LWRS LIGHT WATER REACTOR SUSTAINABILITY

Risk-Informed Performance-Based Approach to Manage Plant Operations: From Data to Decisions

(Data Analytics + Smart Models = Robust Decisions)

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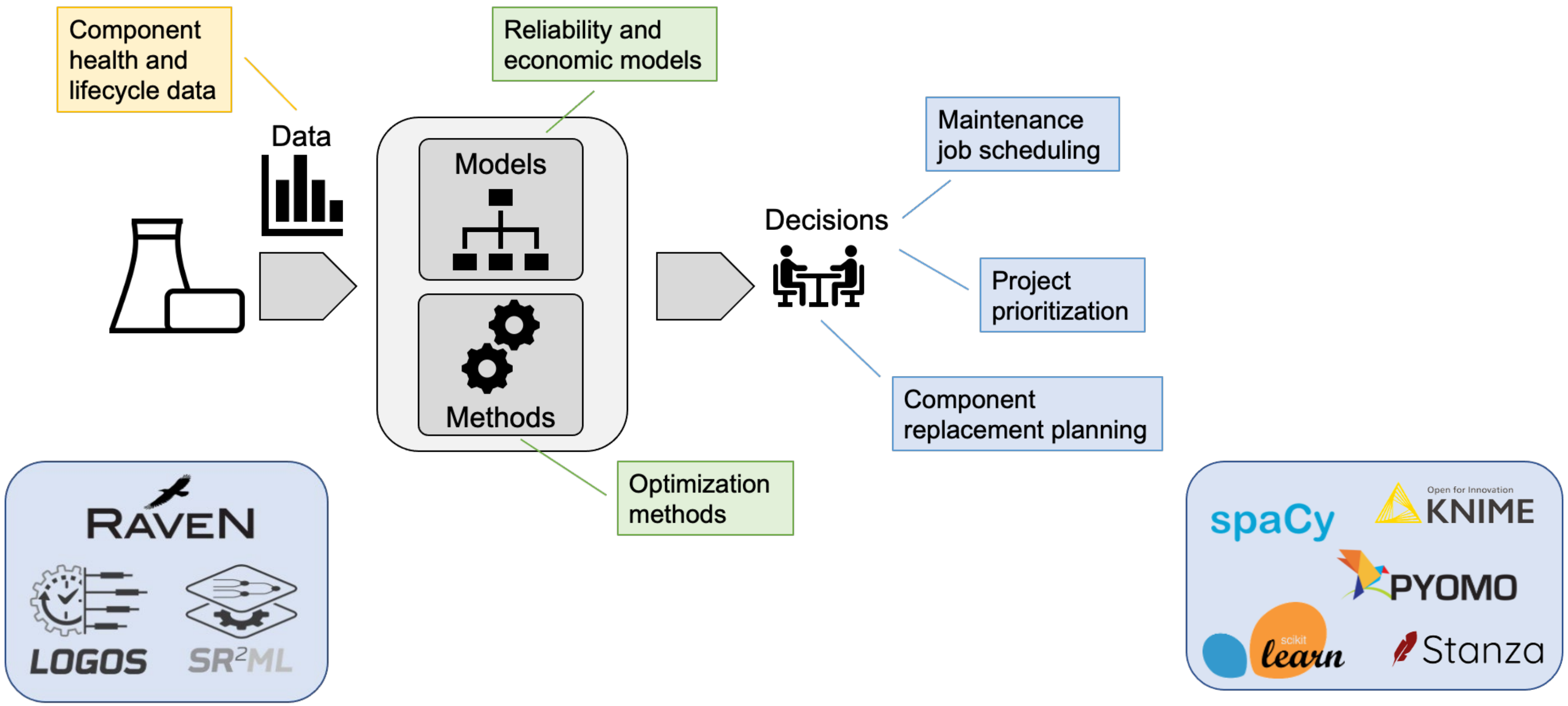
Risk Informed Asset Management Project

- **Context:** Advanced modeling and monitoring technologies have the potential to improve plant performances and reduce operating and maintenance (O&M) costs
  - Rich equipment reliability (ER) data
- **Our Work:** Risk analytics platform
  - Data analytics tools coupled with risk-informed methods to manage plant assets and performances



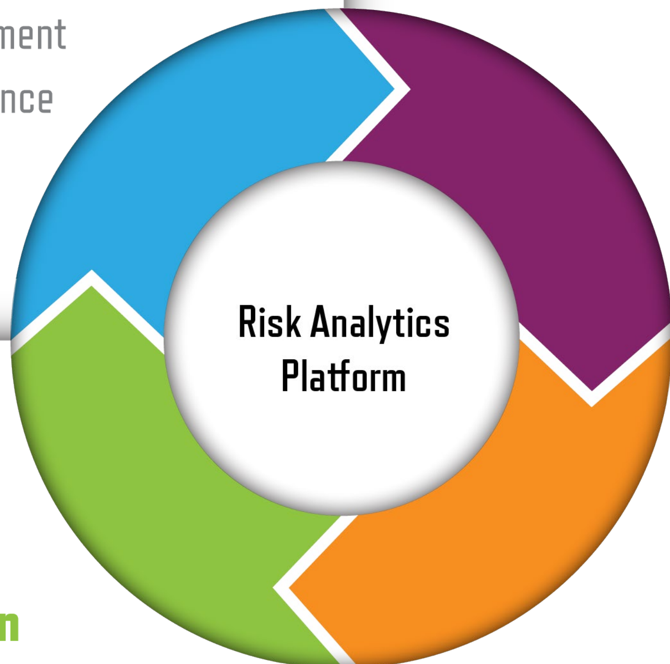
Outline

Goals: O&M reduction costs

- Reliability/ageing management
- Enhance system performance
- Optimize plant resources

ER Data Analytics

- Anomaly detection
- Diagnostics
- Prognostics



Resource Optimization

- Project prioritization
- Project actuation planning
- Job scheduling

Digital Modeling

- Integration of reliability and economic models
- Margin reliability solver

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ER Data Analytics

- **State of practice:** Focusing on finding patterns from data
  - Data can be misleading!

