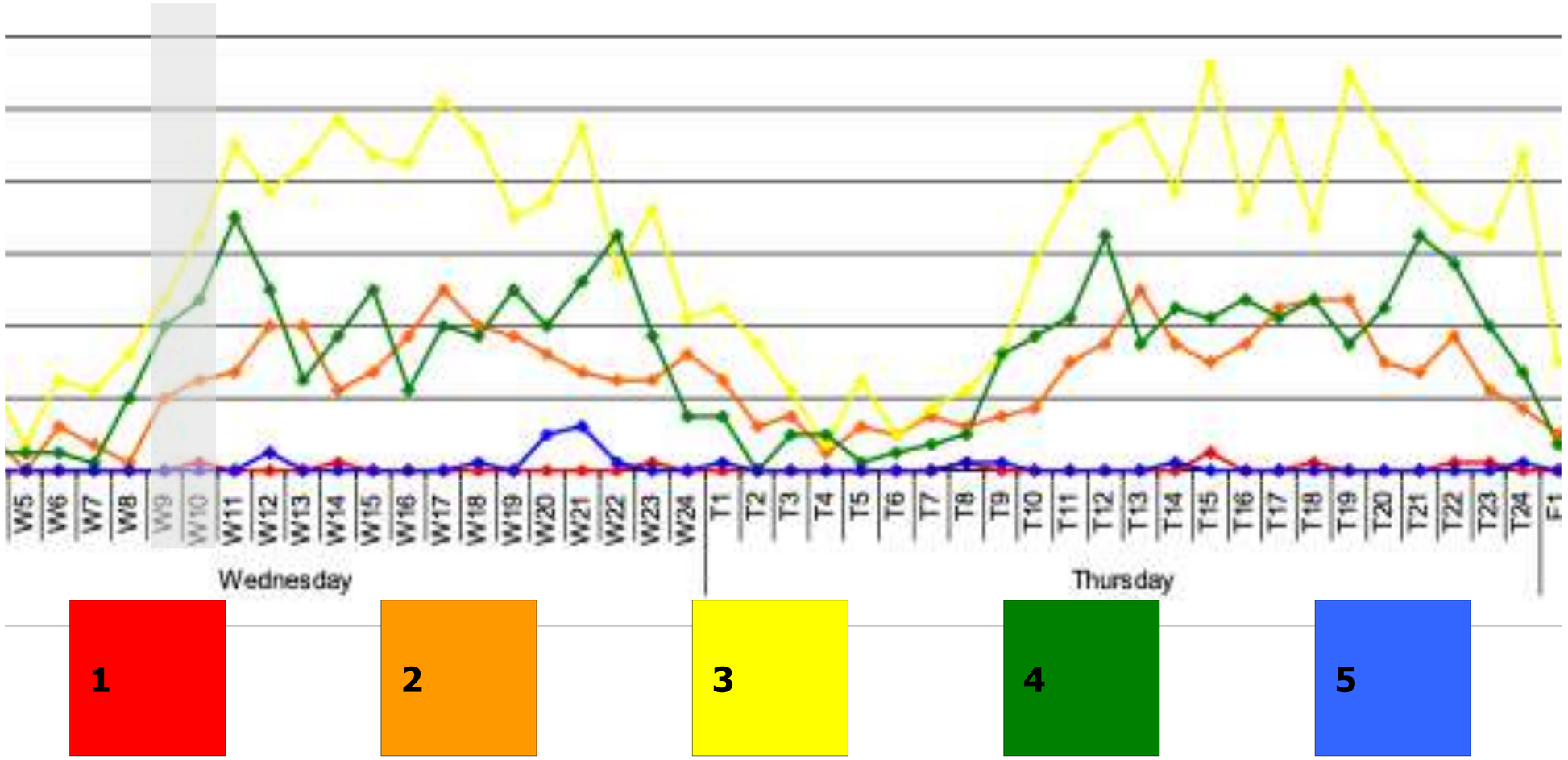


Triage of ER



©ESI Triage Research Team, 2004. Reproduced with permission.

The Emergency Department Patient Flow



- **Emergency Severity Index (ESI)—a five-level emergency department triage algorithm that provides clinically relevant stratification of patients into five groups from 1 (most urgent) to 5 (least urgent) on the basis of acuity and resource needs.**

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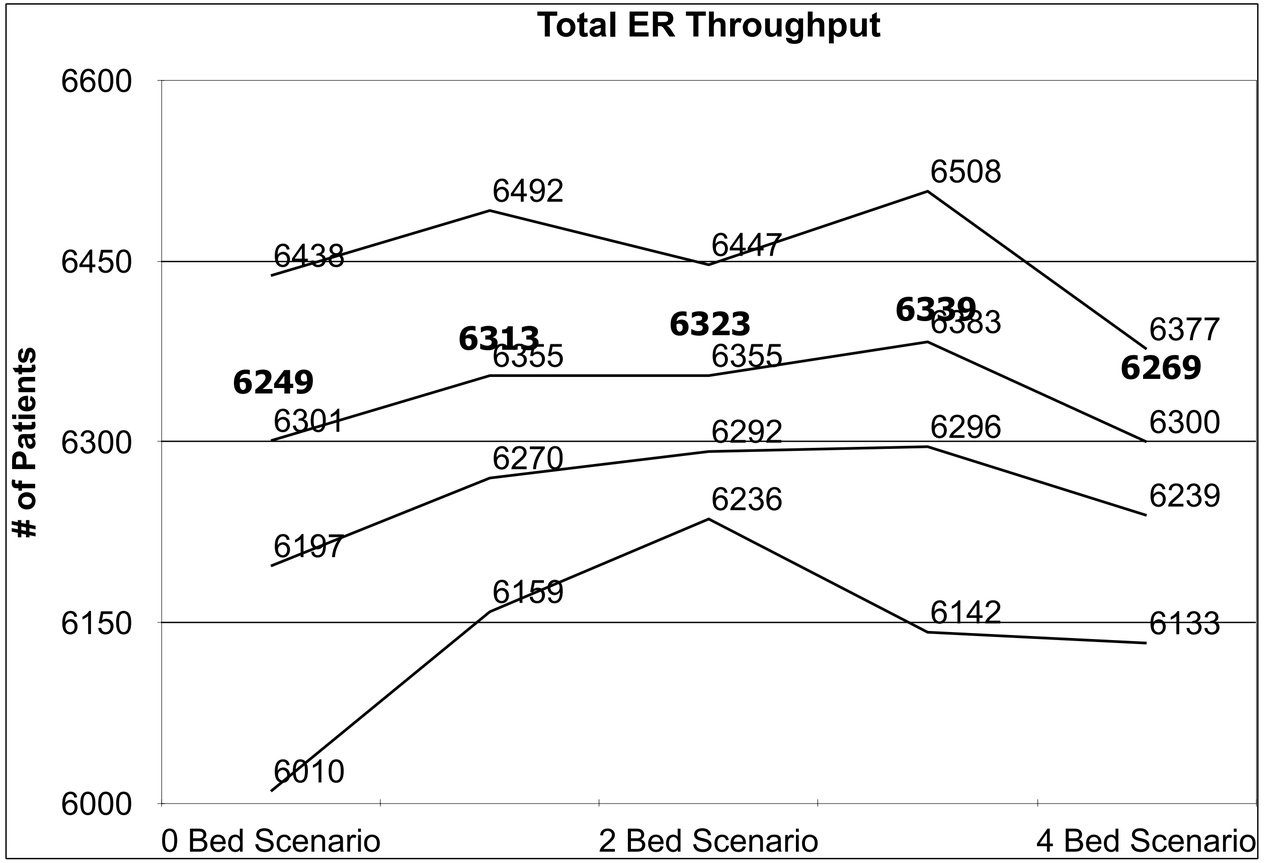
First Approach

- Optimization
  - ED^3 (Emergency Department Design Decomposition)
  - Discrete-Event Simulation model using ARENA software package

  - Number of FT beds (# out of 28 beds)
  - Vary ESI allowed to Fast Track
  - 12,000 ED patient data over 8 months

© Sang-Gook Kim, MIT

No meaningful Improvement with 3 weeks left for final report



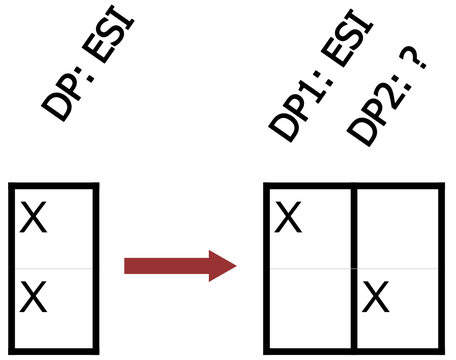
Possible trend, though it is not obvious, we need to break down the throughput for better understanding.

