Trends and Prospective in Risk and Reliability Engineering Research

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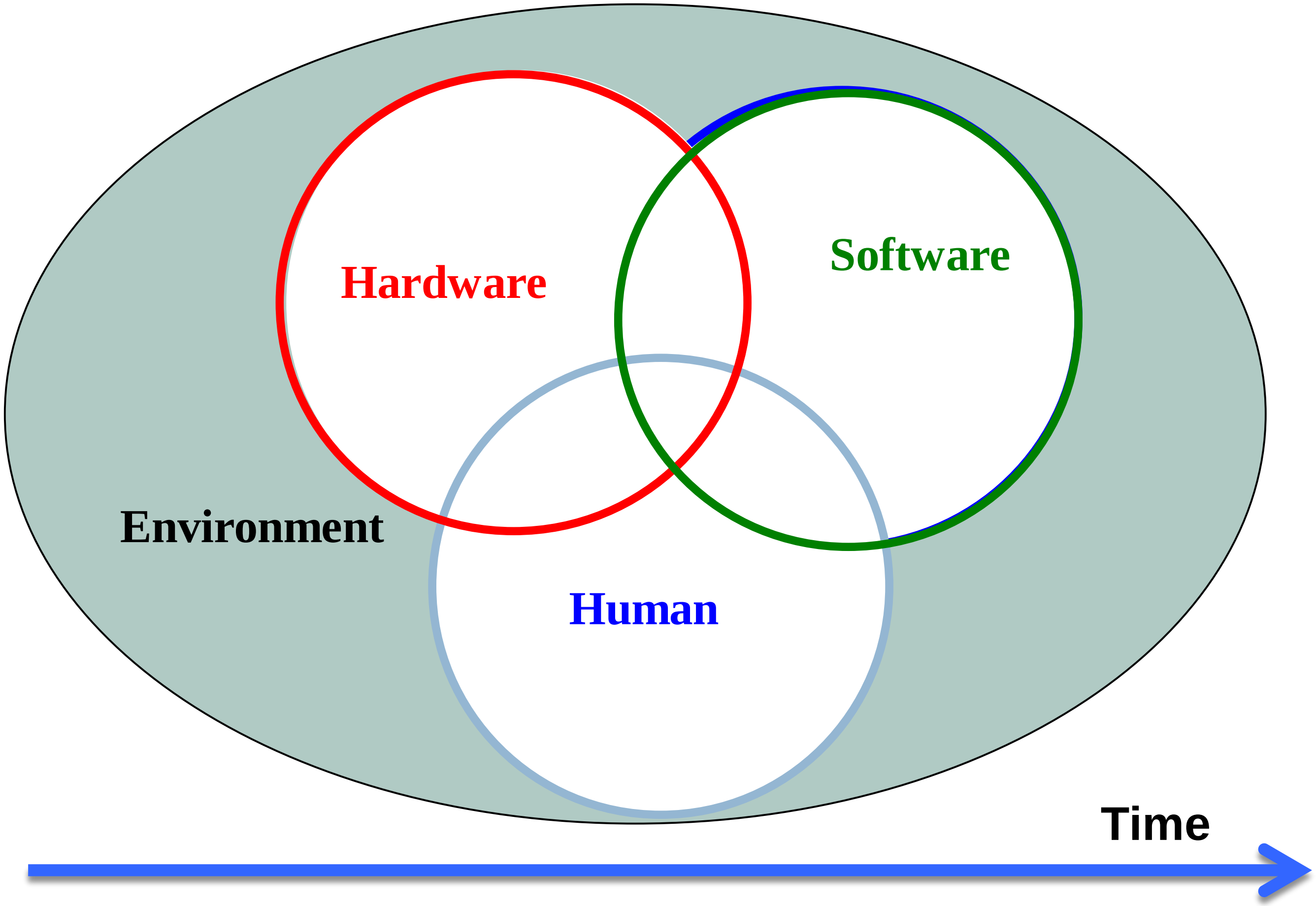
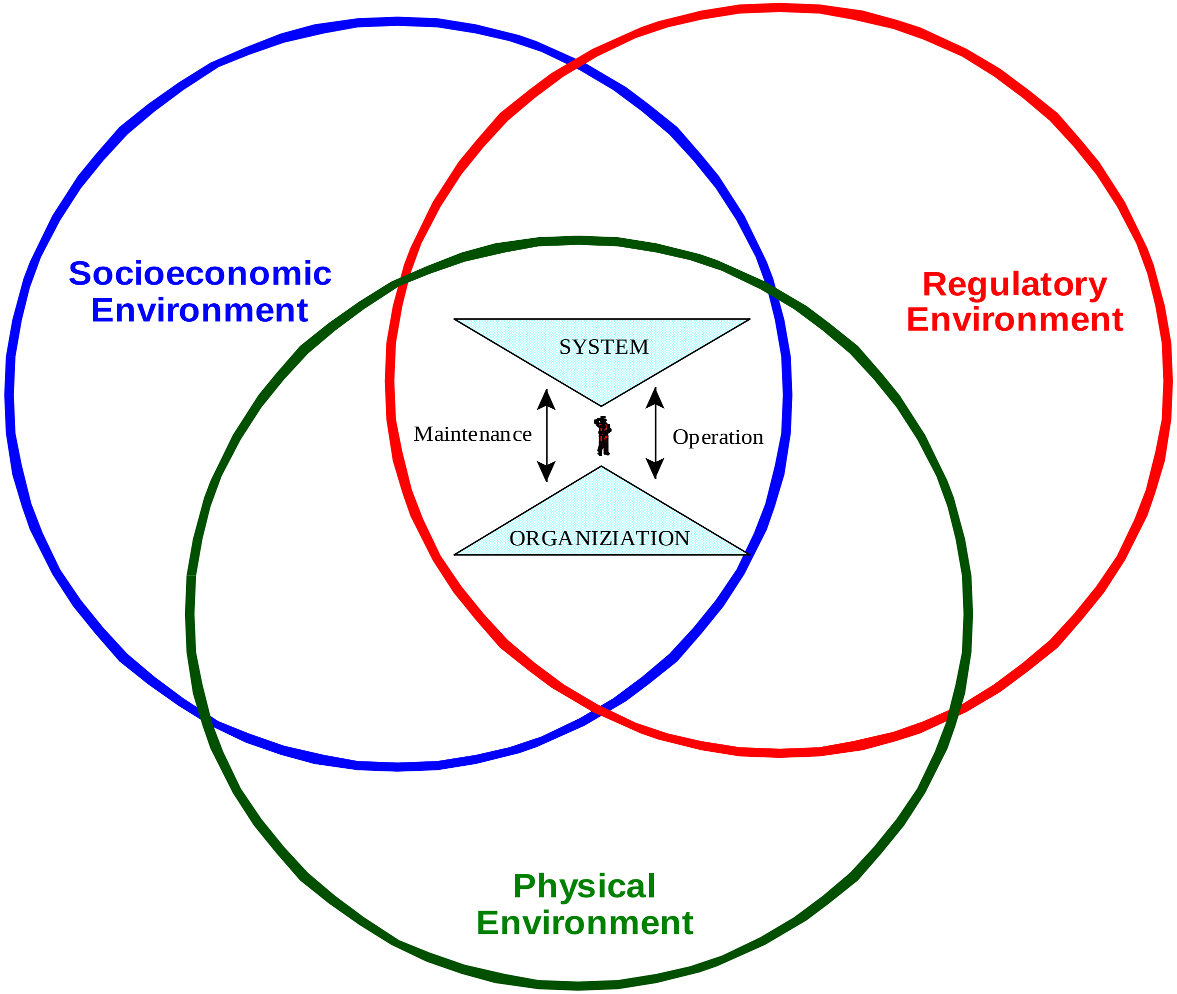
Outline

- Engineered Systems
- Failure and Complexity
- Failure and Damages
- Frontiers in:
  - Reliability Engineering
  - Risk Analysis
  - Prognosis and Health Management (PHM)
  - Resilience