"Machine learning bounded solely by data is doomed to fail" (J. Pearl)

- **Data elements:** Heterogenous ER data format
  - Textual (events, logs): Defined over time point or time interval
  - Numeric (e.g., pump oil temperature)

Are both these elements adequately analyzed simultaneously?

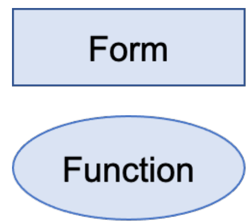
- **Our work:** Causal reasoning behind patterns
  - Integrate numeric and textual data
  - Infer causal relationship among data elements
    - We need to use data along with models

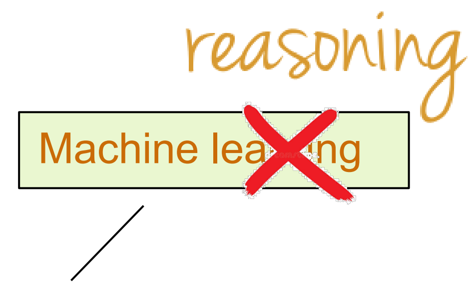
Not all patterns tell us something about the system

- **Approach:** Merge two perspectives
  - System engineer
  - Data scientist
- **Applications**
  - Anomaly detection: Find abnormal behavior from normal conditions
  - Diagnostic: What caused the abnormal behavior?
  - Prognostic: What are the consequences?
  - Integration of ER data into plant digital models

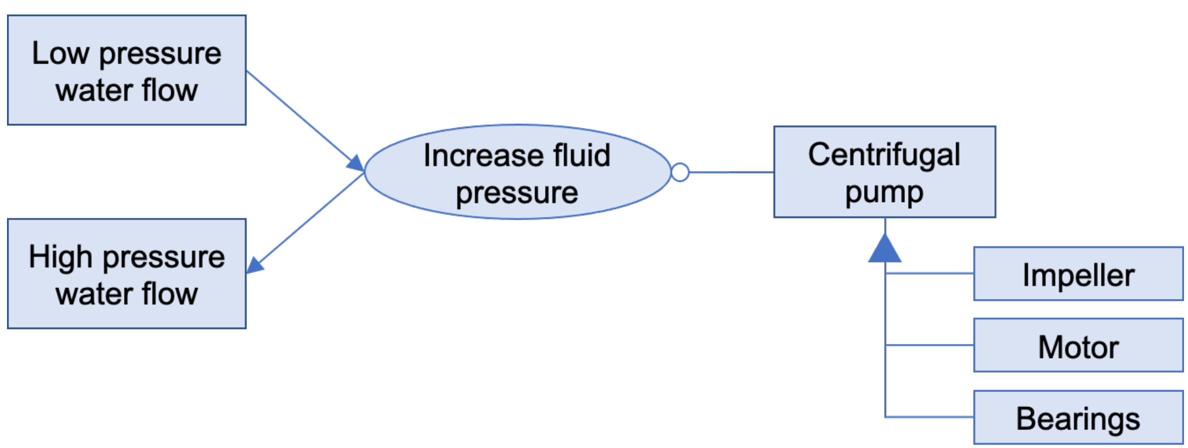
System Engineer Perspective

- **Employ Model Based System Engineering (MBSE) representation of systems and components**
  - Large use of diagrams
    - **MBSE languages:** started with OPM (soon extended to SysML)
  - Diagram elements
    - Form
    - Function
    - Dependencies