Find Functional Couplings

- A Triage Nurse assigns an ESI based on how urgently the patient needs care, and how many resources they will require. The amount of time a patient will spend in ED is not taken into account.
- In practice, patient treatment time is estimated based on their ESI, meaning that DP1 is used to satisfy both FR1 and FR 2, creating a coupling.

FR1: Prioritize Patients Based on Treatment Urgency

FR2: Sort Patients to Facilitate Flow



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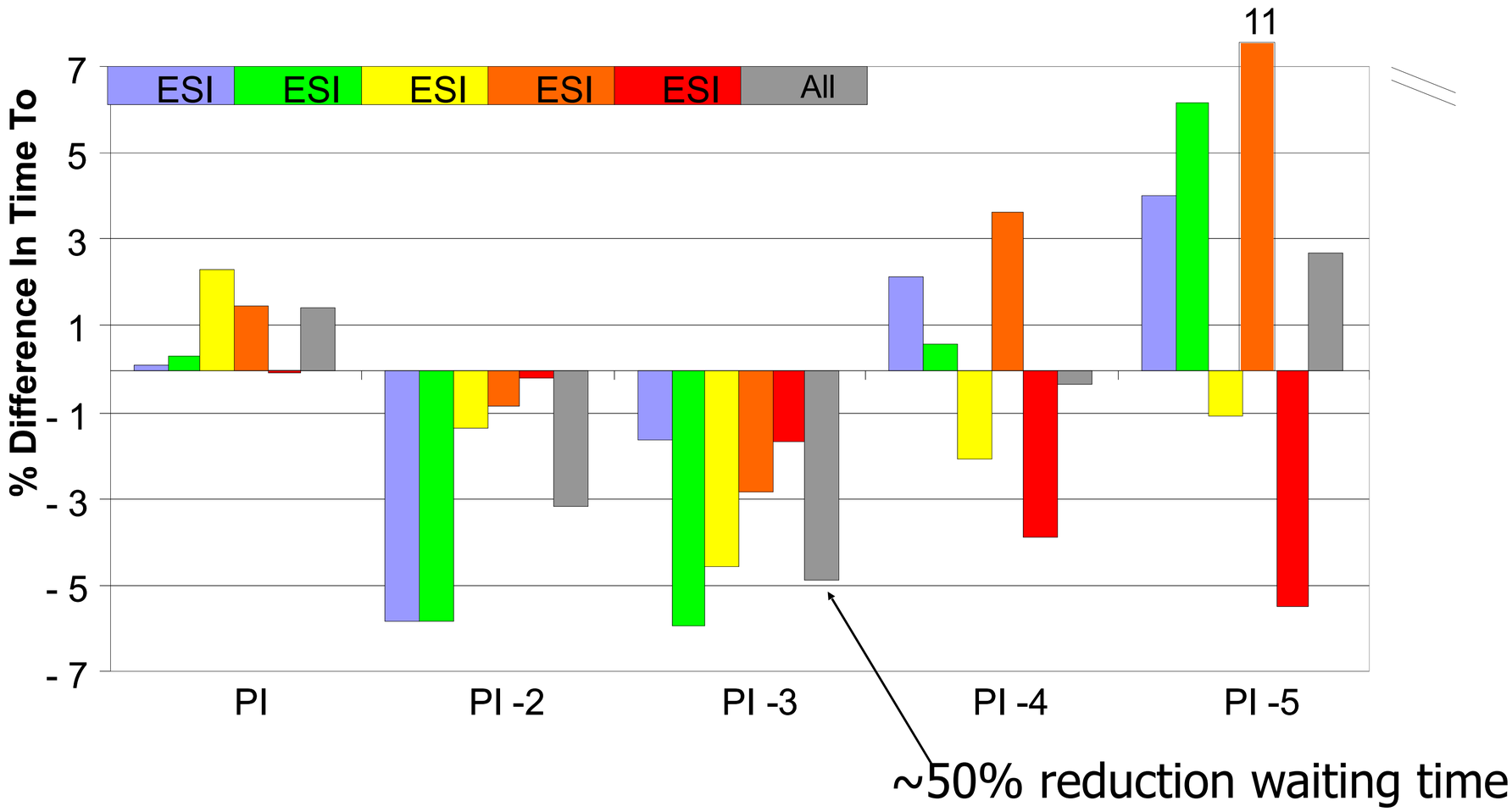
Percent Difference in Time to Bed from 28 Bed Scenario



Observation #2: Uncoupling the functional coupling results in drastic improvements.

J. Peck, S-G. Kim, "Improving Patient Flow through Axiomatic Design of Hospital Emergency Departments," Journal of Manufacturing Science and Technology, Vol.2, Issue 4, P. 255-260, 2010,
ACEP Research Forum, American College of Emergency Physicians Scientific Assembly, Chicago, IL, 2008

Reading Material on Canvas

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Finding FRs

- As a designer, you are completely free to define your problem in any way.
- By definition, each FR is independent of every other FR at the time FRs are established.
- All FRs are equally important.

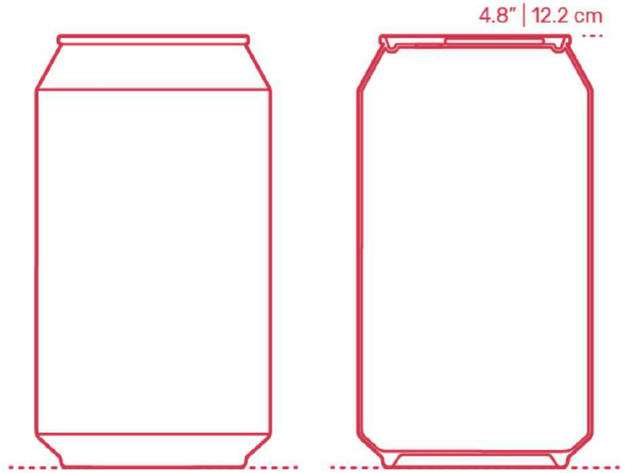
Example: Beverage Can Design

- Consider an aluminum beverage can that contains carbonated drinks.
- How many functional requirements must a can satisfy?
- What are the design parameters (DPs)? How many DPs are there?
- How many physical parts does it have?











Functional Requirements (FRs)

FRs of a aluminum beverage belonging to the main body piece

- Contain carbonated fluid
- with no leakage (sealing)
- Opening
- …

- Cost of material ??

Functional Requirements (FRs)

FRs of a aluminum beverage belonging to the main body piece

Contain carbonated fluid ⟷ Al can

Retain structural rigidity
- axial, radial (curvature, thickness)

Opening easily (pop tab shape)

Compact packing (horizontally, vertically)

Resistance to rust (inside, outside)

Printable

Flow rate, Drinkability

Safety for drinking

Cleanness, hygiene

Tight sealing, gas Leaking rate

Light weight

Cost of material ??

Constraint or FR ?

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Functional Requirements (FRs)

FRs of an aluminum beverage can

Containing carbonated fluid

Retain structural rigidity	Safe drinking	Decoration	Distribution
- Axial stiffness - Radial stiffness -..	- Opening effort - Flow rate - Sharpness - Internal coating -..	- Printable - Slender shape -..	- Stackable - Packing density -..