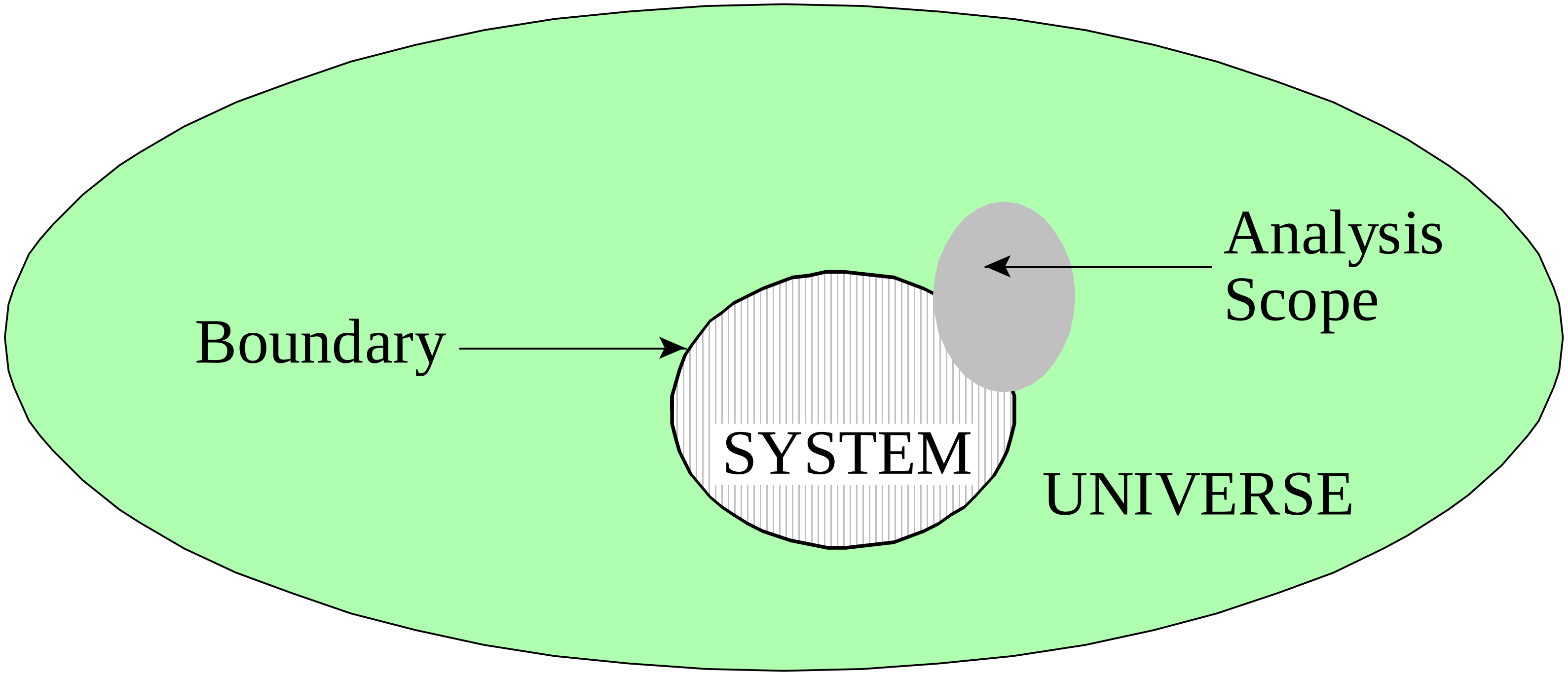
Engineered Systems



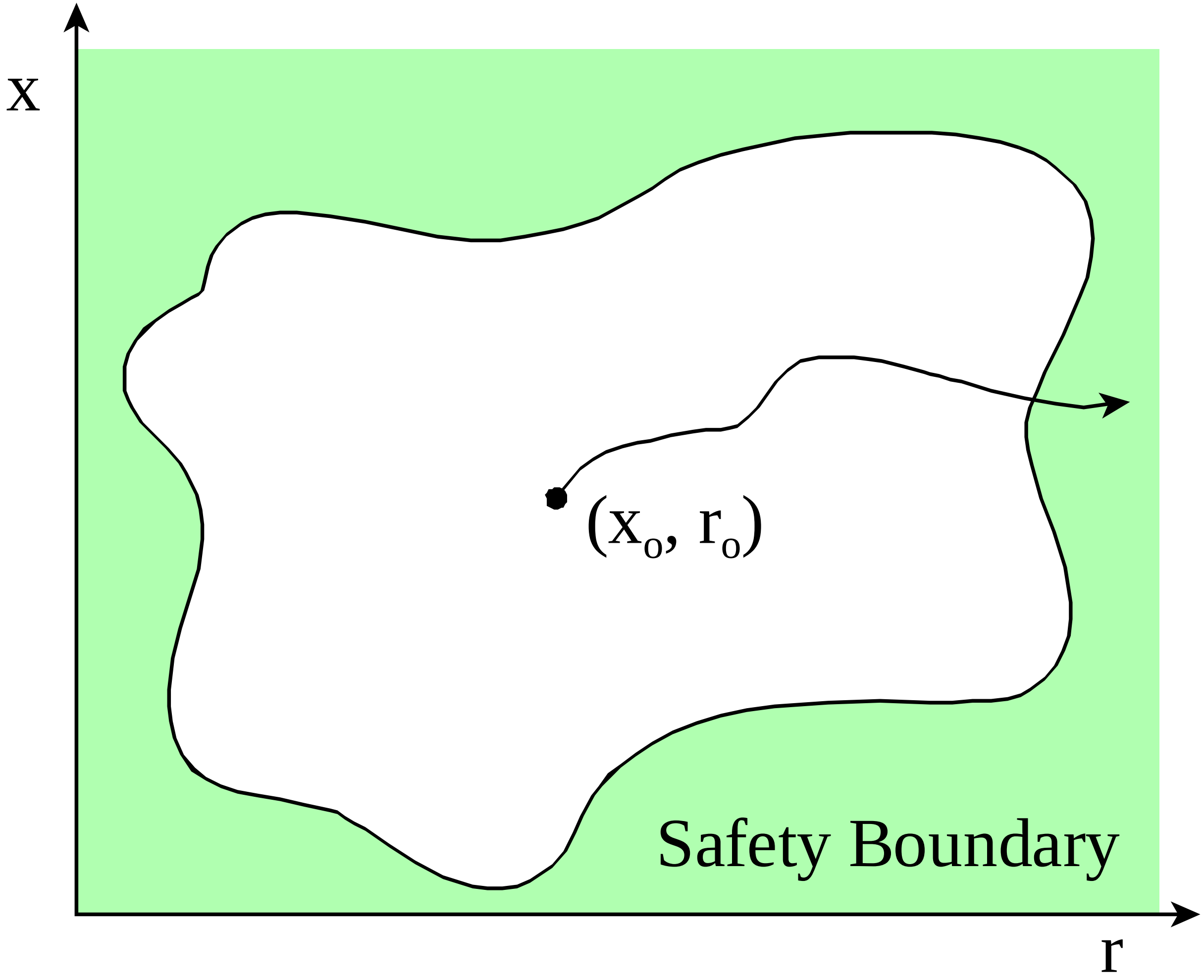
Engineered Systems; Closer Look



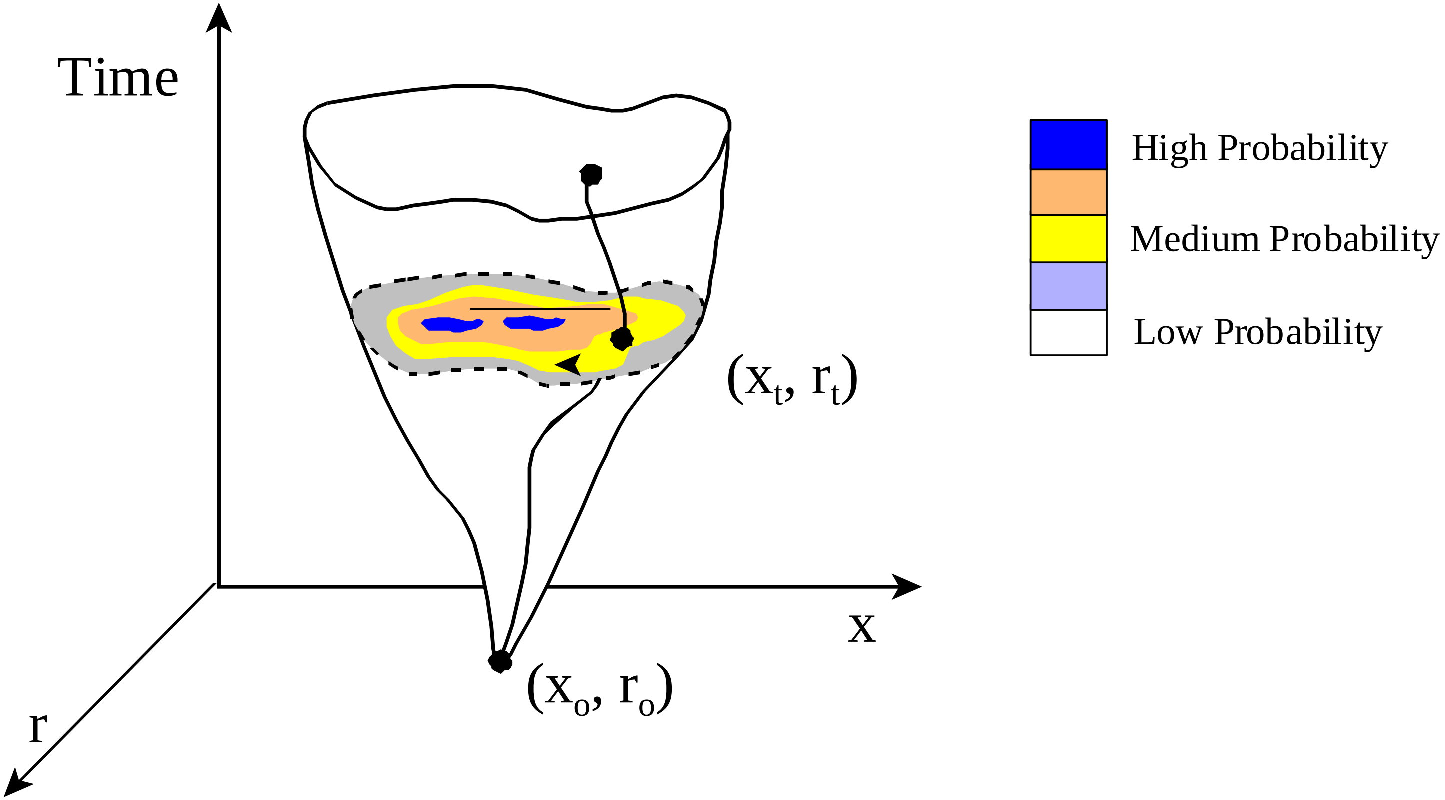
Defining the Subject of Analysis



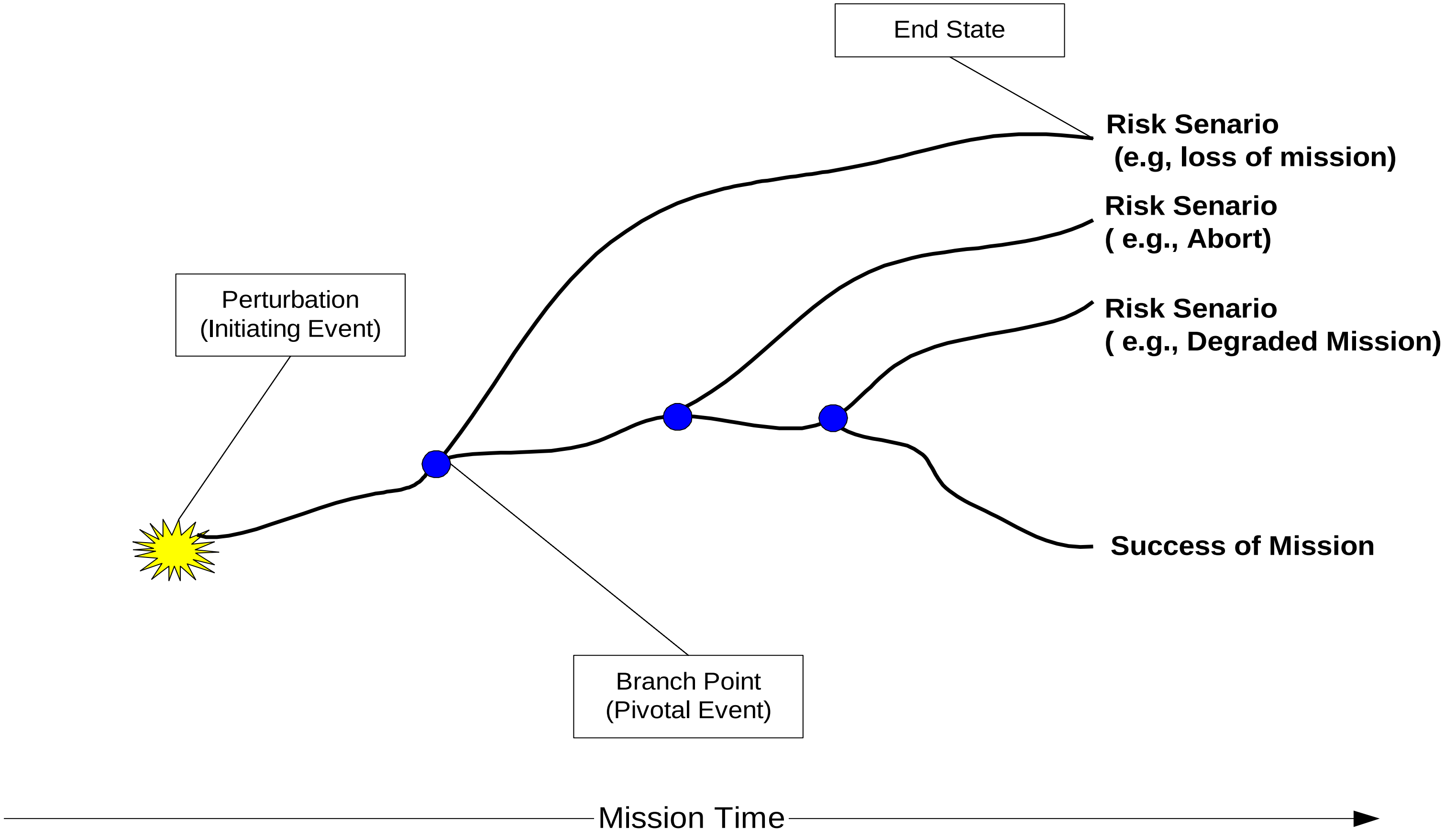
Generalized Concept of Risk Scenario



Conceptual Probabilistic Model of System Evolution



Anatomy of a Risk Scenario



Evolution of The Discipline

1. Complexity and Failures
2. Reliability Engineering
3. Life Cycle Risk Management
4. Prognostics Health Management
5. Resilience