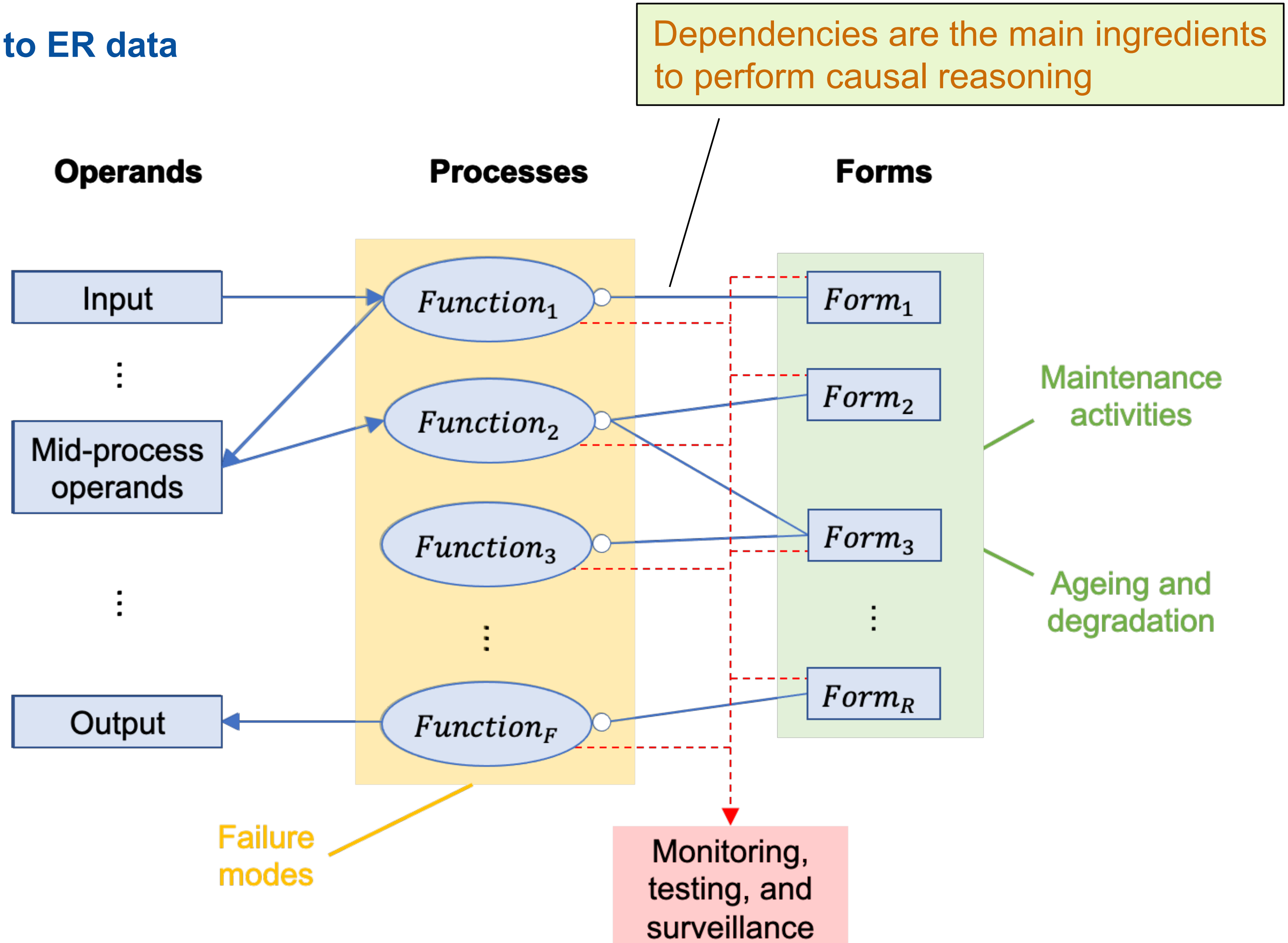


- **Uses**
  - Understand “what a text is talking about”
  - Foundational models to identify causal links between data elements
- **Emulate system engineer knowledge** about component/system architecture



System Engineer Perspective

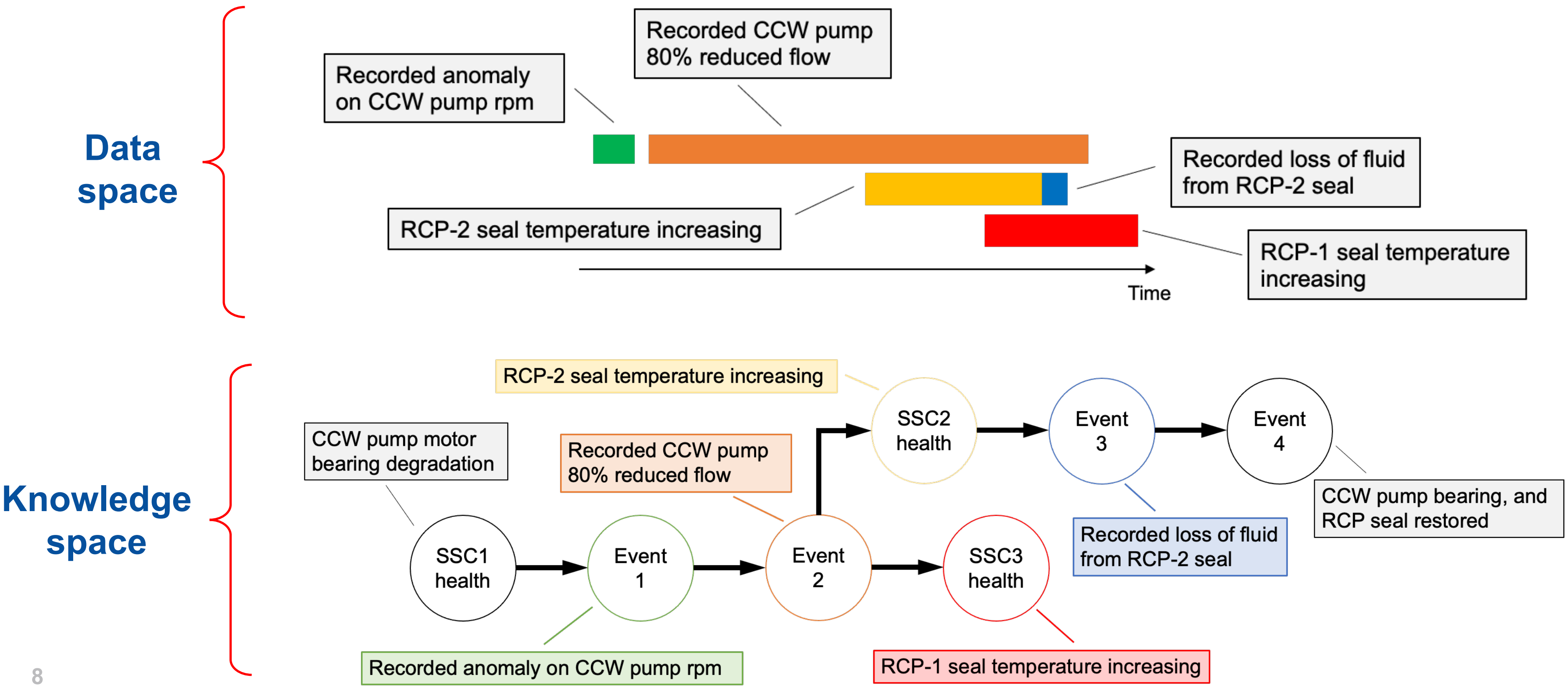
- **Link to ER data**



Data Scientist Perspective

Causal reasoning (not really inference)

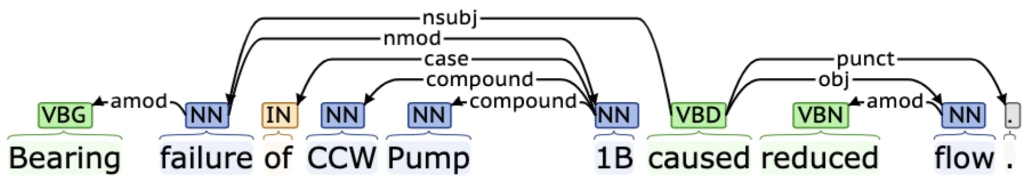
- **Data scientist view:** Discover causal relationship between data elements
  - Integrate ER data with system/component MBSE models
  - Directed Acyclic Graph (DAG) based data structure
- **Challenge:** Integration of textual and numeric data
  - **Approach:** Symbolic conversion of all data elements



Analysis of Textual Data

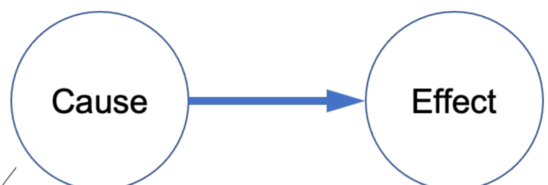
- Example
  - "Bearing failure of CCW Pump 1B caused reduced flow."
- **NLP syntactic analysis**