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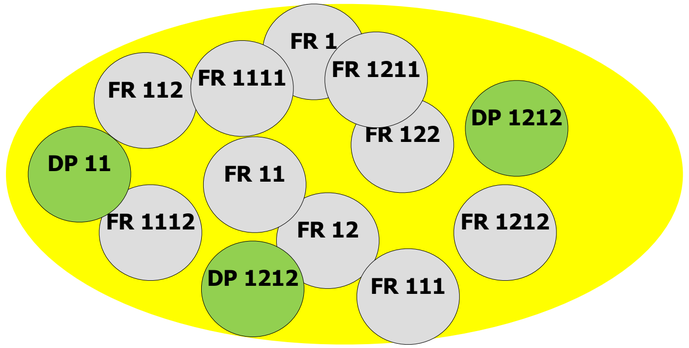
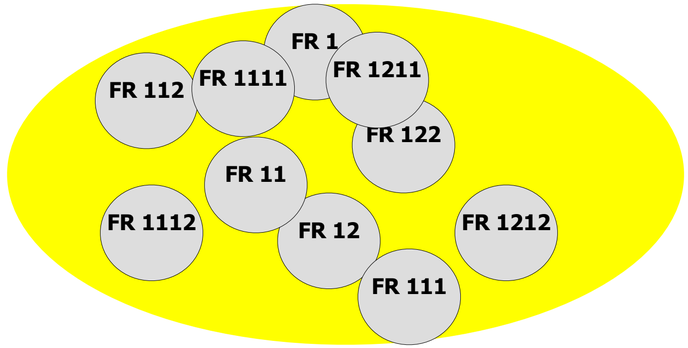
Understandng the problem

- Recognize two domains of design.
- Separate “What’s (FRs)” from “How’s (DPs)”.







FRs: functional requirements
DPs: Design parameters

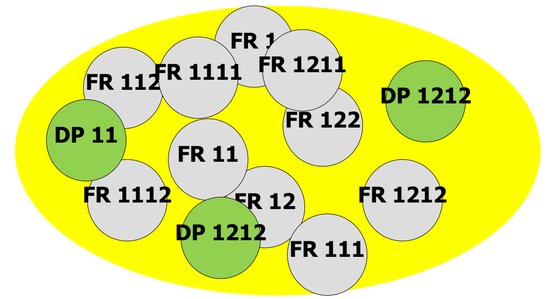
Can AI think in Axiomatic Thinking

DO's

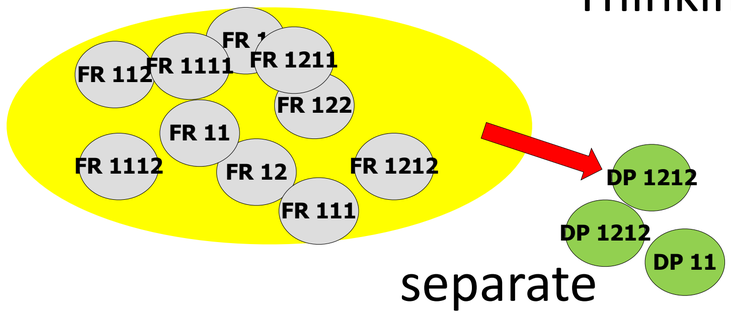
- Figure out users and stake holders' needs, and constraints.
- Focus on "what's"
- Put aside "how's"