Problem statement

Failures

Loss of revenues

Unplanned shut-down,
D.C. Cook NPP

Fatalities and contaminations

Oil rig explosion in 2010,
Gulf of Mexico

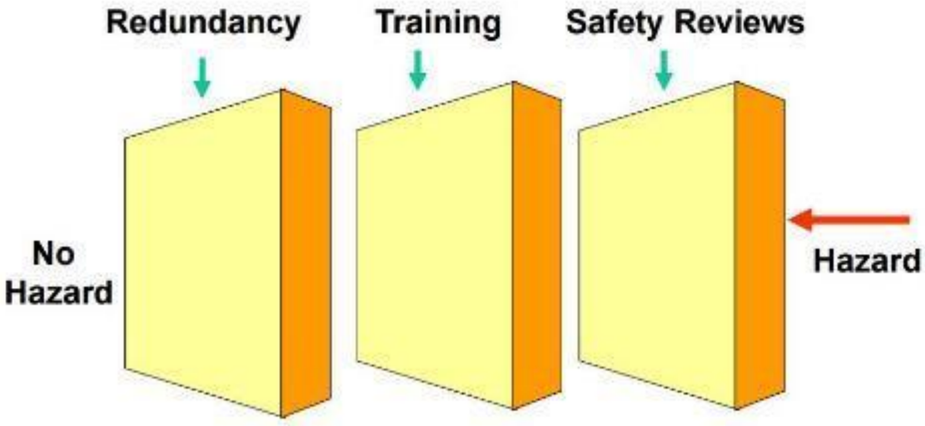
Problem statement

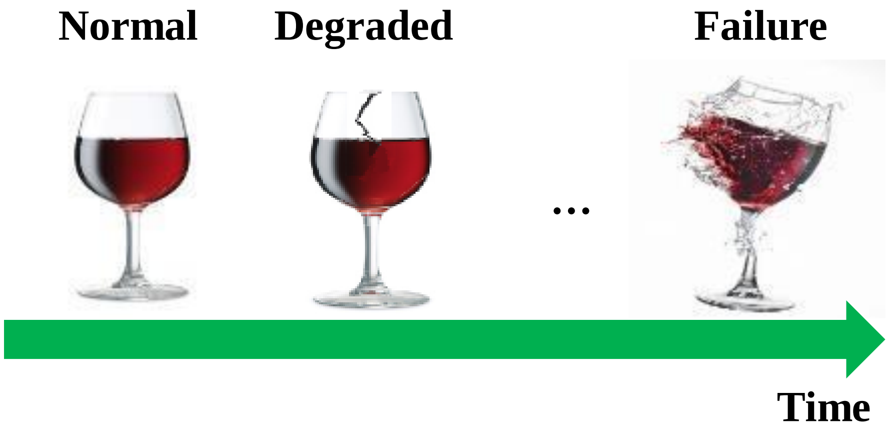
Failures

Prevented by

Design for Reliability

Maintenance



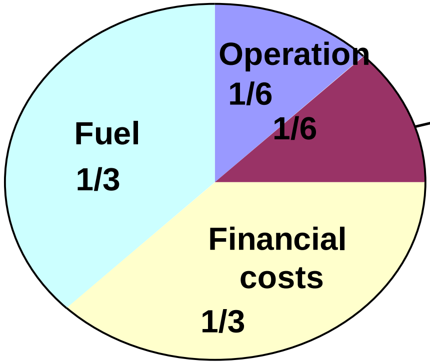


Relevance of the Problem

- According to Network **Rail (UK)**, rail infrastructure failures and defects are responsible for **14 million minutes of delay per year**

- Delays in civilian **aircraft industry** cost **22 billion US $ in 2011**

- **Nuclear industry (France)**



Maintenance
(about 1.5 billions euros/year)

Where Do Failures Originate

Mature Nuclear Power Production Failures

- People → 38%
- Procedures + Processes → 34%
- Equipment → 28%

72% of all failures

10 Year ASME Boiler Test Code Equipment*

- 23,338 Accidents → 83% human oversight or lack of knowledge
- 720 injuries → 69% human oversight or lack of knowledge
- 127 deaths → 60% human oversight or lack of knowledge

Engineers--can you really reduce problems working only on the hardware?

* Source: ASME National Board Bulletin, Summer 2002, Volume 57, Number 2, Page 10, "Ten Years Of Incident Reports Underscore Human Errors As Primary Cause Of Accidents", **http://nationalboard.org/SiteDocuments/Bulletins/SU02.pdf**

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4. Prognostics Health Management
5. Resilience Engineering

Reliability Engineering

- Determine ***why*** and ***how*** systems and processes fail
- Measure, track, and ***predict*** levels of reliability in various phases of system/process life cycle
- ***Improve*** system/process reliability by removing failure causes
- Provide ***input to decision*** makers on how to achieve the above objectives in an optimal way

Methods of Reliability Engineering

- Understanding why and how things fail
  - “science of failure”
  - Materials, Physics of Failure, Human Behavior
- Life Prediction - Statistical and Probabilistic Methods
- System Logic Modeling and Failure Path Identification
  - Fault Tree, Reliability Block Diagram,
  - Event Sequence Diagrams
- Probabilistic Physics of Failure
- System/Process Multi-scale Probabilistic Simulation

Methods for Reliability Improvement

- Design for Reliability
  - Failure Mechanism Prevention
  - Redundancy and Functional Diversity
  - Fault Tolerance
- Reliability Growth
- Preventive Maintenance/RCM
- Health Monitoring

Key Areas of Research: Reliability

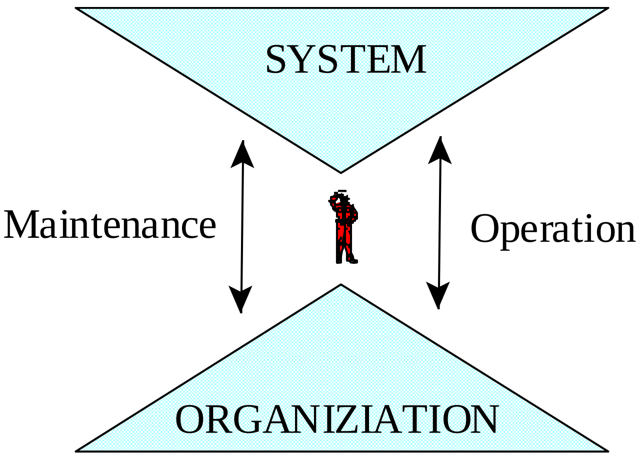
- Issues with the Traditional Field / Test Data
  - "One Size Fits All" concept! E.g., Constant Failure Rate
  - Reliability Estimates Rarely Match Reality
- Probabilistic Physics-of-Failure (PPoF)
  - More than 50-Years of History in PoF (More Recently PPoF)
  - Accelerated Reliability Testing for PPoF Model Development
  - Empirical Model for Unit-Specific Models of Reliability Assessment
  - Simulation-Based Reliability Assessment / Numerical Complexity

Key Areas of Research: Reliability

- Hybrid Reliability
  - – Combined System Analysis Techniques: BBN, DBN, FT, ET, Markov and Semi-Markov, FEM and FDM, FM, RBD.
- Sensor-Based (Precursors) / Big Data Reliability Analysis
  - – Data Fusion, Machine Learning (GRP, SVM,..)
  - – Signal Processing, Detection Probability
  - – Representative Sample-Based Approach
  - – Massively Parallel Processing (MPP)
- PHM of Cyber-Physical Complex Systems and Structures
- Science of Reliability Engineering