> - Sentence segmentation and word tokenization
> - Part of speech (POS) tagging
> - Named entity recognition (NER)



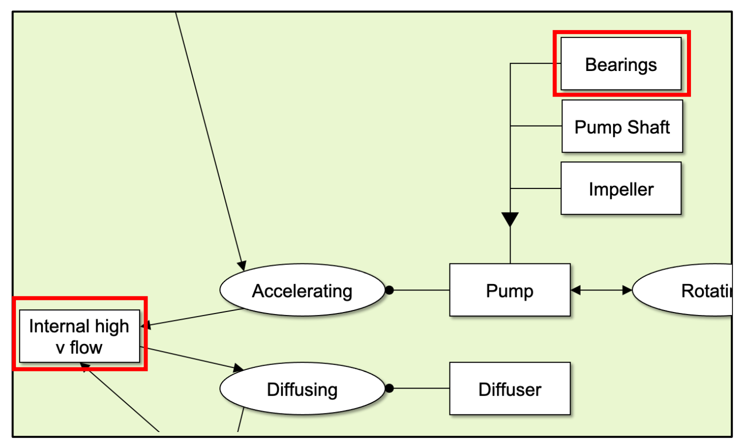
> - Identify the sentence logic structure
> - Identification of specific nouns, verbs and adjectives
> - Identify OPM elements (form or function)

- **NLP semantic analysis**
  - Rely on component/system OPM models
  - Generated causal model



(CCW Pump 1B, bearing, failed)

(CCW Pump 1B, internal high v flow, degraded)



Centrifugal pump OPM model

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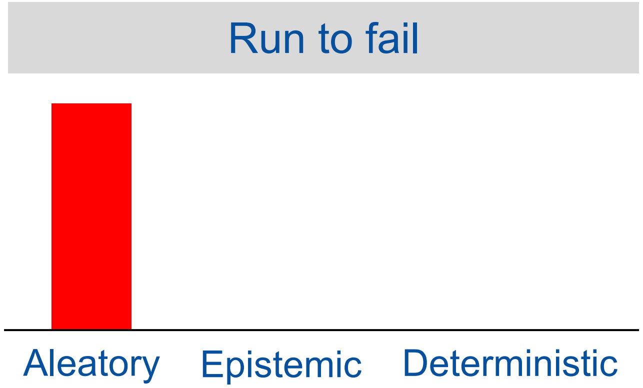
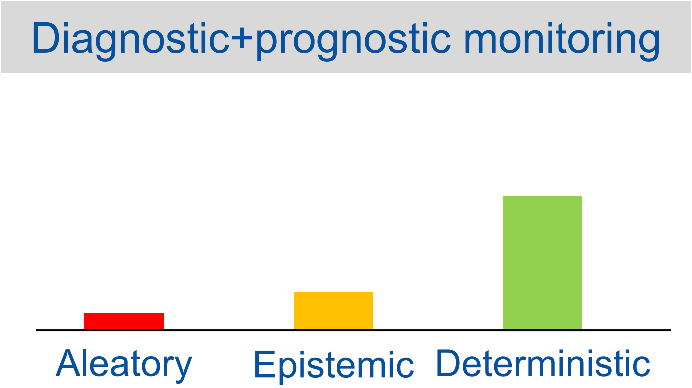
Issues with Current Reliability Approaches

- **Is ER data effectively integrated into plant reliability models?**
  - Easy for components designed to run to fail (i.e., MTTF)
  - What about condition, diagnostic, and prognostic data?
- **State-of-the-art reliability modeling**
  - Bounded by language based on failure rate or failure probability concepts
    - E.g., linear ageing model
  - Does use of “system failure probability” support ongoing decision-making?
- **Thoughts on the concept of failure rate**
  - Rate of occurrence of an aleatory variable
  - Assume testing, surveillance, diagnostic/prognostic monitoring are performed
    - Am I still dealing with an aleatory variable?

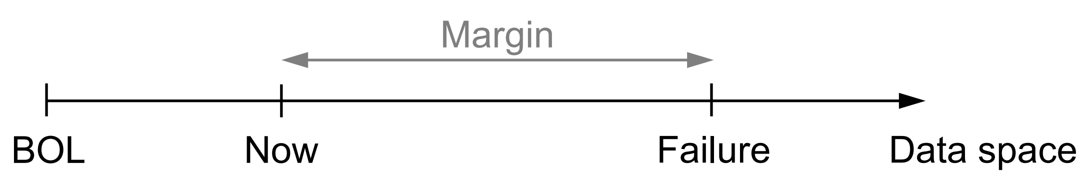




Reliability Modeling: A New Language

- **Discussion during car trip (February 2020)**
  - “Every time we talk about system/component failure probability we lose system engineers attention.”
  - “We need to change language such that we can link ER data to decisions.”
  - “System engineers are more used to the concept of margin.”
  - “What if we link ER data to decisions in terms of margins?”

- **Margin definition**: The “**distance**” between present/actual status and an (estimated) undesired status for a specific component



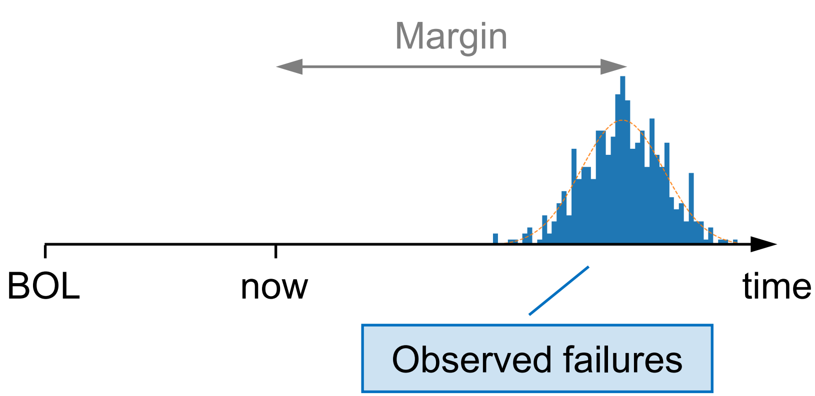
- What if we talk about reliability in terms of margins?
  - This change implies a **redefinition of risk**