Don'ts

- Do not mix "what's" and "how's"
- Not solution neutral



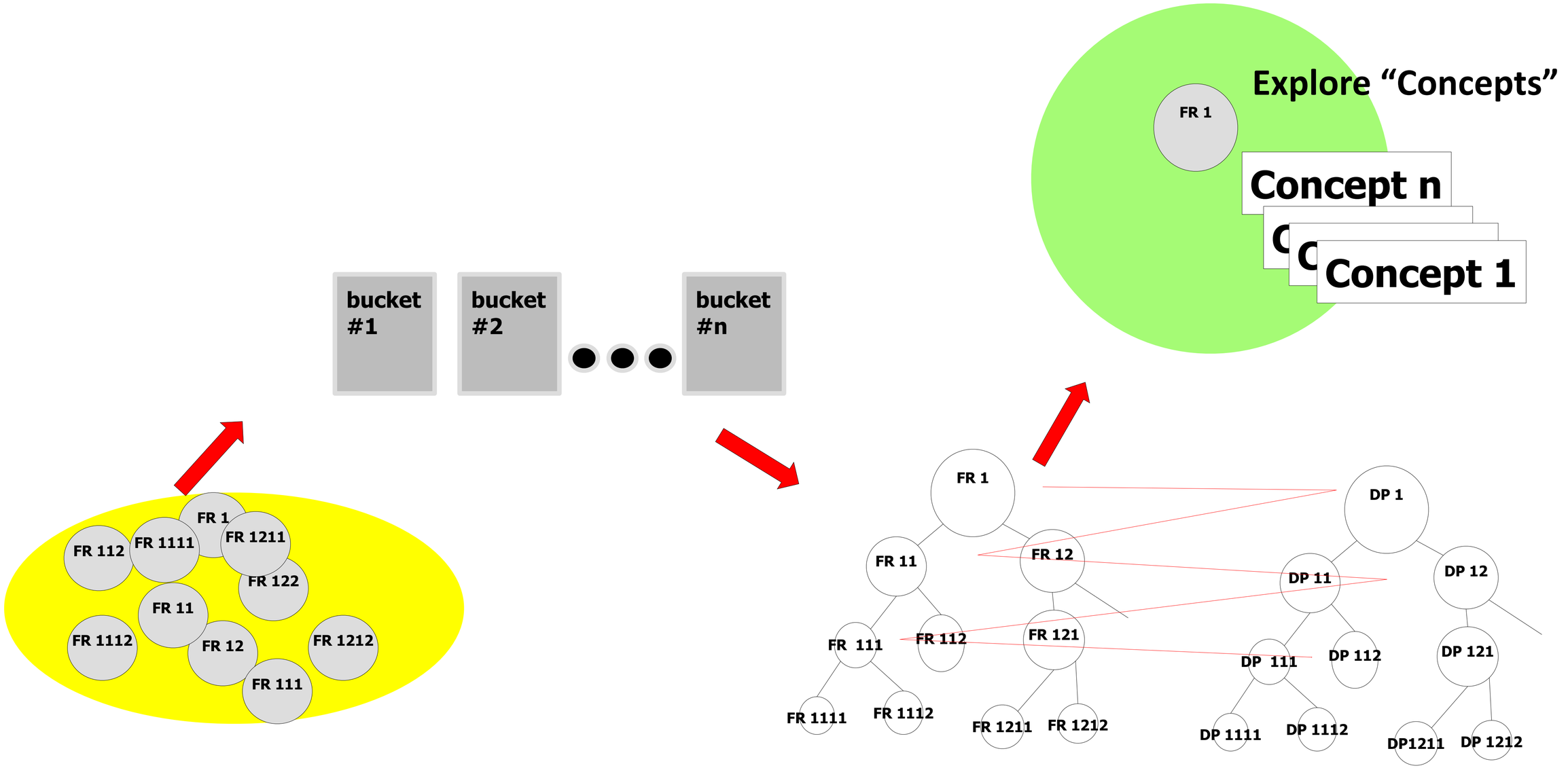
Functional Thinking



separate

Solution Agnostic

Abstraction and Conceptualization



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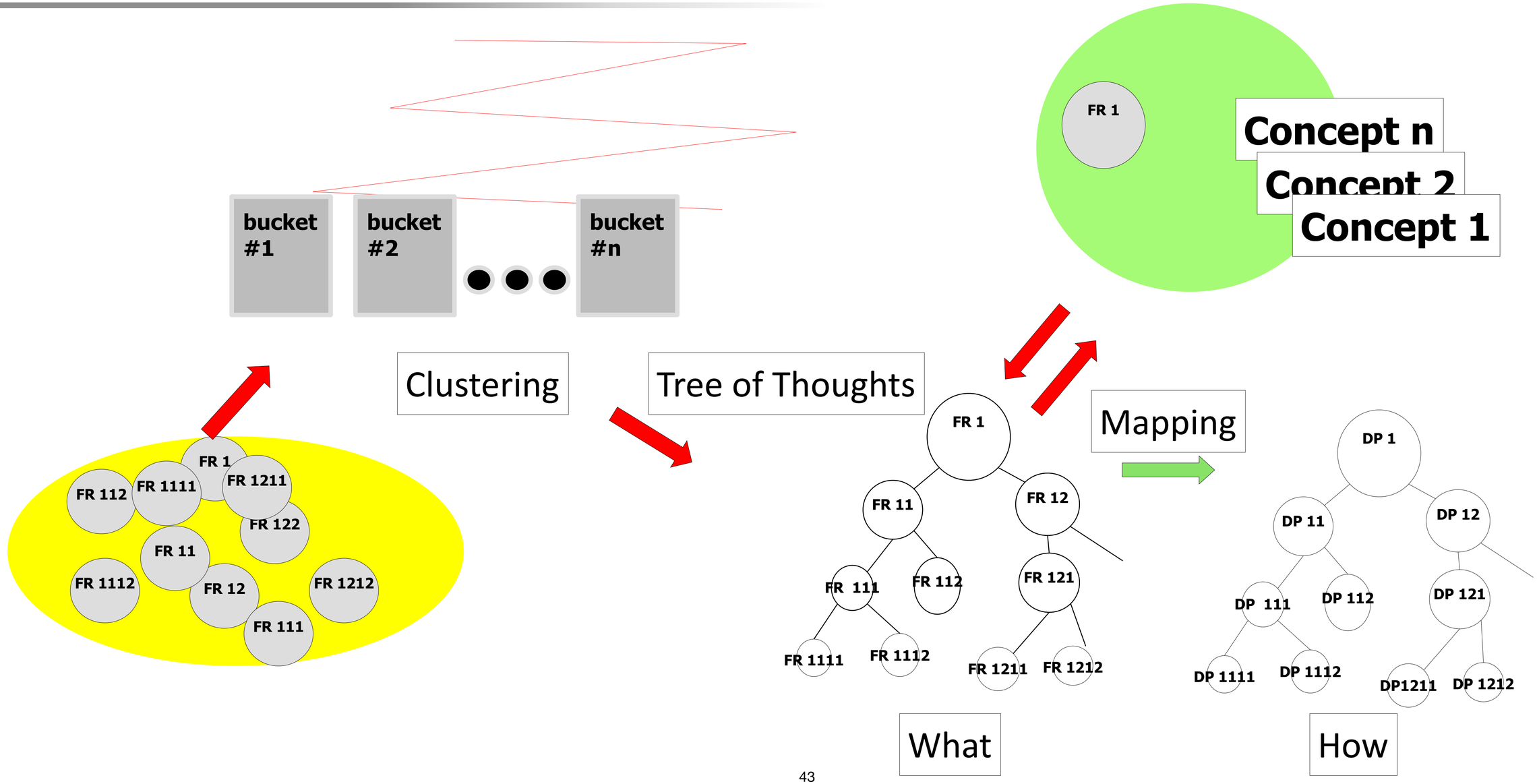
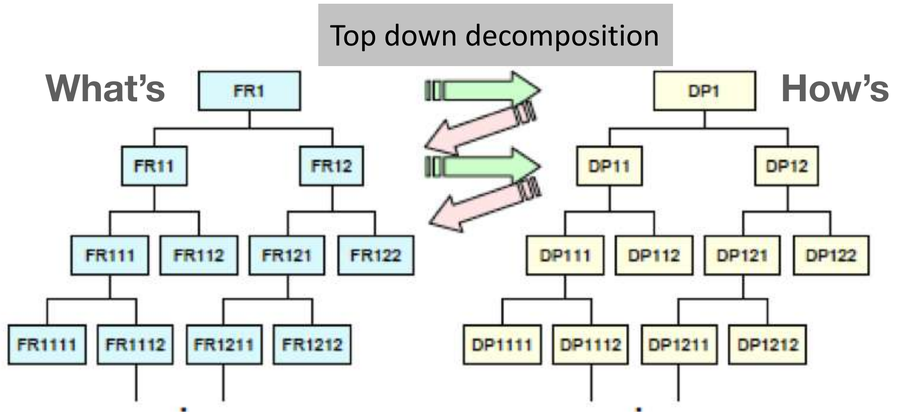
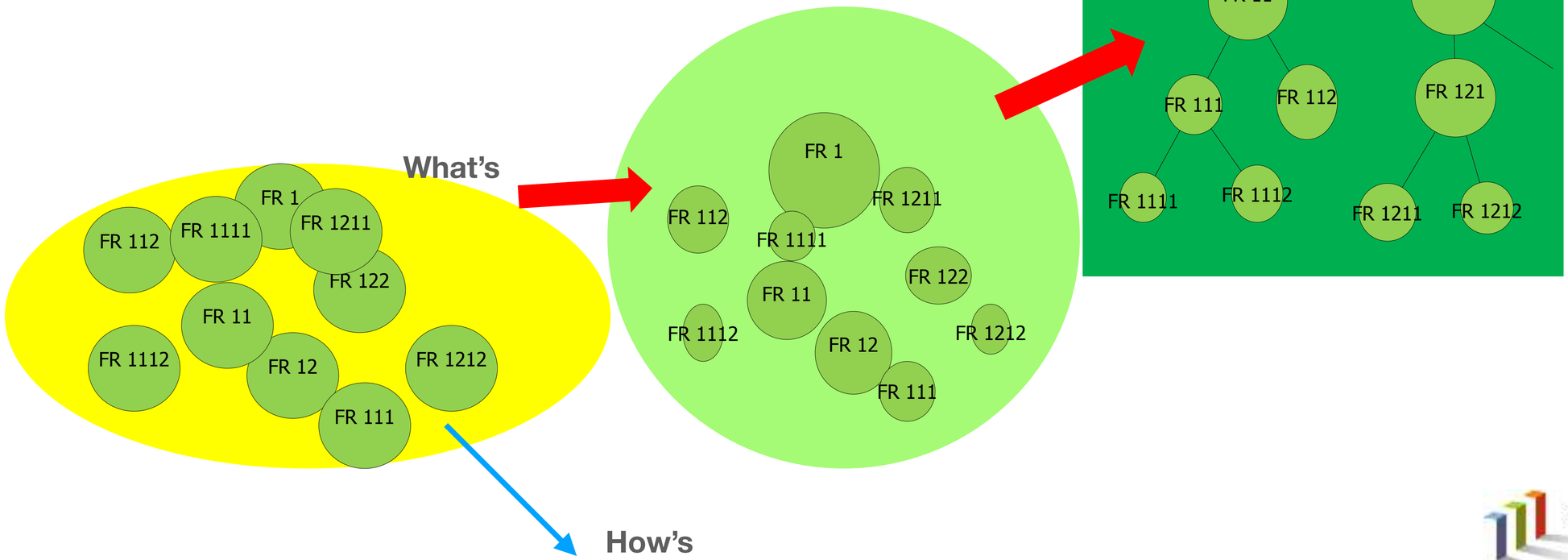
Can AI abstract findings and generate concept?