Soft Causal Relations

Human, Organizational, and Regulatory Environment

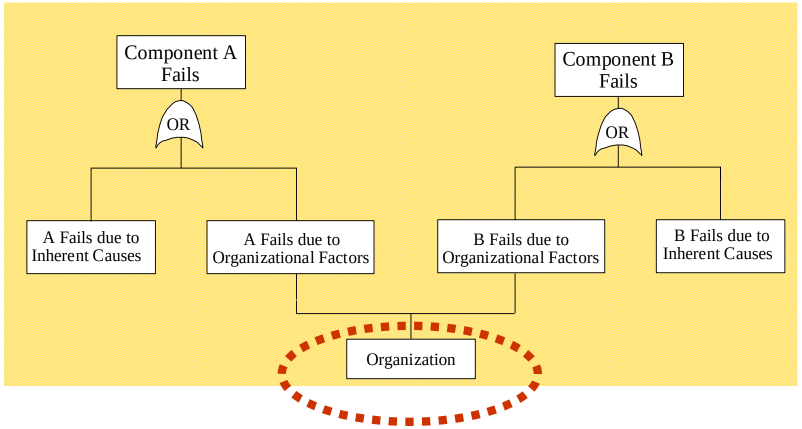


SYSTEM

Maintenance

Operation

ORGANIZIATION



Component A Fails

OR

Component B Fails

OR

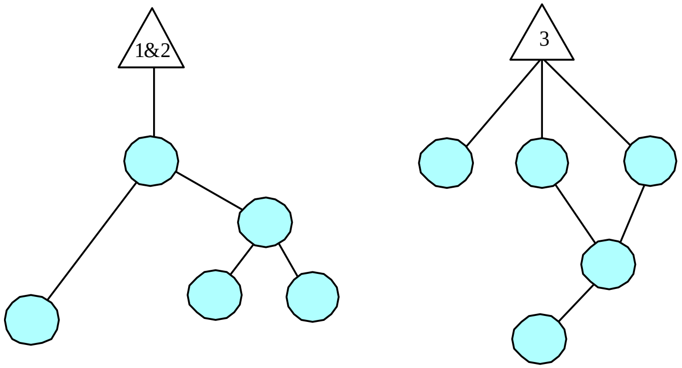
A Fails due to Inherent Causes

A Fails due to Organizational Factors

B Fails due to Organizational Factors

B Fails due to Inherent Causes

Organization



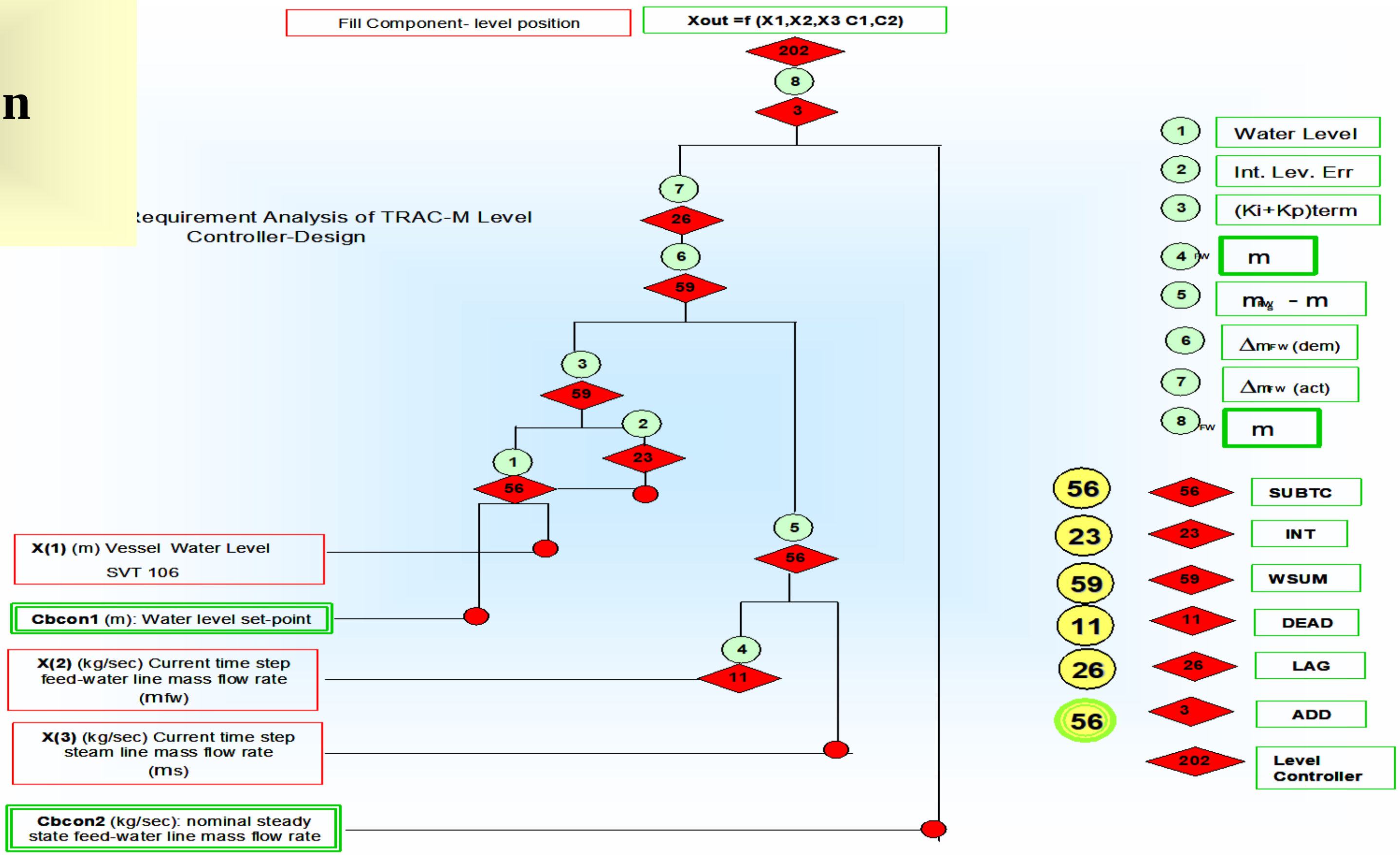
1&2

3

Influence Diagram

Software Failure Modeling

Functional Decomposition



Requirement Analysis of TRAC-M Level Controller-Design

Fill Component- level position

Xout =f (X1,X2,X3 C1,C2)

X(1) (m) Vessel Water Level SVT 106

Cbcon1 (m): Water level set-point

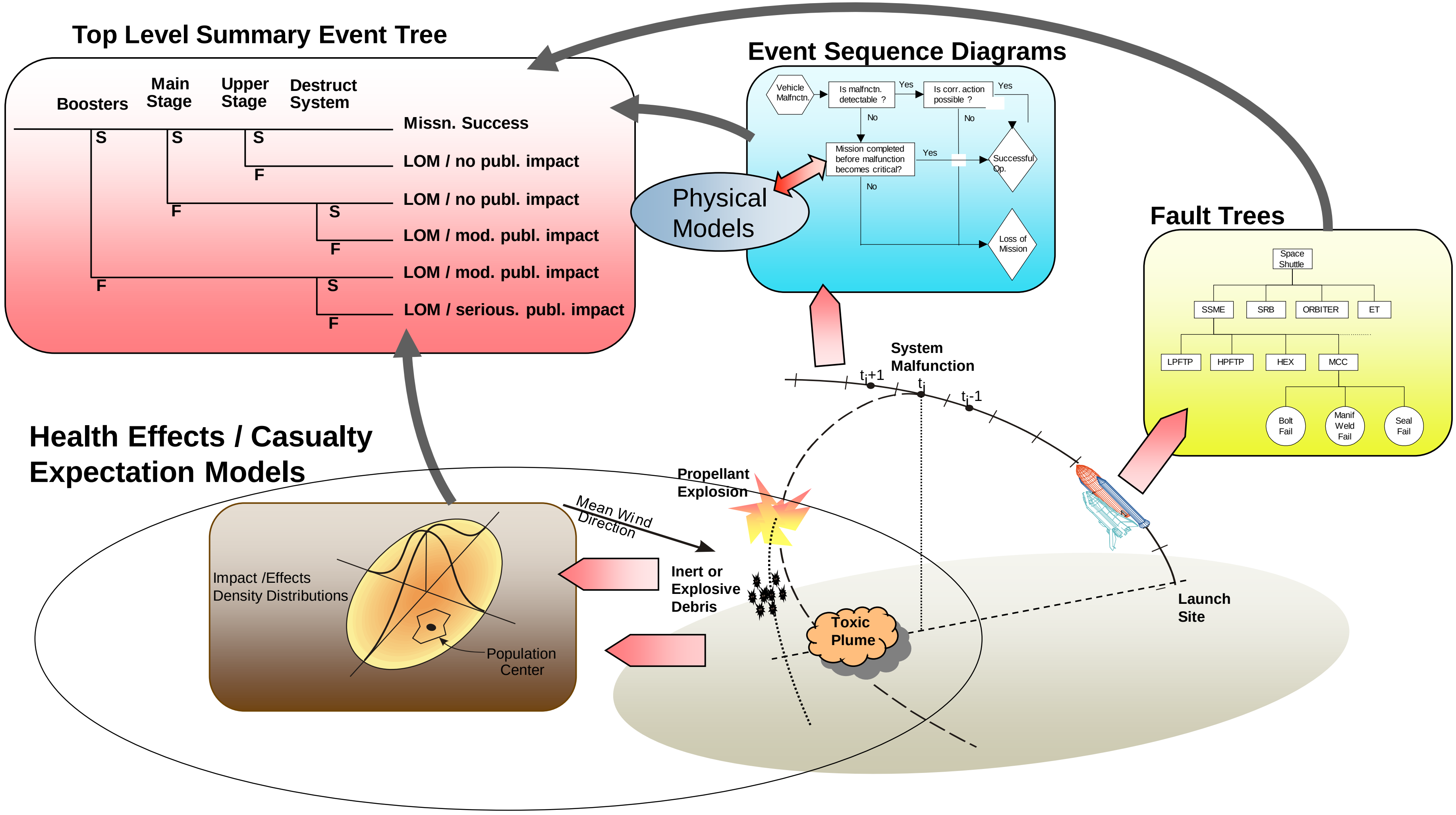
X(2) (kg/sec) Current time step feed-water line mass flow rate (mfw)

X(3) (kg/sec) Current time step steam line mass flow rate (ms)

Cbcon2 (kg/sec): nominal steady state feed-water line mass flow rate

1	Water Level
2	Int. Lev. Err
3	(Ki+Kp)term
4	m_{FW}
5	$m_{FW_S} - m$
6	Δm_{FW} (dem)
7	Δm_{FW} (act)
8	m_{FW}
56	**SUBTC**
23	**INT**
59	**WSUM**
11	**DEAD**
26	**LAG**
3	**ADD**
202	**Level Controller**

Phenomenological and Logic Based Models



Top Level Summary Event Tree

Event Sequence Diagrams

Fault Trees

Health Effects / Casualty Expectation Models

Evolution of The Thinking

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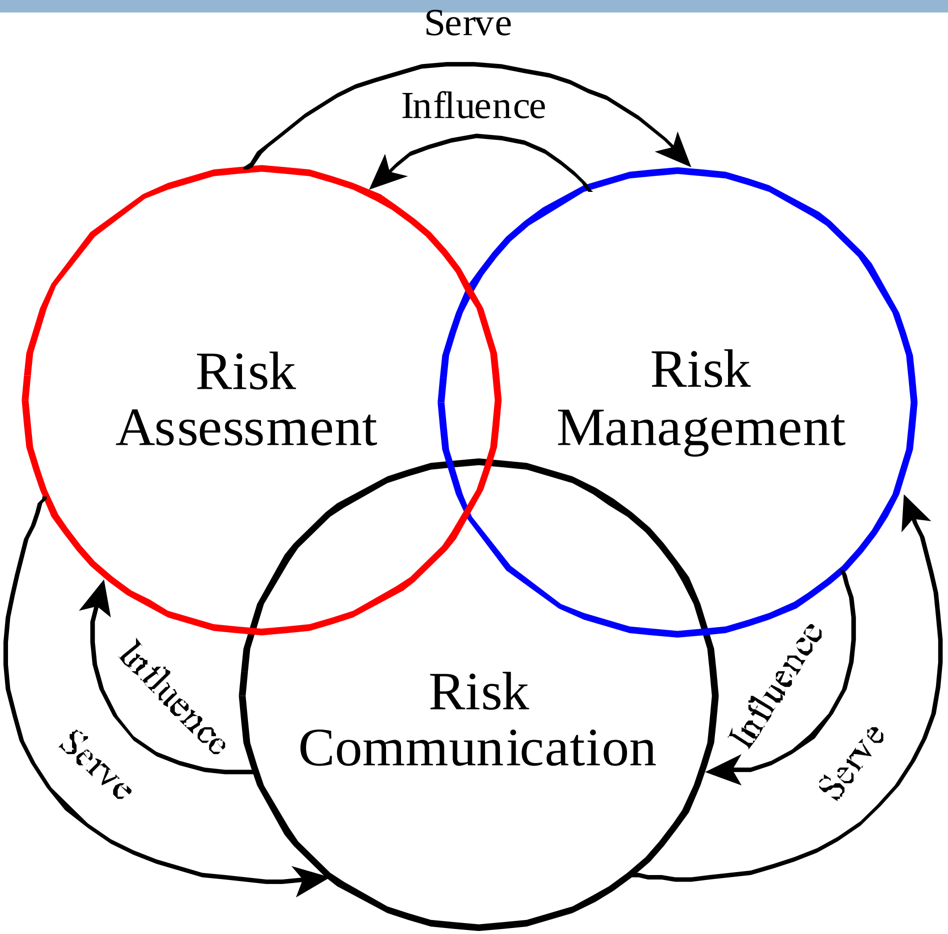
Risk Analysis