Regulatory definition		System engineer definition
What can go wrong What are its consequences **How likely it is**	→	What can go wrong What are its consequences **How distant it is**

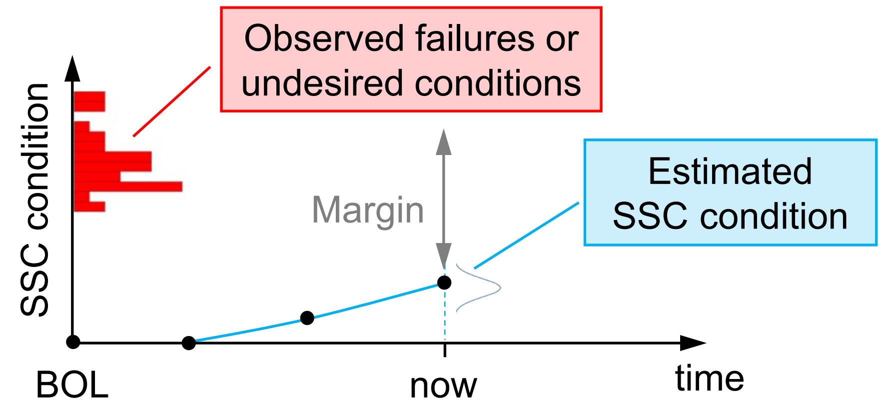
Reliability Modeling: A New Language

- Margin is defined over actual and past ER data
  - Direct integration of ER data
- **Margin values change with time**
  - New SSC condition data are observed — Degradation: Margin ↓
  - ER operations (e.g., maintenance) are performed — Margin ↑

Corrective maintenance



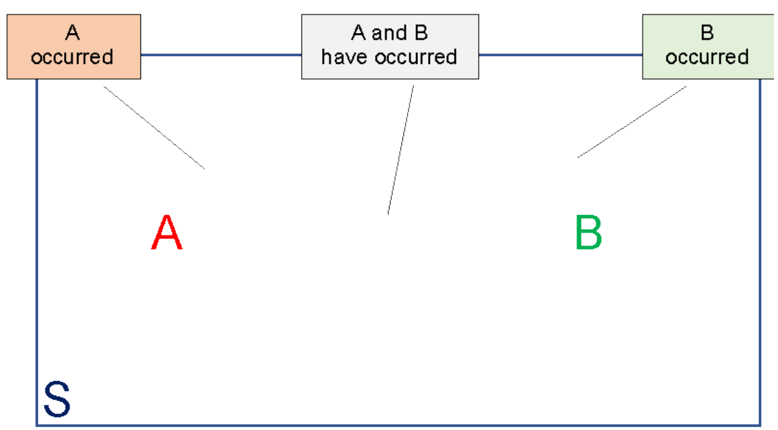
Condition-based maintenance



Reliability Modeling: A New Language

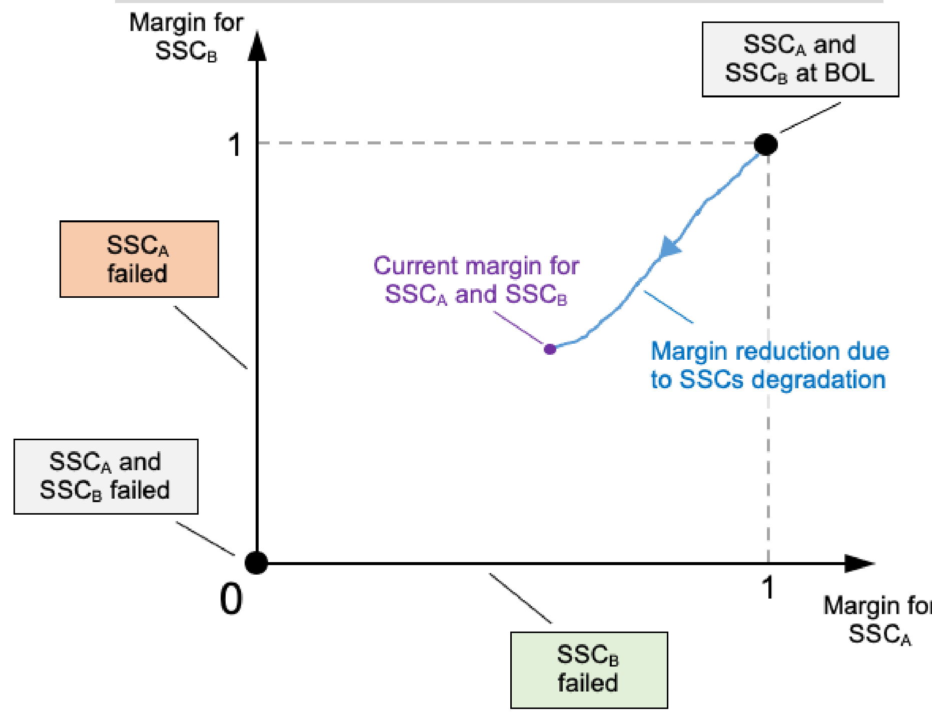
- System reliability models are typically based on fault trees
  - Deterministic models that depicts system architecture from a functional perspective
  - Boolean algebra operations used to calculate top event probability (set theory based)
- Can I use fault trees to propagate margin values up to the top event?