Extracting and abstracting Functional Requirements (FRs) is not easy.

$$\overrightarrow{FR} = [DM]\overrightarrow{DP}$$





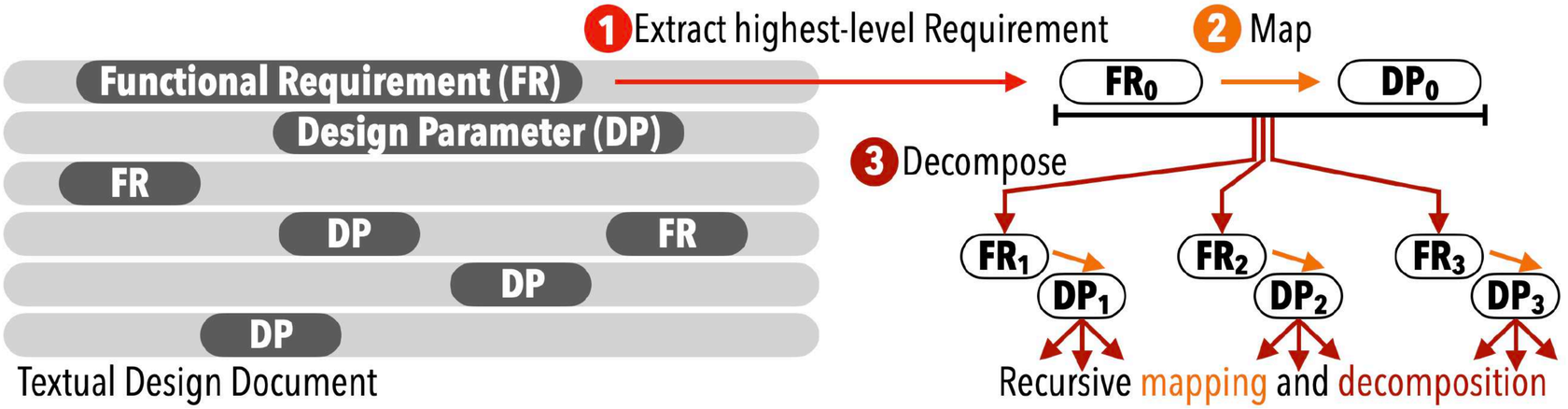
Can I train AI think in Axiomatic way?

Thinking Design Machine

MITMECHE

Extracting functional decisions in design and manufacturing

- Process for extracting functional structure from text document



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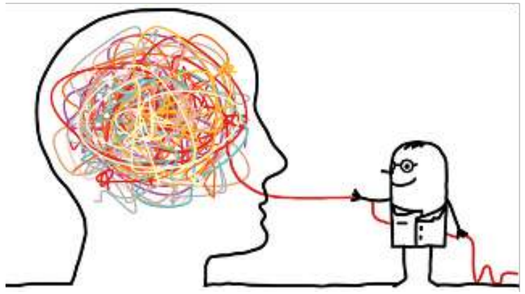
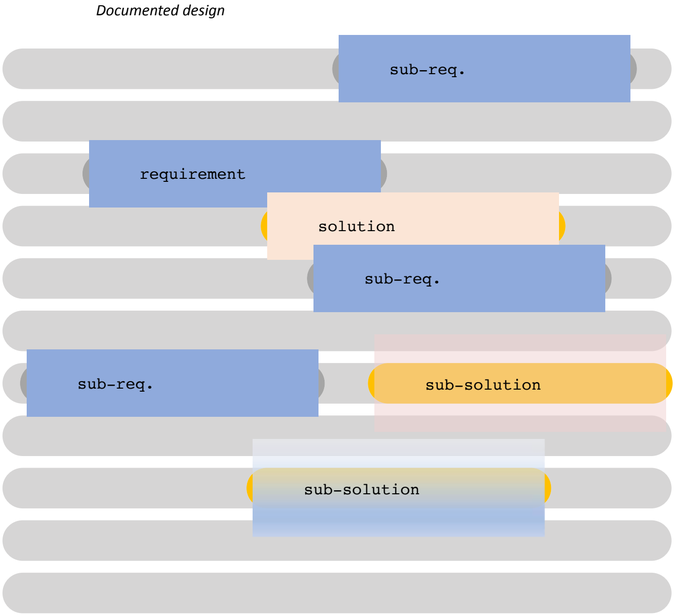
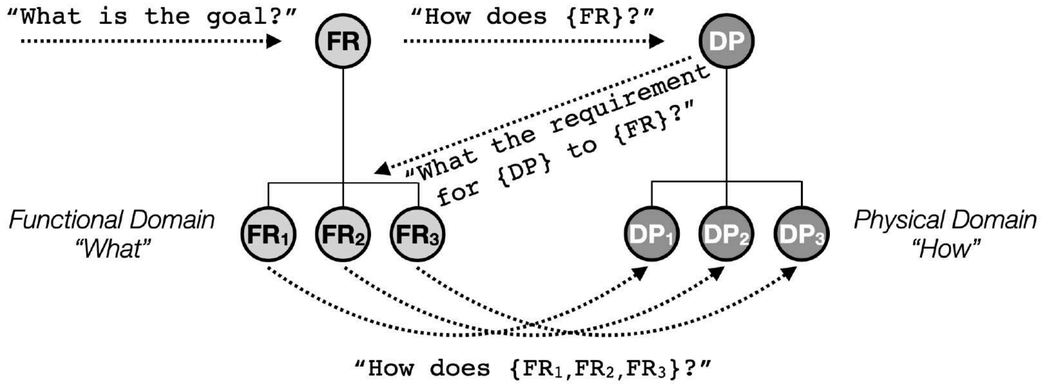
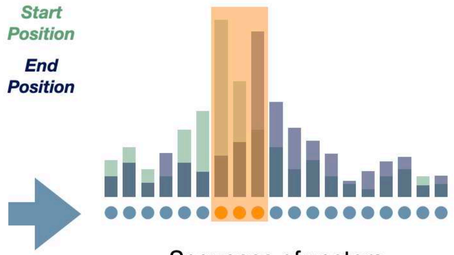
"Tree of Thoughts" reading from design documents

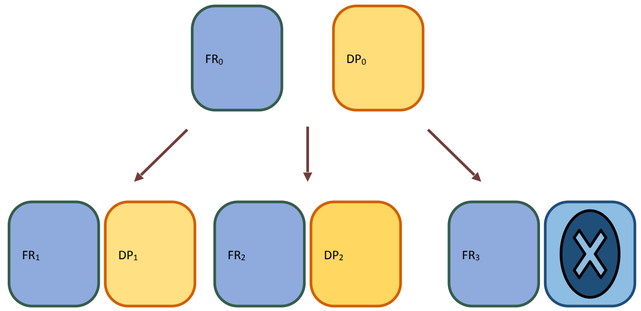
Recursive ‘question and answer’ to extract the design decisions, FRs and DPs.









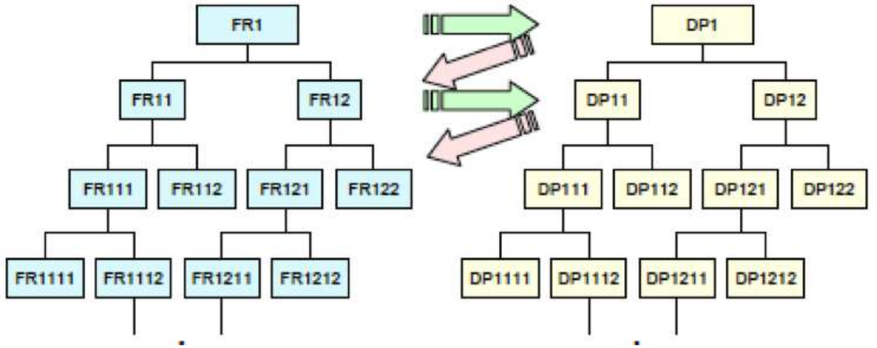


H. Akay, S. Kim, “Reading functional requirements using machine learning-based language processing,” CIRP Annals v70.1, 2021

H. Akay, Yang, M., Kim, S-G., 2021, Automatic Design Requirement Extraction from Text with Deep Learning, Proceedings of the American Society of Mechanical Engineers IDETC/CIE, 85390

Design of Agents

- Define functions (Functional Requirements)
- Separate “What’s (FRs)” from “How’s (DPs)”.
- Build "Tree of FRs" as high as possible.
- Repeat to form Tree of Thoughts