- Determine potential ***undesirable consequences*** associated with use of systems and processes
- Identify ***scenarios*** **by which** such consequences could materialize
- Estimate the ***likelihood*** (e.g., probability) of the scenarios
- Provide ***input to decision*** makers on optimal strategies to reduce the levels of risk

ELEMENTS OF RISK ANALYSIS



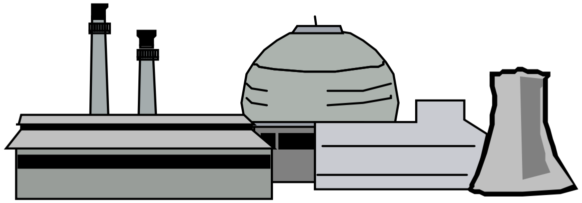
Decision maker whether risk manager or communicator must be part of risk assessment

Applied to System Life Cycle

- Design
- Development
- Installation
- Operation
- Decommissioning

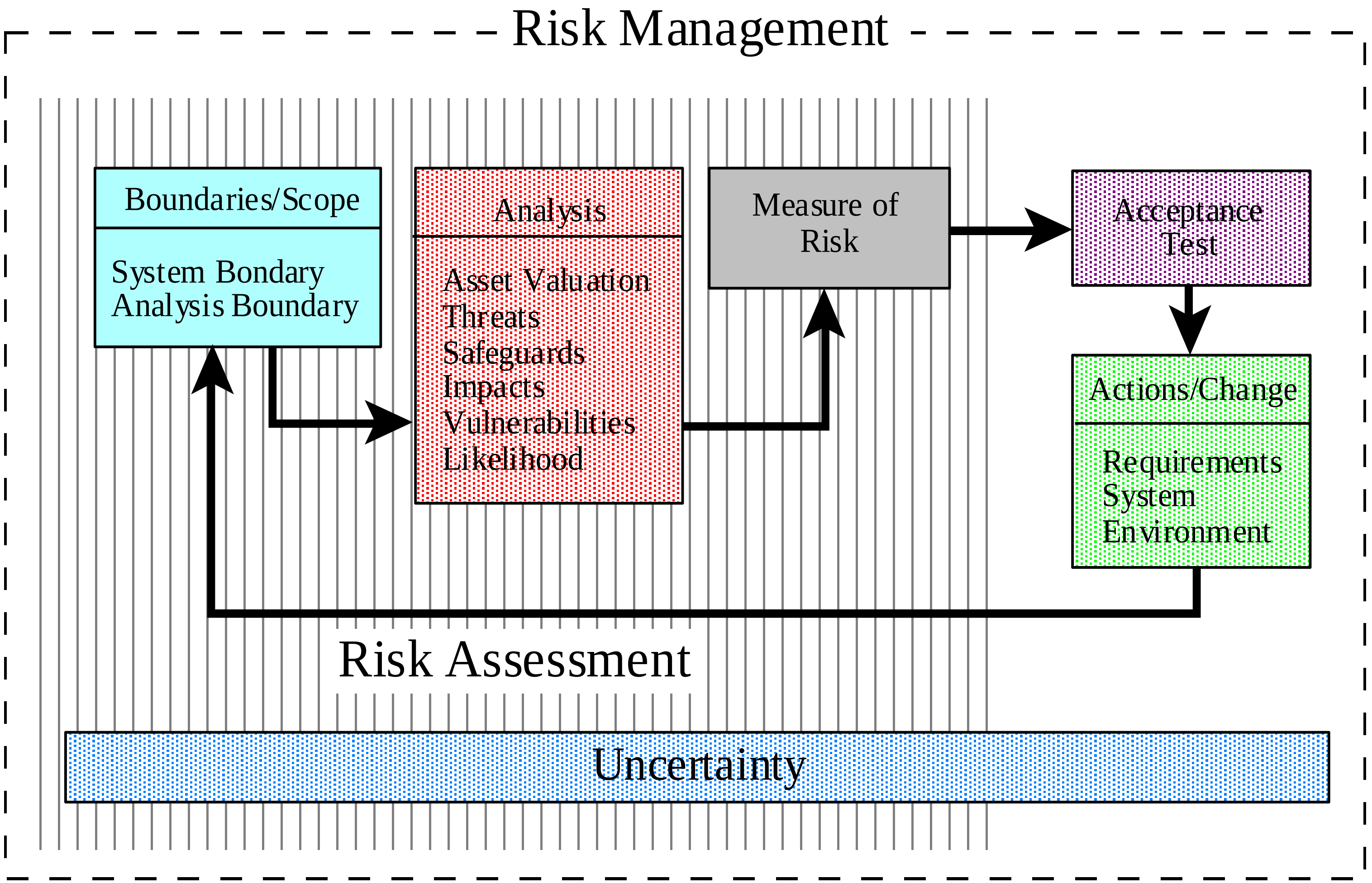
Probabilistic Risk Assessment in the Nuclear Power Industry

- 1975, Reactor Safety Study, WAHS-1400
  - Public health risk due to potential accidents in commercial nuclear power plants
  - First comprehensive, large scale probabilistic risk assessment (PRA) of a complex system
  - Established the core techniques of engineering systems PRA



- 1980-1988: Numerous full scope PRAs of commercial nuclear power plants performed by the industry
- 1994-2000 PRA-based IPEs of all NPPs
- 1998: Risk-informed regulatory approach embraced by NRC
- Long Term Waste Disposal (e.g., Total System Performance Assessment for Yucca Mountain Site, DOE)

NIST IT Security Risk Management Framework



Risk Management

Boundaries/Scope

System Bondary
Analysis Boundary

Analysis

Asset Valuation
Threats
Safeguards
Impacts
Vulnerabilities
Likelihood

Measure of Risk

Acceptance Test

Actions/Change

Requirements
System
Environment

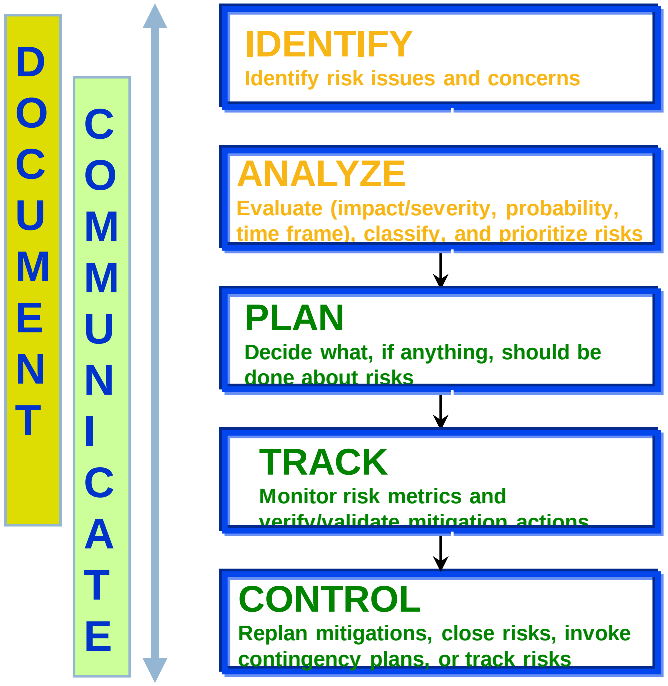
Risk Assessment

Uncertainty

NASA Risk Management Perspective

NASA RM Process Terms

(NPG8705.x, Dec. 2000)



DOCUMENT

COMMUNICATE

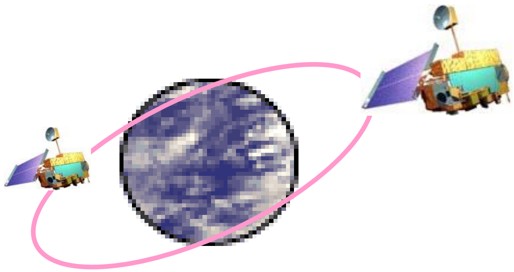
IDENTIFY
Identify risk issues and concerns

ANALYZE
Evaluate (impact/severity, probability, time frame), classify, and prioritize risks

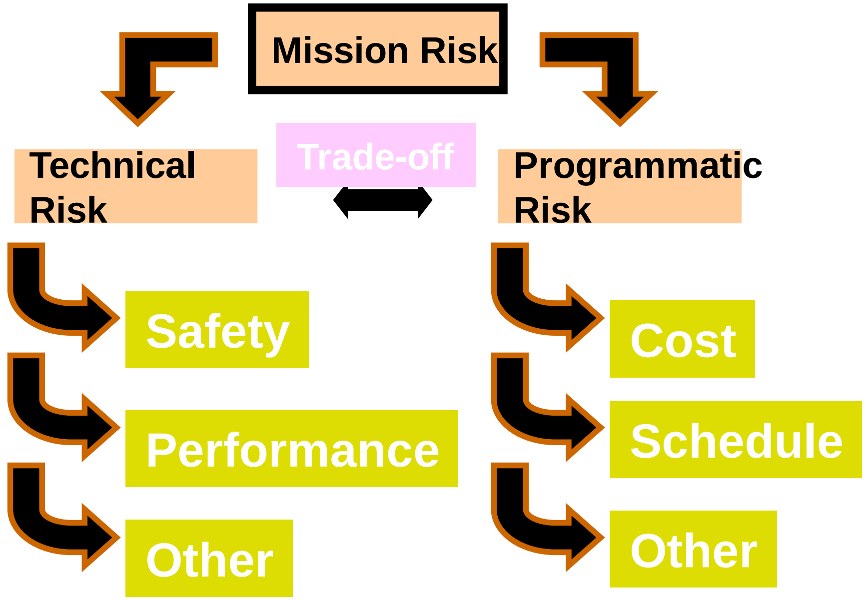
PLAN
Decide what, if anything, should be done about risks

TRACK
Monitor risk metrics and verify/validate mitigation actions

CONTROL
Replan mitigations, close risks, invoke contingency plans, or track risks



NASA Risk Element Terms



Mission Risk

Technical Risk

Trade-off

Programmatic Risk

- Safety
- Performance
- Other

- Cost
- Schedule
- Other

Key Areas of Research: Risk Frontiers

- Infrastructure Safety-Security-Resilience (SSR)
  - – Electronic Information Flow Embedded in Nearly Every Aspect of Modern Life
  - – Integrity of Complex Systems and Networks: Cyber-Human-Software-
- Physical Systems
  - – Highly Connected Infrastructure Networks: Electricity, Gas, and Water
- Pose Major Societal Risks Through Cyberspace Attacks
  - – Risk Management and Resilience
  - – Societal Disruption, Health, Safety and Resilience Goals

Key Areas of Research: Risk Frontiers-Cont.