Set representation



$$P(A\ OR\ B) = P(A) + P(B) - P(A \cap B)$$
$$P(A\ AND\ B) = P(A|B) \cdot P(B) = P(B|A) \cdot P(A)$$

Margin representation



$$\widetilde{M}(A\ AND\ B) = dist[(\widetilde{M}_A, \widetilde{M}_B), (0,0)]$$
$$\widetilde{M}(A\ OR\ B) = min(\widetilde{M}_A, \widetilde{M}_B)$$

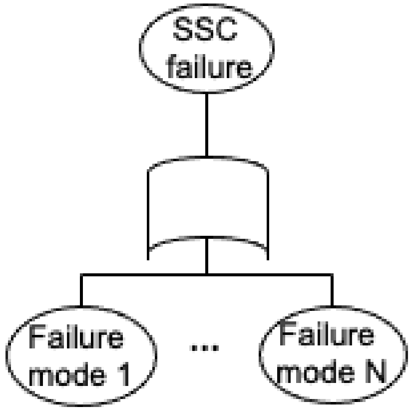
Reliability Modeling: A New Language

- Margin calculations can be **carried out directly from the minimal cut (or path) sets** generated by any PRA code
- Operation through metric spaces are much **faster** compared to Boolean logic operations

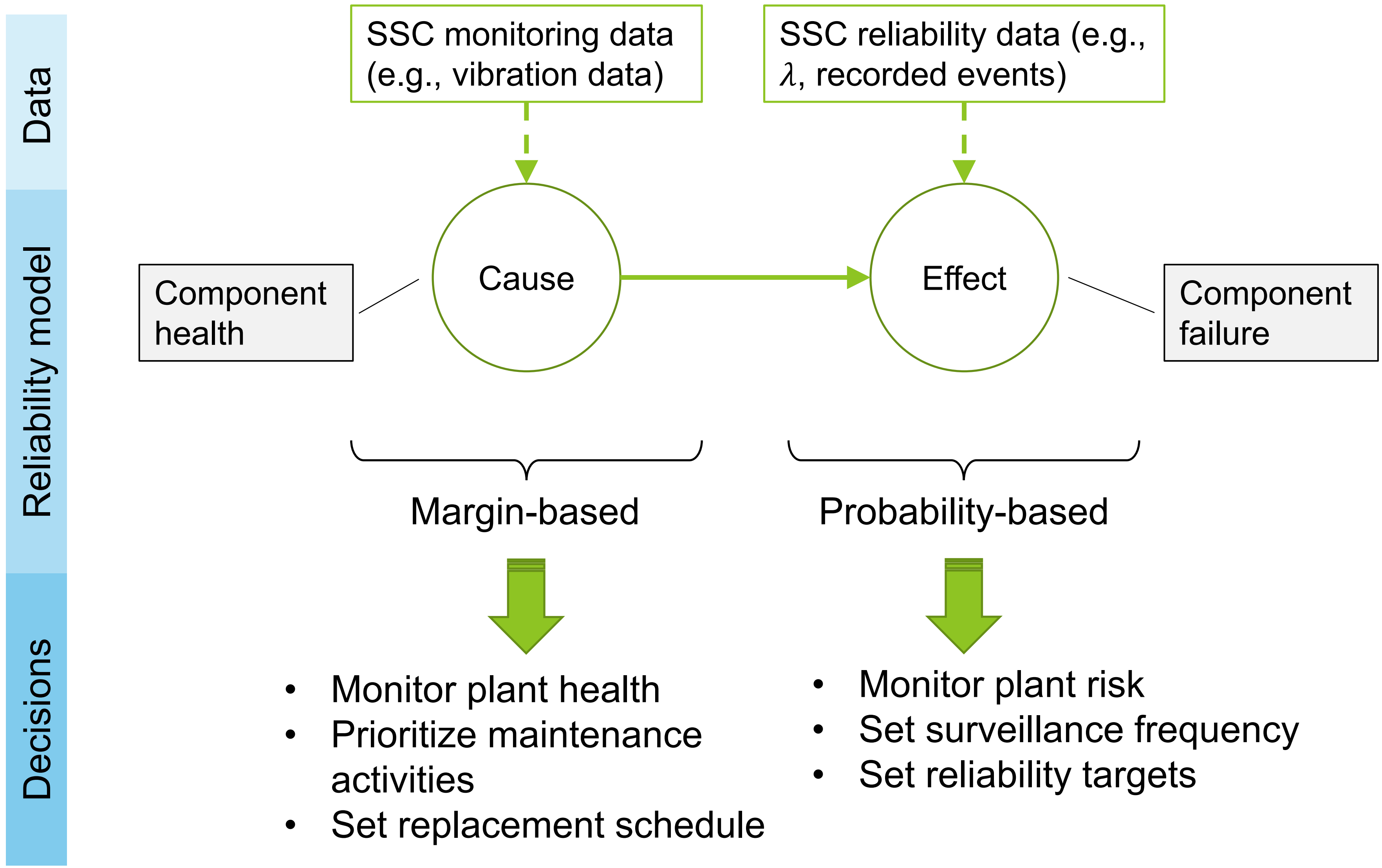
$$P(A \cup B) = P(A) + P(B) - P(A \cap B)$$

Operation	Set based	Margin based
A OR B	$P(A) + P(B) - P(A \cup B)$	$\min(\tilde{M}_A, \tilde{M}_B)$
A AND B	$P(A\|B)\,P(B)$	$\sqrt{\tilde{M}_A^2 + \tilde{M}_B^2}$

- Several SSC are characterized by several failure modes
  - Each failure mode is modeled through its own margin
- **Risk importance measures**
  - Borrowed from sensitivity analysis theory: $S_{BE} = \frac{\partial\, \tilde{M}(TE)}{\partial\, \tilde{M}(BE)}$
- **Applications**
  - Monitor system/plant health
  - Prioritize failure modes that impact system/plant reliability



Links Between Reliability Modeling Approaches



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Plant Resources Optimization

- **Resources: personnel, budget, assets, time**

- **What does optimization mean?**
  - Maximize value of spent $
  - Minimize maintenance crew activities
  - Maximize ER workforce productivity
  - Maximize SSC lifecycle performance (availability/reliability)
  - Minimize SSC lifecycle cost