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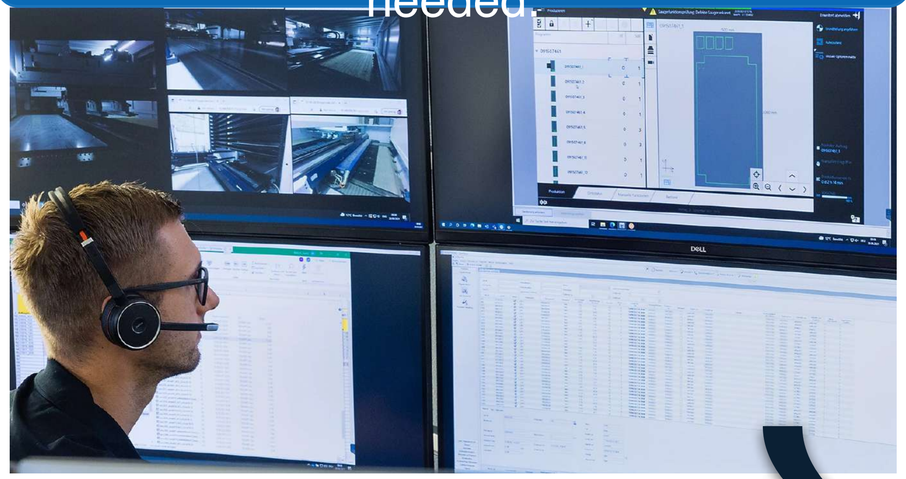
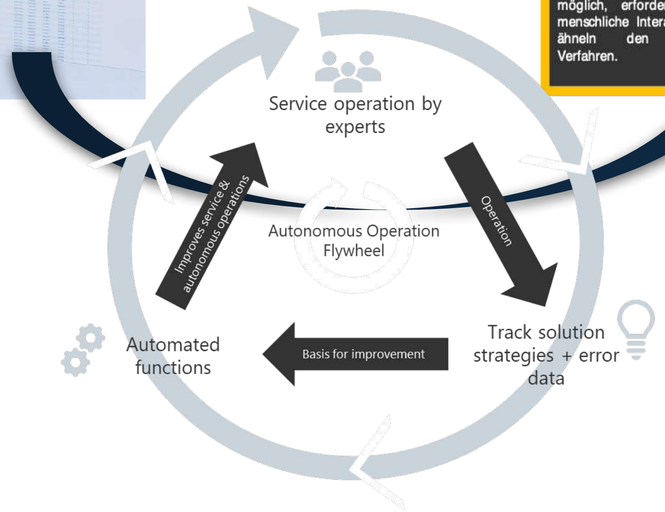
Remote operator as starting point -> Goal: automatic troubleshooting

Today: Remote Operator extensive skills and comprehensive training is needed





Vision: Machine can eliminate faults itself.



Confidential

Design of remote troubleshooting agent

Transform what to achieve to Agent submodules

- Define functions (Functional Requirements)
- Separate “What’s (FRs)” from “How’s (DPs)”.
- Build "Tree of FRs" as high as possible.
    1. Buckets and "up & down"
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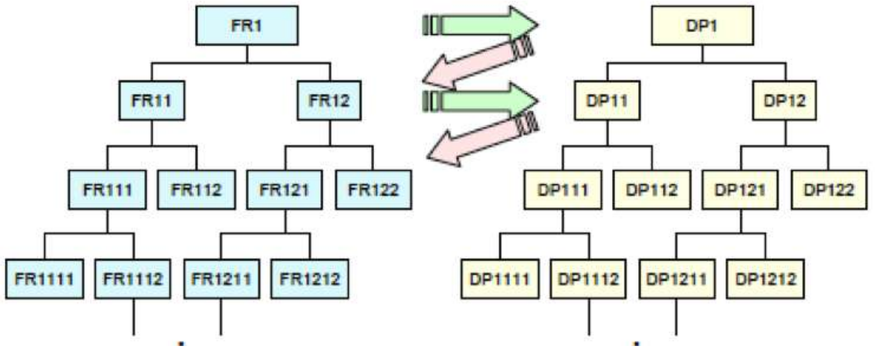
    4. Then decompose FR1 to FR11 ..FR1n.
    5. Map FR1, .. FR1n to DP1, ..DP1n
- Repeat 1-5 until reach terminal nosdes



Machining breakdown

Multi-modal data from real machining operations and breakdowns

System visualization (Real-Data)

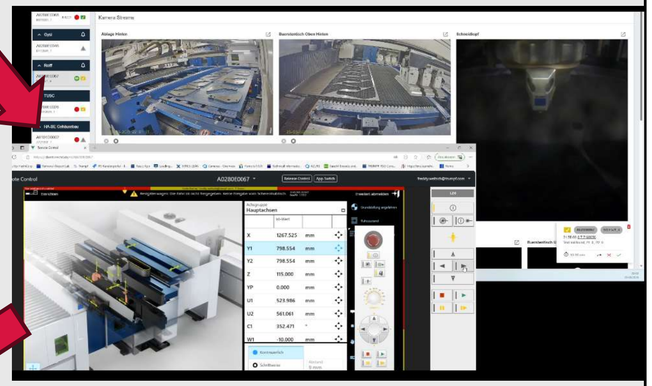
source_timestamp	node_id	value
2025-03-25T20:57:10.362+00:00	179	{"ConditionI
2025-03-25T20:57:12.381+00:00	179	{"ConditionI
2025-03-25T20:57:12.381+00:00	179	{"ConditionI
2025-03-25T20:57:15.367+00:00	179	{"ConditionI
2025-03-25T20:57:15.377+00:00	3039	TRUE
2025-03-25T20:57:15.377+00:00	3037	4
2025-03-25T20:58:08.721+00:00	53	FALSE
2025-03-25T20:58:08.721+00:00	54	TRUE
2025-03-25T20:58:08.721+00:00	59	1160
2025-03-25T20:58:08.731+00:00	3038	1
2025-03-25T20:58:08.731+00:00	3015	FALSE
2025-03-25T20:58:08.731+00:00	3034	0
2025-03-25T20:58:08.927+00:00	35.StoppedMalfunction	TRUE
2025-03-25T20:58:08.927+00:00	35.Stopped	TRUE
2025-03-25T20:58:08.927+00:00	35.Running	FALSE

Detecting production faults

Input multi-modal data:

- Dynamic real-time videos
- Static knowledge graph
- Machine signals

Multimodal Large Language Model Analysis





Which camera allows for the fastest analysis of faults and derivation of solutions?

Description:

> 300.000 tsd. Videos + machine data available for training

Real machining data:

- 14 Camera angles, PLC data, OPC_UA error codes (100+, 1-2mins around failures, incl. resolution)
- Machining handbook and faults' descriptions .Pdf

Goal: Adapt autonomously to disturbances during the production

-> Select best camera to view the error +
propose resolution strategy based on best practices

Currently underway:

- Static training: PDFs → graph-based knowledge for MLLM pretraining & querying
- Dynamic analysis: Video in OpenCV with VLM/MLLM (e.g., Qwen 2.5)