- Life-Cycle Risks of Advanced Energy Systems

– Renewable Systems (Building, Environmental, Internal and External)

– Nuclear Energy (Fission and Fusion)

– Climate Change Risks of Disruptions in Sustained Energy Supply

- Health System Risks
- Simulation-Based Dynamic Probabilistic Risk Assessment

– High Power Computing Leading to Less Inductive Risk Models

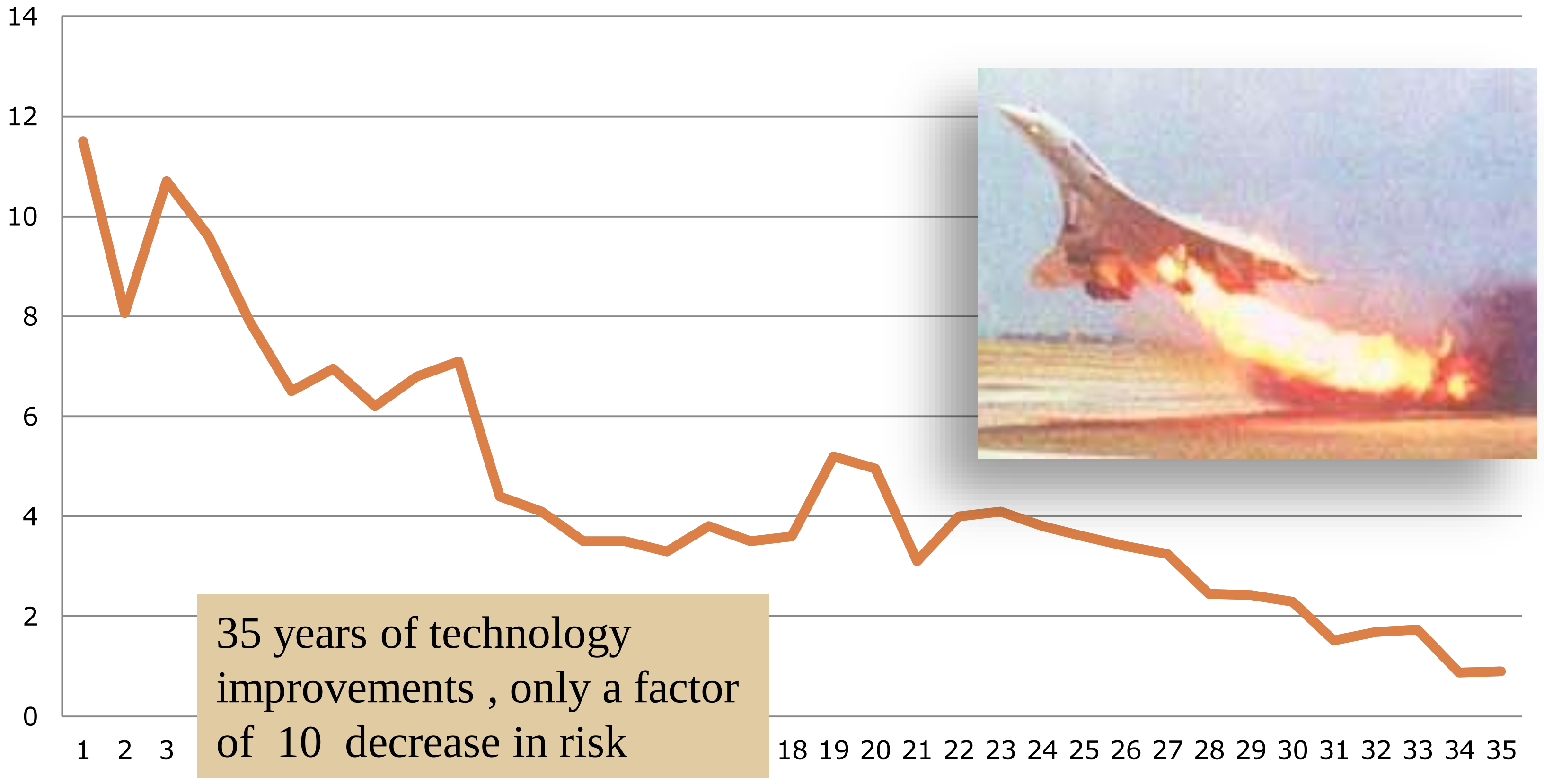
– More Deductive Computer-Assisted Risk Scenario Generation

Understanding the Limitations

Aviation Accident Rates

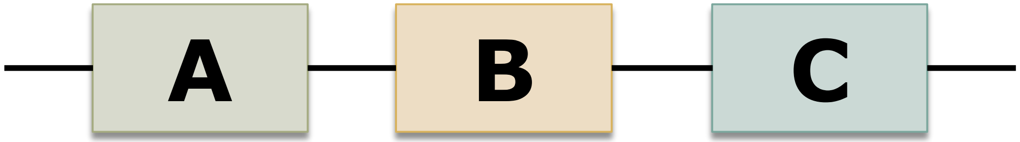
1970-2005

Number of fatal accidents/ million departures

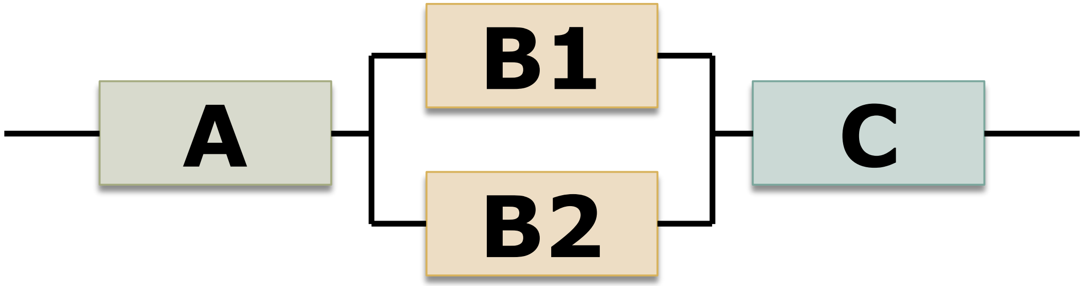


35 years of technology improvements , only a factor of 10 decrease in risk

Calculated vs. Real: the case of CCF



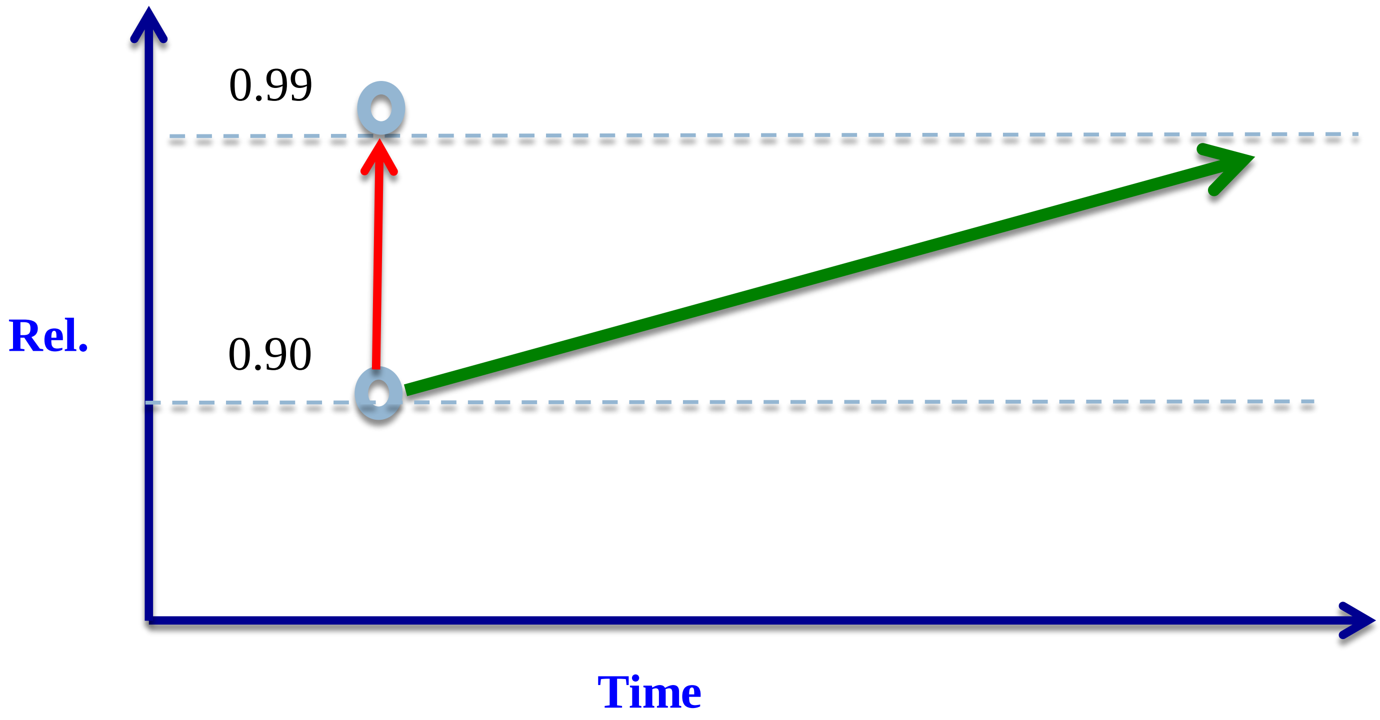
$$Q_S = Q_A + Q_B + Q_C$$



$$Q_S = Q_A + (Q_B)^2 + Q_C$$

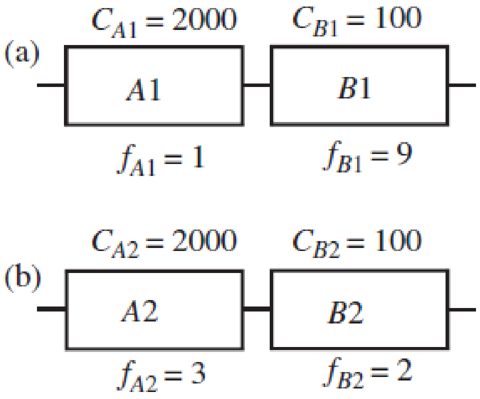
$$Q_S = Q_A + [(1-\beta)(Q_B)]^2 + \beta\, Q_B + Q_C$$

Numbers Move Faster Than Reality



RBD vs. DFR; Non-Repairable-Reliability Metrics

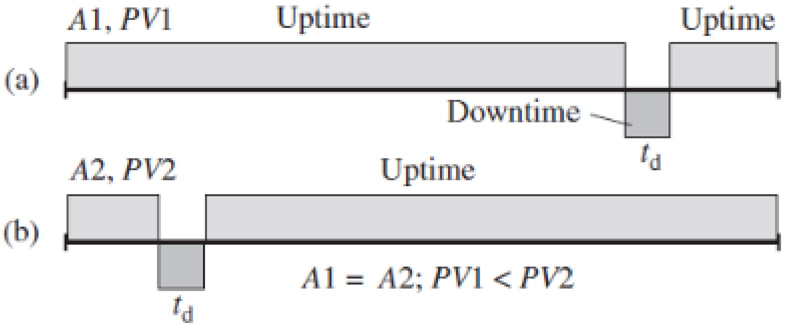
- Selection of a System Solely Based on its Reliability Can Be Miss-Leading,
  - Even If All Components In The System Are Characterized By Constant Failure Rates
  - Are Arranged In Series.