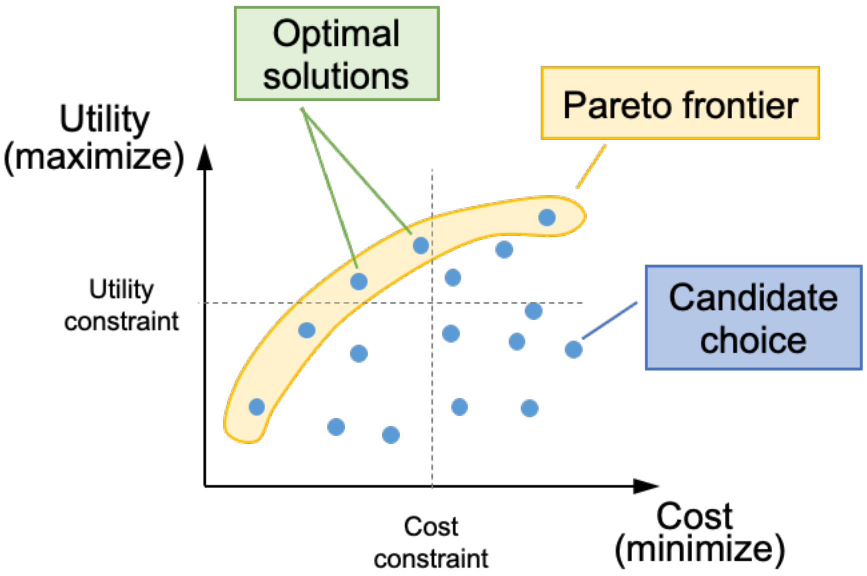
- **Applications**
  - Task scheduling (short-term horizon decisions)
  - Project planning and scheduling (long- and mid-term horizon decisions)

- **A simulation-based approach**
  - Optimization methods
    - <u>Data based</u>: linear integer (deterministic, stochastic, distributionally robust)
    - <u>Model based</u>: single- and multi-objective
      - E.g., gradient-based, genetic algorithms, Pareto frontier
  - Integrate reliability and economic models

Multi-Objective Optimization

- **Objective:** balance multiple factors in the decision process
  - E.g., costs and reliability

- **Applications**
  - Determine optimal set of maintenance activities
  - Evaluate optimal alternatives for maintenance posture
  - Determine system optimal monitoring configuration



- **Method:** Multi-objective optimization
  1. Trade-off exploration: evaluate system costs and utility for several options
  2. Identify Pareto frontier
  3. Propagate uncertainties
  4. Impose utility/cost constraints

Project Prioritization/Scheduling

- **Goal:** Select optimal set of projects and actuation schedule that maximizes overall NPV

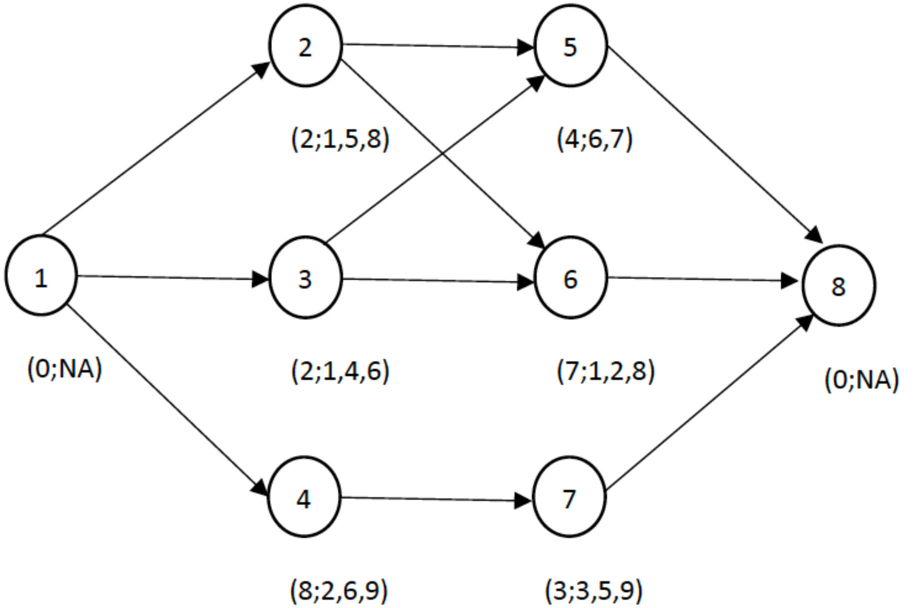
- **Input data:** Candidate projects (e.g., SSC replacement)
  - Options for each project (timing, duration, and costs)
  - Budget constraints per year and per resource (e.g., capital funds, O&M funds)
  - Consequences of stochastic events (e.g., SSC failure)

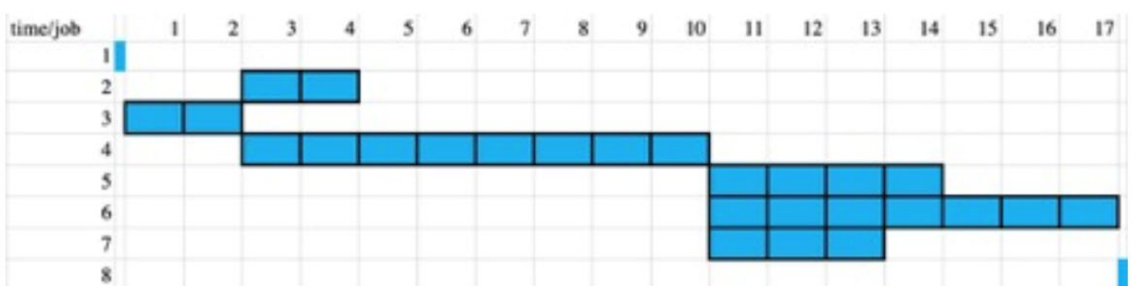
- **Output data:** Selected projects and prioritization and optimal project schedule

	T1	T2	T3	T4	T5	T6	Risk
	$ 50K	$ 90K	$ 90K	$ 90K	$ 70K	$ 40K	
M1-B		$ 40K					0.25
M2-B			$ 50K				0.36
M3-B				$ 35K			0.18
M4-A				$ 40K			0.18
M5-A		$ 45K					0.2
M6-A	$ 25K						0.168
M7-A			$ 30K				0.72
Total	$ 25K	$ 85K	$ 80K	$ 75K	0	0	2.058

Task Scheduling

- **Applications**
  - Scheduling of maintenance and surveillance activities
  - Scheduling of outage activities
- **Input data**
  - Crews (skill set, availability)
  - Tasks (duration, dependencies, skills)
- **Objective:** minimize time to perform all tasks
- **Methods**
  - Mixed integer linear optimization
- **Output data**
  - Task schedule assigned to each crew