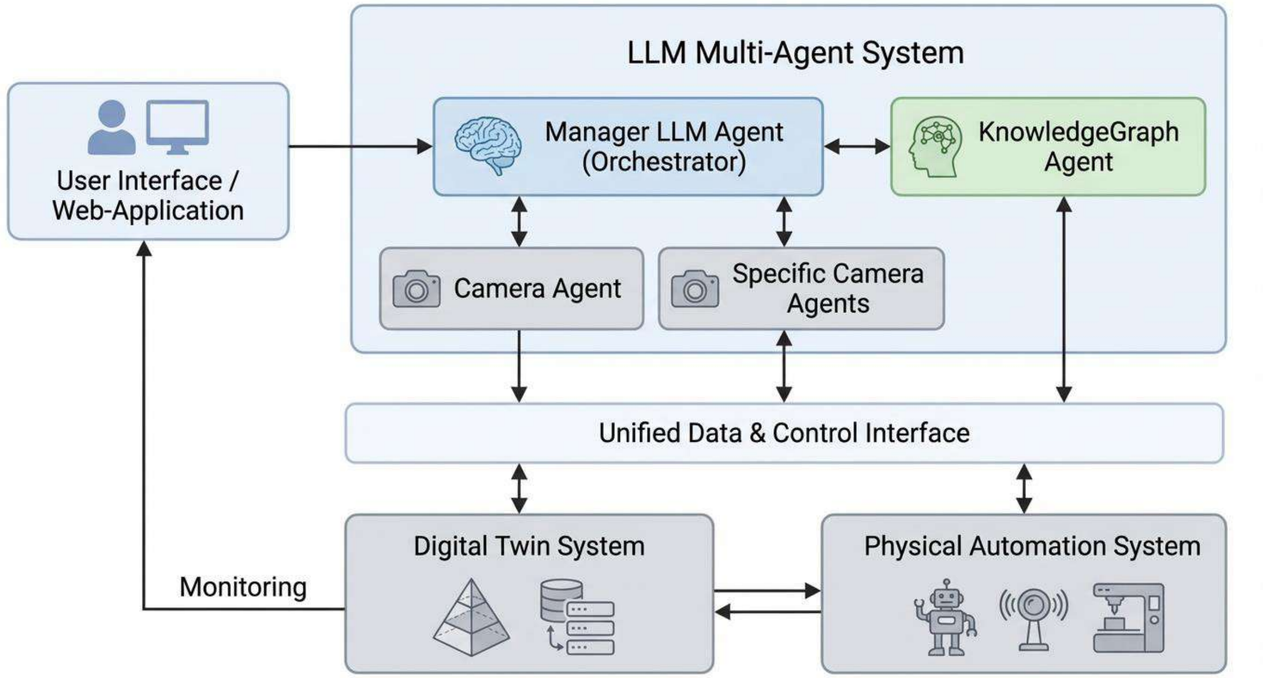
Expected outputs fast-response fault reports:

- Optimal camera view ranking
- Fault cause identification
- Recovery & mitigation strategies

Confidential

Multimodal LLM-VLM Multi Agent Solutions

Physical View



- **Is this a functional view of physical view?**
- **How could we design AI Agents?**

Design of remote troubleshooting agent

Functional View

Transform what to achieve to Agent submodules

- Define functions (Functional Requirements)
- Separate “What’s (FRs)” from “How’s (DPs)”.
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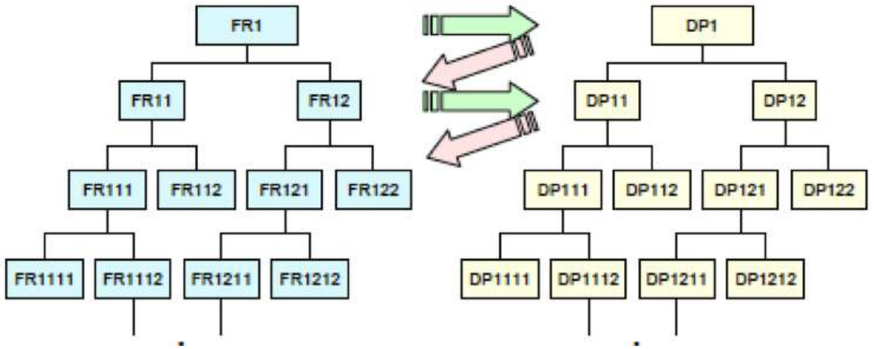

Design of Remote Troubleshooting Agents

Functional View

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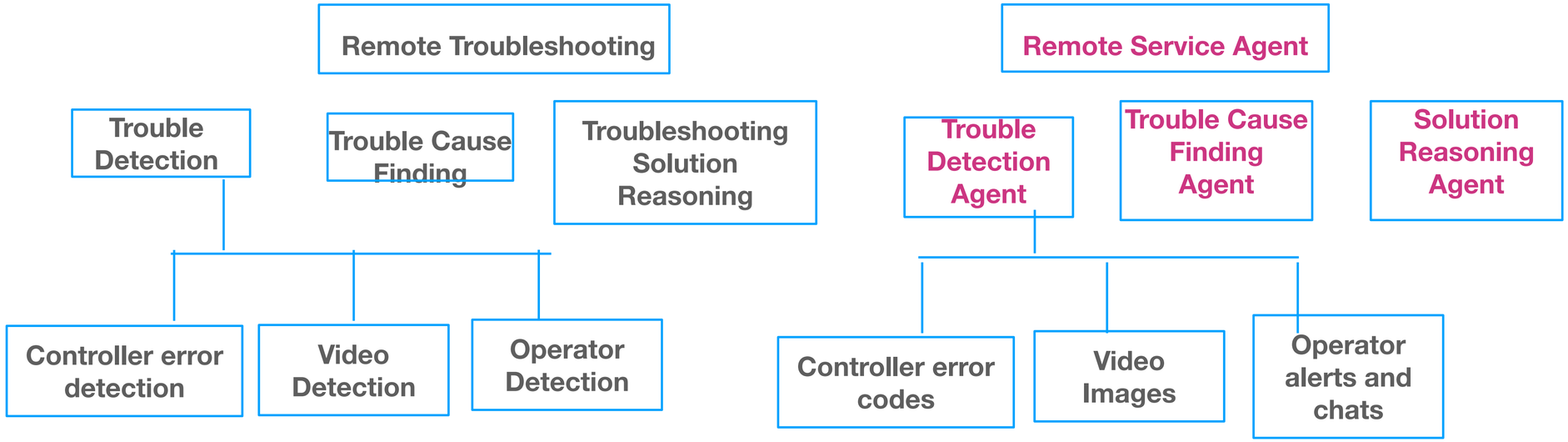
- Repeat



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Design of Remote Troubleshooting Agents

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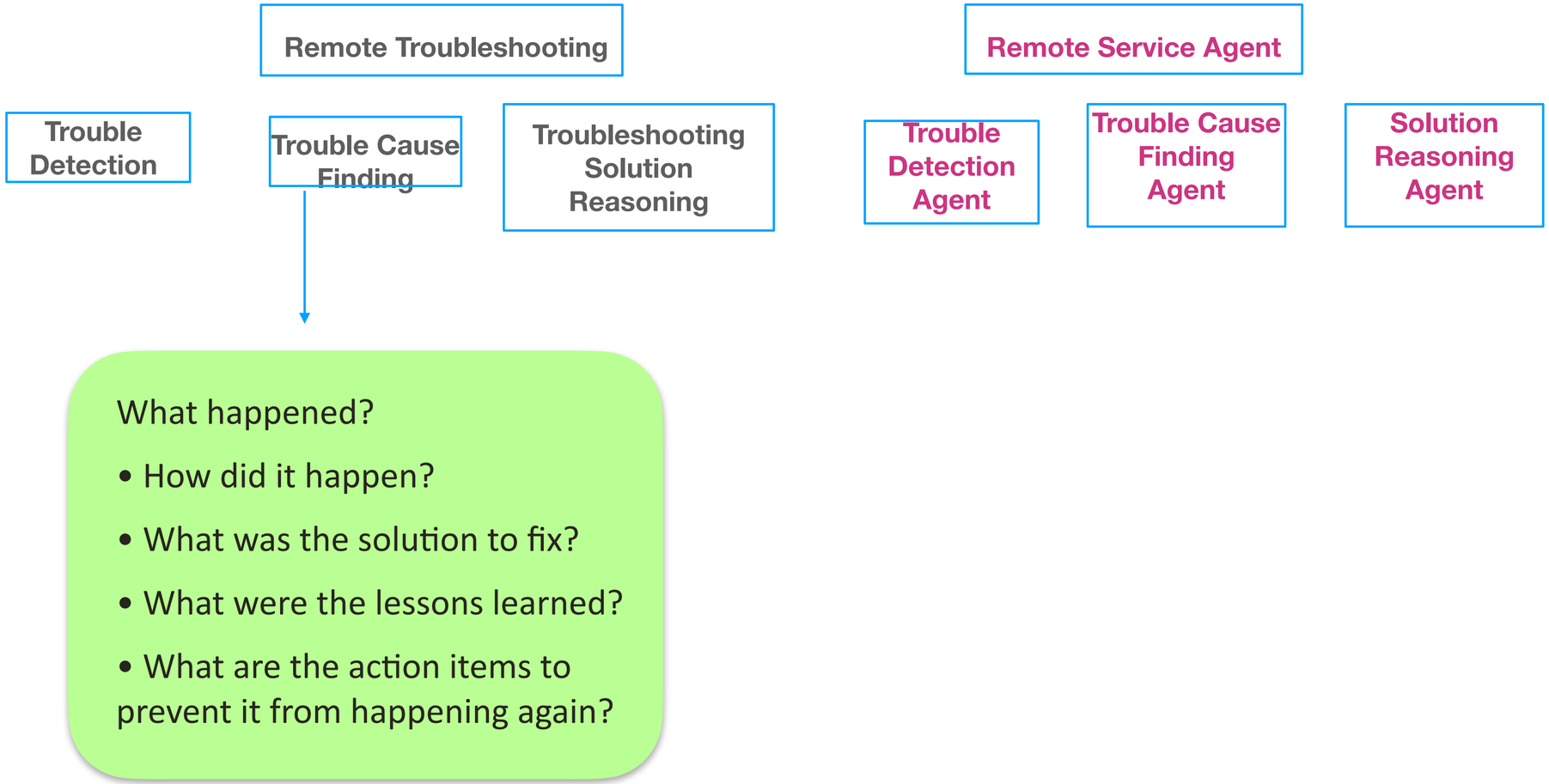