$$\overline{L}_1 = f_{A1}C_{A1} + f_{B1}C_{B1} = 1 \times 2000 + 9 \times 100 = 2900$$

$$\overline{L}_2 = f_{A2}C_{A2} + f_{B2}C_{B2} = 3 \times 2000 + 2 \times 100 = 6200$$

RBD and DFR; Differences-Availability



$$PV = \frac{1}{(1+r)^k}$$

$r = Interest\ rate$

$k = Operation\ Duration\ in\ Years$

discount rate $r = 7.5\%$, $k1 = 25$ and $k2 = 2$, yields

$$\frac{PV_2}{PV_1} = \frac{(1+r)^{k1}}{(1+r)^{k2}} \approx 5.28$$

- ➢ OUR Proposal is Risk-Based Design for Reliability
- ➢ Corporate better understands the values on the reliability improvement

Challenges

- Believability of results
  - Model vs. reality
  - Quality of analysis (Numbers that do not correlate with reality)
- Overly simplistic methods for complex problems
  - and the opposite…
- Legacy methods that have outlived their usefulness
  - FMEA – unraveling complexity
  - Weibull – answer to all questions
- Statistical angle of reliability

Evolution of The Thinking

1. Failures and Complexity
2. Reliability Engineering
3. Life Cycle Risk Management
4. Prognostics Health Management
5. Resilience Engineering

Prognostics and Health Monitoring Technologies

- Enablers
  - Rapid advancements in
    - Sensor technologies
    - Information processing capabilities
    - Data Fusion & Inference methods
    - PHM of Cyber-Physical Complex Systems and Structures

- Challenges include
  - Science Based or Empirical Degradation Models for Various Failure Mechanisms
    - Failure Mechanisms Interactions
  - System-Level PHM
  - X-ware Complexity Issues

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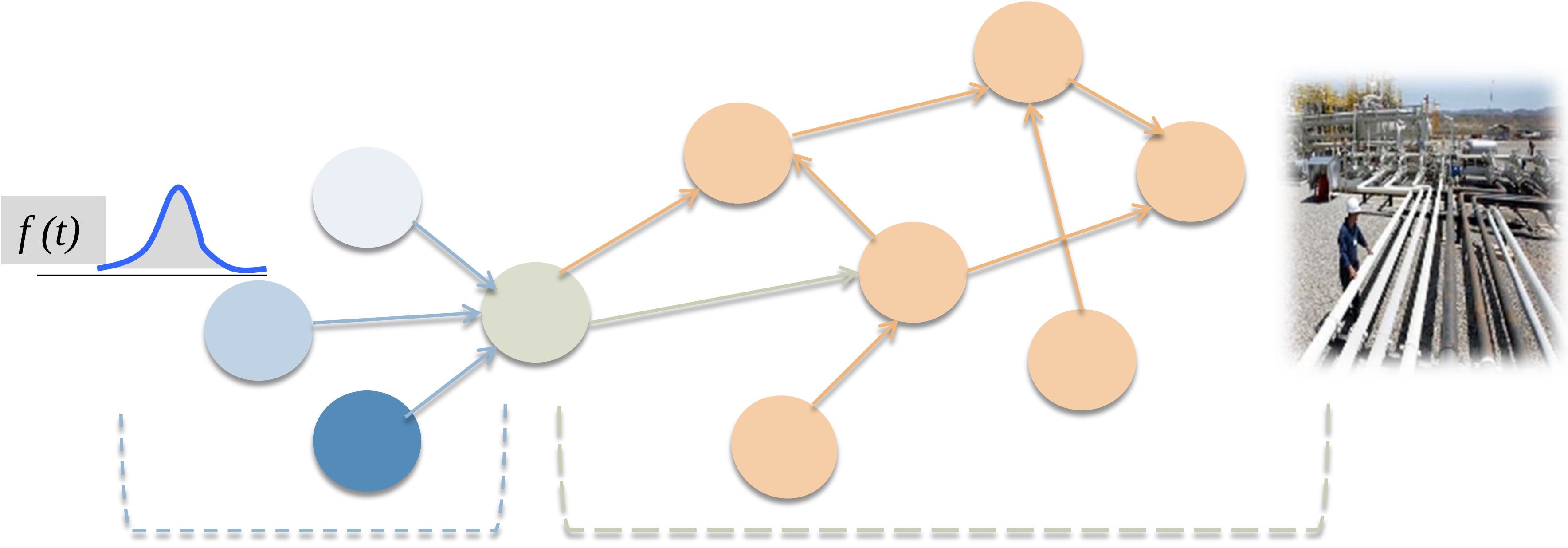
Bayesian Network in SHM

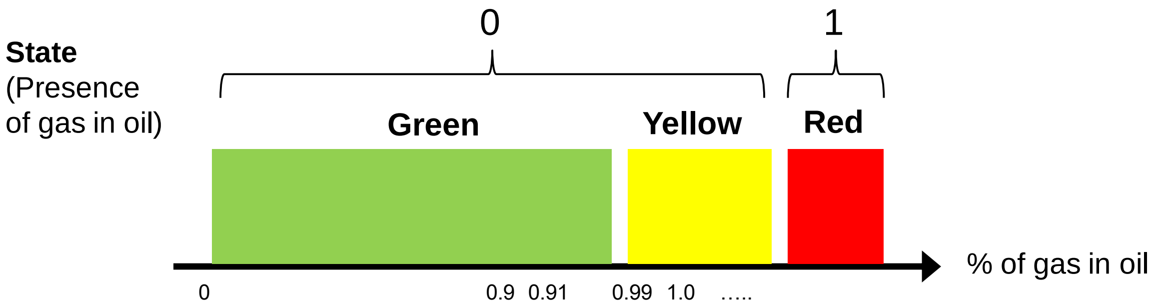
- □ Compact and seamless integration of the ***data model*** and ***System model***

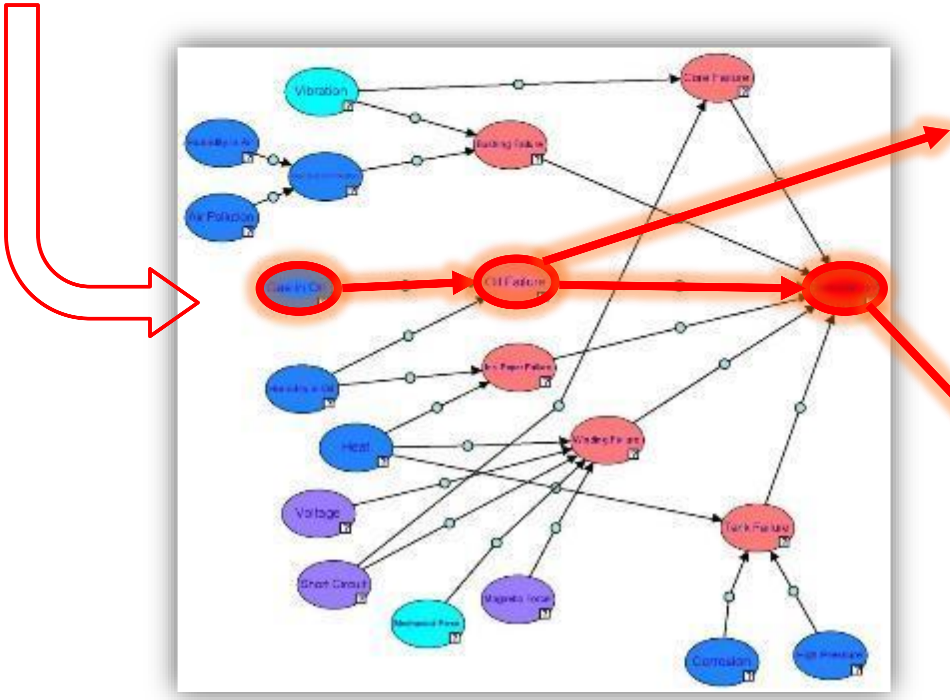


Data Model

System Model

BBN Based Online Health Monitoring



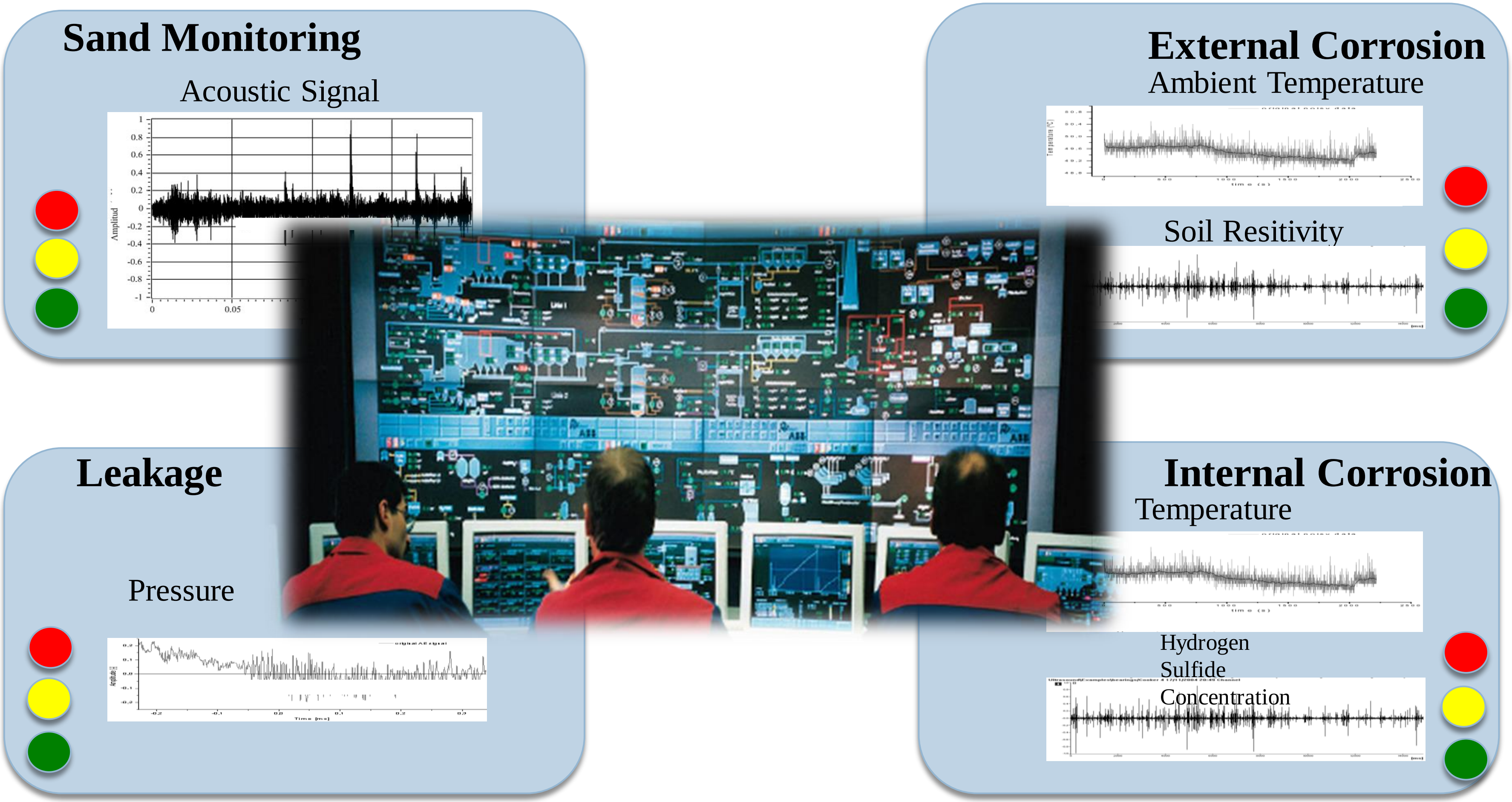


Presence of Gas in Oil	Prob. of Oil Failure
1	%5.08
0	%0.07

Presence of Gas in Oil	Prob. of System Failure
1	%3.16
0	%2.66

Dynamic Bayesian Network

Dynamic Health / Integrity Management System



Sand Monitoring

Acoustic Signal

🔴
🟡
🟢

External Corrosion

Ambient Temperature

Soil Resitivity

🔴
🟡
🟢

Leakage

Pressure

🔴
🟡
🟢

Internal Corrosion

Temperature

Hydrogen Sulfide Concentration

🔴
🟡
🟢

Fatigue Damage Characterization Based of Thermodynamic Entropy

- Diminishing the strength until failure [J. Lemaitre and J. Dufailly, 1987]
- Engineering context:

External work (mechanical, thermal, electrical, chemical or their combinations)

- gradual alteration of matter
- dissipation of energy.