Conclusions

- Project overview: **Linking data to decisions**

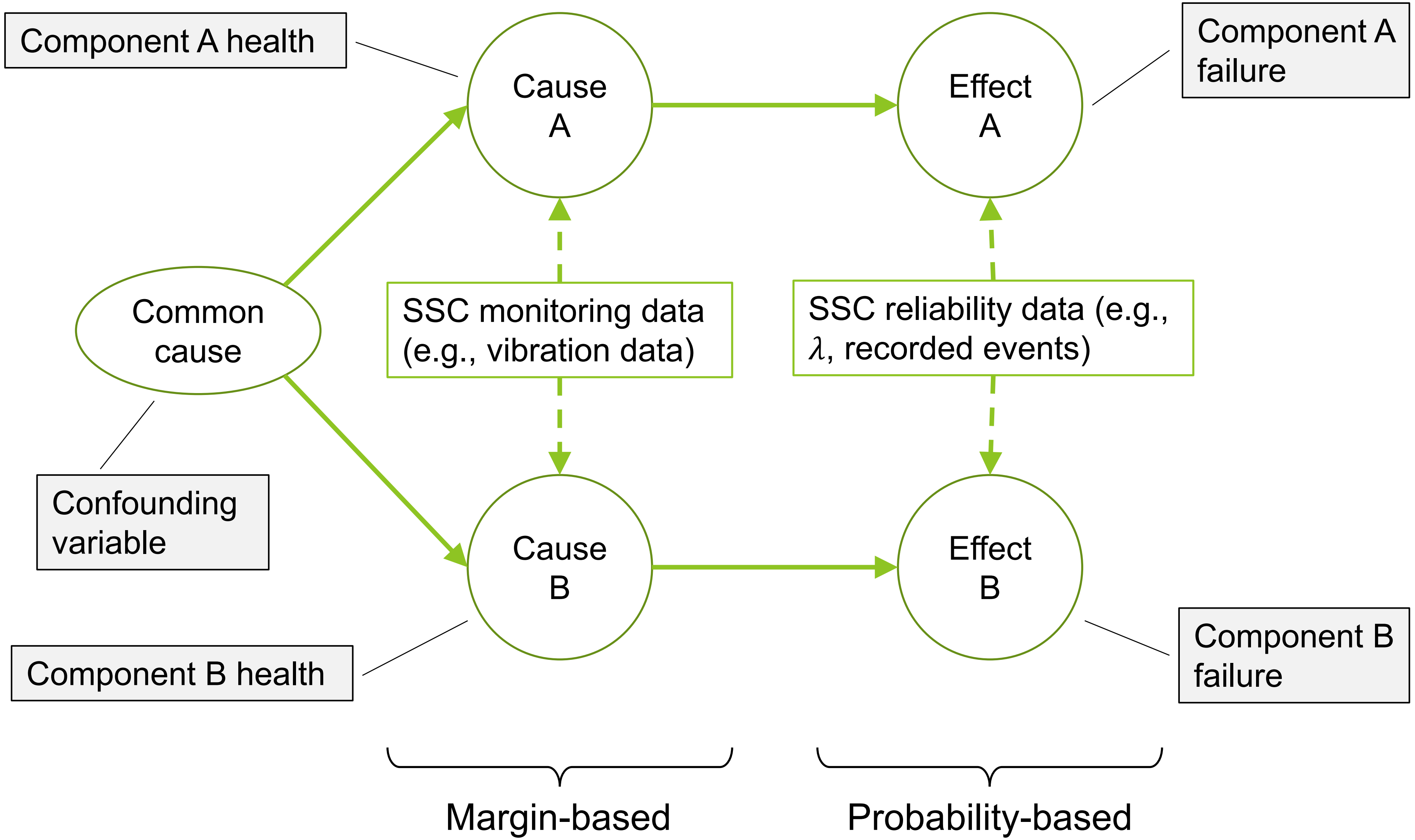
- **ER data analytics**
  - Causal inference of numeric data and events
  - System and data perspective: moving away from a data-driven mindset

- **Reliability modeling using margin-based solvers**
  - Easy integration of data analysis methods
  - Compatible with employed system reliability models (fault trees)
  - Complete and explainable representation of system plant health
    - Target both system engineers and plant managers/decision-makers
  - Support plant health/asset management decisions through explainable models/data

- **Plant resource optimization**
  - Long-term: Prioritization projects that provide higher value
  - Medium-term: Project execution planning
  - Short term: Job scheduling

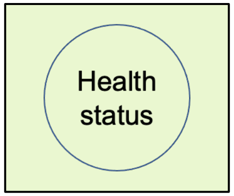
Backup Slides

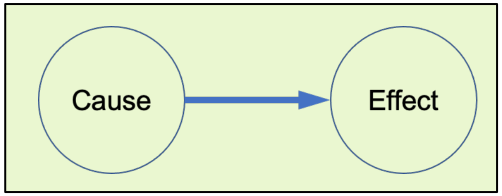
CCFs, Probability and Margin Calculations



Analysis of Textual Data

- Two classes of textual reports have been defined
  1. **Class 1:** reports that describe
     - Event (e.g., SSC malfunction)
     - Information about SSC health (e.g., excessive corrosion on pump impeller)
  2. **Class 2:** reports that describe a causal relation between two nodes





- **NLP analysis pipeline**
  - **Syntactic analysis**
    - Sentence segmentation and word tokenization
    - Part of speech (POS) tagging
    - Named entity recognition (NER)
  - **Semantic analysis (Information extraction)**
    1. Identification of specific nouns, verbs and adjectives
    2. Identify the sentence logic structure
    3. Identify OPM elements (form or function)
    4. Reconstruct DAG element
       - Class 1: (Comp.; OPM elem.; health)
       - Class 2: (Comp.; OPM elem.; health) → (Comp.; OPM elem.; health)

Status nouns	Status verbs	Status adjectives
Failure	Fail	Unable
Degradation	Degrade	Ineffective
Breach	Break	Anomalous
Fracture	Decline	

ok, degraded, failed or anomalous

Integration of Textual and Numeric Data