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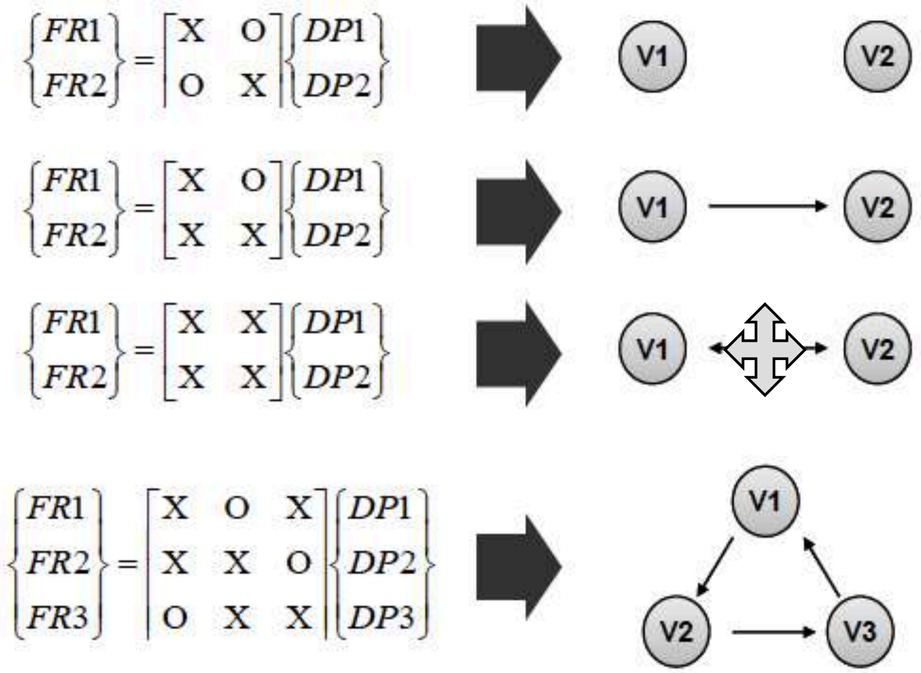
Functional Couplings of Agents

- Orchestration Agent
- Determine execution sequence or decisions
- Follow FR-DP graph
- Make additional queries to find necessary data, information .



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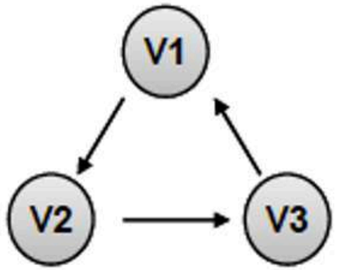
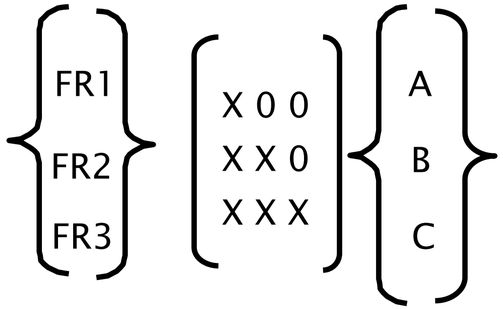
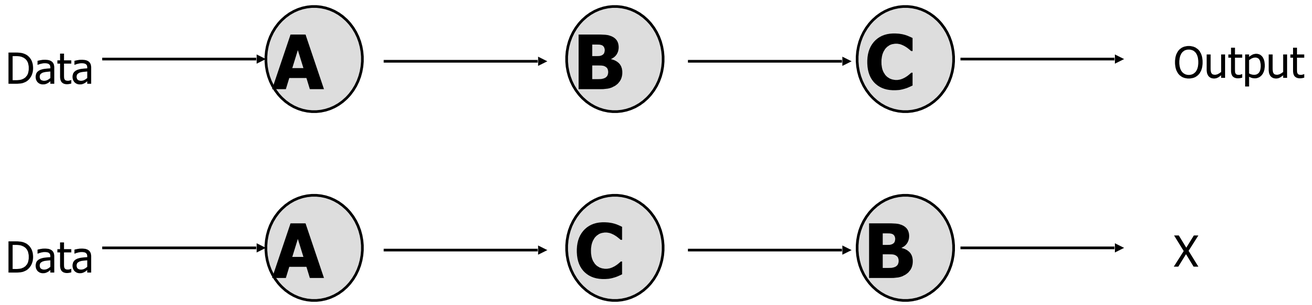
Organizational design

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X & O & X \\ X & X & O \\ O & X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix}$$







Summary:

- Functional thinking is the way to assess the systems design problem.
- Axiomatic approach to design can provide a scientific framework for system architecting.
- System's FR tree (Function Graph) can be the backbone of the digital thread connecting all the activities and decisions of a system.
- True digital transformation will become feasible.

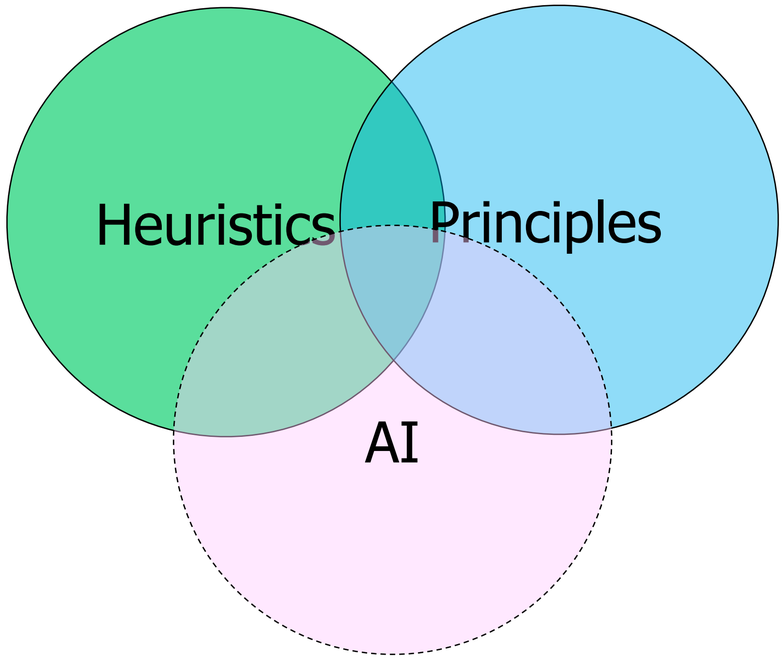
Take Home Messages

- Is Multimodal Modeling a “What” or “How” ?
- Is AI a “What” or “How” ?
- What do you want with AI?
- Systems thinking !!





How to solve large and complex problems?



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