- The definition of damage varies at different geometric scales:

Fatigue Mechanism

Nanoscale:	the configuration of the atomic bonds
Microscale:	the accumulation of the slip bands
Mesoscale:	the growth and coalescence of microcracks
Macroscale:	the growth of macrocracks

- The definition of damage is relative to a reference state:

Fatigue Mechanism

reduction in the Young's modulus

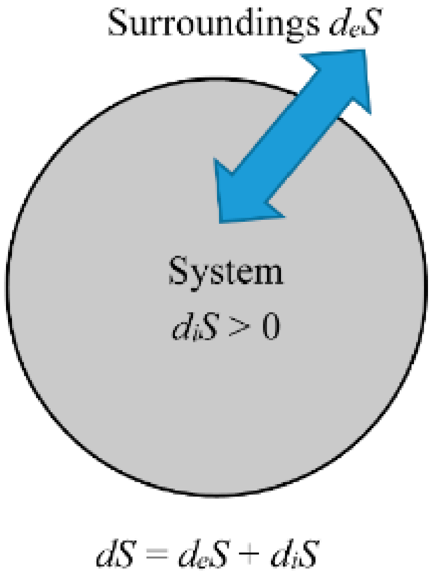
load-carrying capacity

crack length …

Thermodynamic Damage

- Thermodynamically, all damage mechanisms share a common feature, which is dissipation of energy.

Damage ≡ Dissipation (entropy generation)



d_eS: entropy exchange (flow) with the surroundings

d_iS: the entropy generation inside the system

$$\frac{d_i S}{dt} = \dot{\gamma} = X_i J_i, \quad i = 1, 2, \ldots, n$$

X_i: Generalized thermodynamic forces
J_i: Thermodynamic fluxes
i: the number of different processes acting on the system.

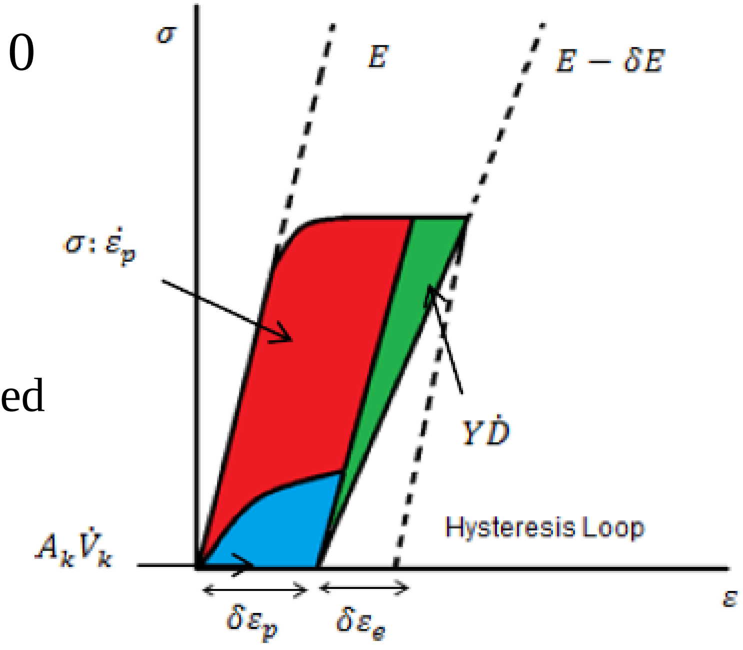
Thermodynamic Damage

- **Advantages**
  - Commonly Mechanical Element of entropy generation dominate the total entropy generation.
  - The entropy generation can be explicitly expressed in terms of physically measureable quantities.
  - Thermodynamics allows for quantifying every dissipative process in the system that gives rise to the entropy generation, irrespective of the underlying degradation phenomena.
  - For reliability study, entropy approach includes all degrading mechanisms when multiple competing and common cause failure mechanisms are involved,
    - a damage parameter for diagnosis and prognostics is more favorable in comparison with the PoF models

Fatigue Damage

$$\dot{\gamma} = \frac{1}{T}\left(\boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}_p - A_k \dot{V}_k - Y\dot{D} - \frac{\mathbf{q}}{T}.\nabla \mathbf{T}\right) \geq 0$$

σ	the stress
εp	the plastic strain rate
T	the temperature
V_k	internal variable
A_k	the thermodynamic force associated with an internal variable
q	the heat flux
Y	the elastic energy release rate
D	the damage



- Heat Equation

$$\rho C\dot{T} - k\nabla^2 T = \dot{W}_p$$

ρ	density
C	the specific heat
k	the thermal conductivity
Wp	plastic work

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Resilience

- The resilience integrates robustness, resourcefulness and recovery for system adaptation with all undesired conditions.
  - Robustness: the ability of an system to withstand extreme weather events as well as gradual changes (e.g. sea level rise) and continue operating.
  - Resourcefulness: the ability to effectively manage operations during extreme weather events.
  - Recovery: the ability to restore operations to desired performance levels following a disruption.
  - Adaptation of an energy system to climate change refers to the process of adjustment of all components of the energy system to actual or expected climate and its effects.

Resilience-cont.

- The ultimate safeguard is to make systems resilient by design

- Resilient systems would have inherent abilities to
    - adapt to changing environment,
    - tolerate emergent failure mechanisms,
    - self-recover

Resilience Analysis

- There are several quantitative and qualitative approaches for the resilience analysis.
- The quantitative methods include probabilistic resilience analysis.
- **S:** system with *n* components,
- the probabilistic resilience $\mathrm{res}_{\mathrm{pr}}$*(***S***; β):* largest number of component failures
- such that **S** is still *up* with the probability 1 -*β,* that is

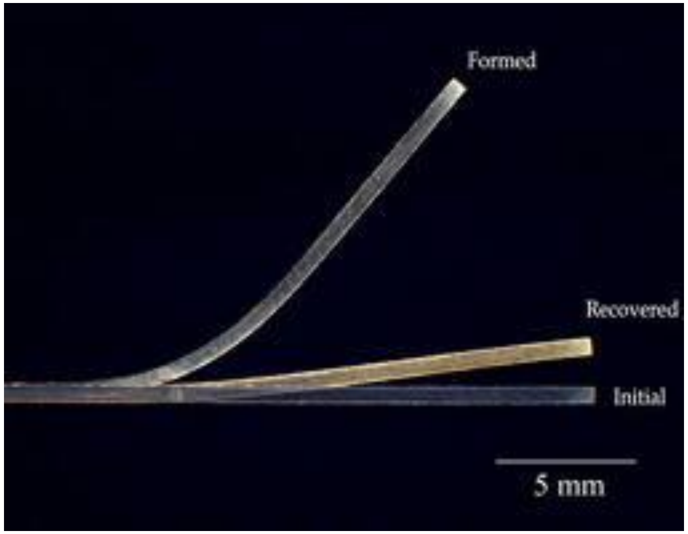
$$\mathrm{res}_{\mathrm{pr}}(\mathrm{S};\beta) = \max\{I : \sum_{i=1}^{I} P(S,i) \leq \beta\}$$

Pathway to Resilience

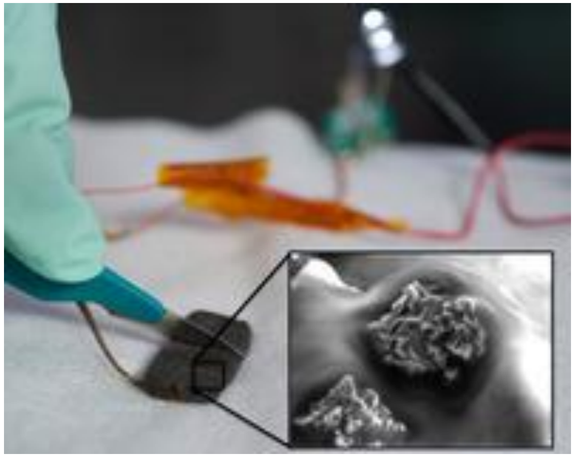
1. Materials
2. Mechanical and Electrical Function Delivery
3. Sensing, Monitoring, and Control
4. Software
5. Human (operators, maintainers, users, decision-makers)

Shape Memory Alloys (SMAs)

- Metals that "remember" their original shapes.
- Nickel-titanium alloys one of the most useful SMAs
  - Applications: military, medical, safety, and robotics
    - ✓ Surgical Tweezers
    - ✓ Orthodontic wires
    - ✓ Eyeglass frames
    - ✓ Guide for catheters



“Self-Healing Plastic”



- Human Skin:
  - Flexible
  - Sensitive to stimuli: touch & pressure,
  - Conducts electricity
  - Survives wear & Tear: self-healing
- Composite material composed of an organic polymer with embedded nickel nanostructured microparticles, which shows **mechanical and electrical self-healing** properties at ambient conditions.

* **Benjamin C-K. Tee, Chao Wang, Ranulfo Allen & Zhenan Bao** *Nature Nanotechnology* ***7, Published online 11 November 2012***

Software Functionality

- Easier to achieve
  - Functional Linkages are soft, can be rerouted or reconfigured

- Fault Tolerance is well established

- “Safe mode”

Mechanical and Electrical Functionality

- Most difficult
    - Hard functional coupling (in contrast to software)
    - Need New design paradigms
    - Solution is closely tied to materials issues

Mechanical and Electrical Functionality

- Achievable first steps at system level
  - Design to migrate to different states for different environments
    - Multiple anticipated states
    - Detect and deflects (seen in some resilient networks)
  - Function in degraded state
    - “Safe mode” for essential function in response to unanticipated events
    - “Sleep mode” while recovery is in progress
- 3-D printing of failed parts?

Thank You