UCLA B. John Garrick Institute for the Risk Sciences

- **Established in November of 2014**
- **Research**
  - More than 20 full time and adjunct faculty
  - Research Centers
    - Center for Reliability & Resilience Engineering
    - Center for Risk Research
    - SMART Health Research Center (with School of Medicine)
  - New state of the art facilities and laboratories
- **Education**
  - Online MS and Graduate Certificates (admitting Fall 2015)
  - Minor Field for On-Campus Undergraduate and Graduate Students

Evolution of The Thinking

1. Traditional Engineering
2. Reliability Engineering
3. Life Cycle Risk Management
4. PHM
5. Resilience

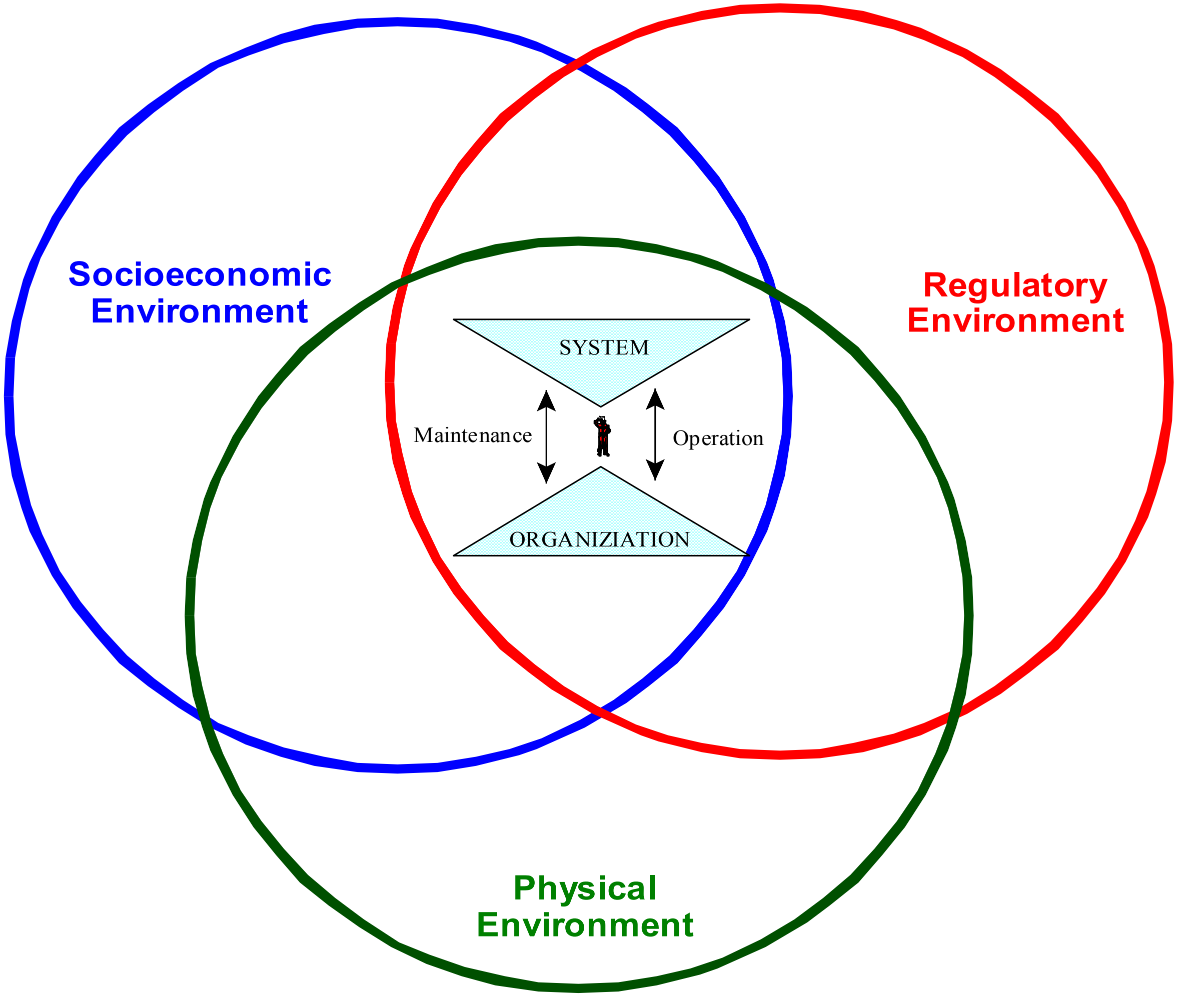
Reliability Engineering

- 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

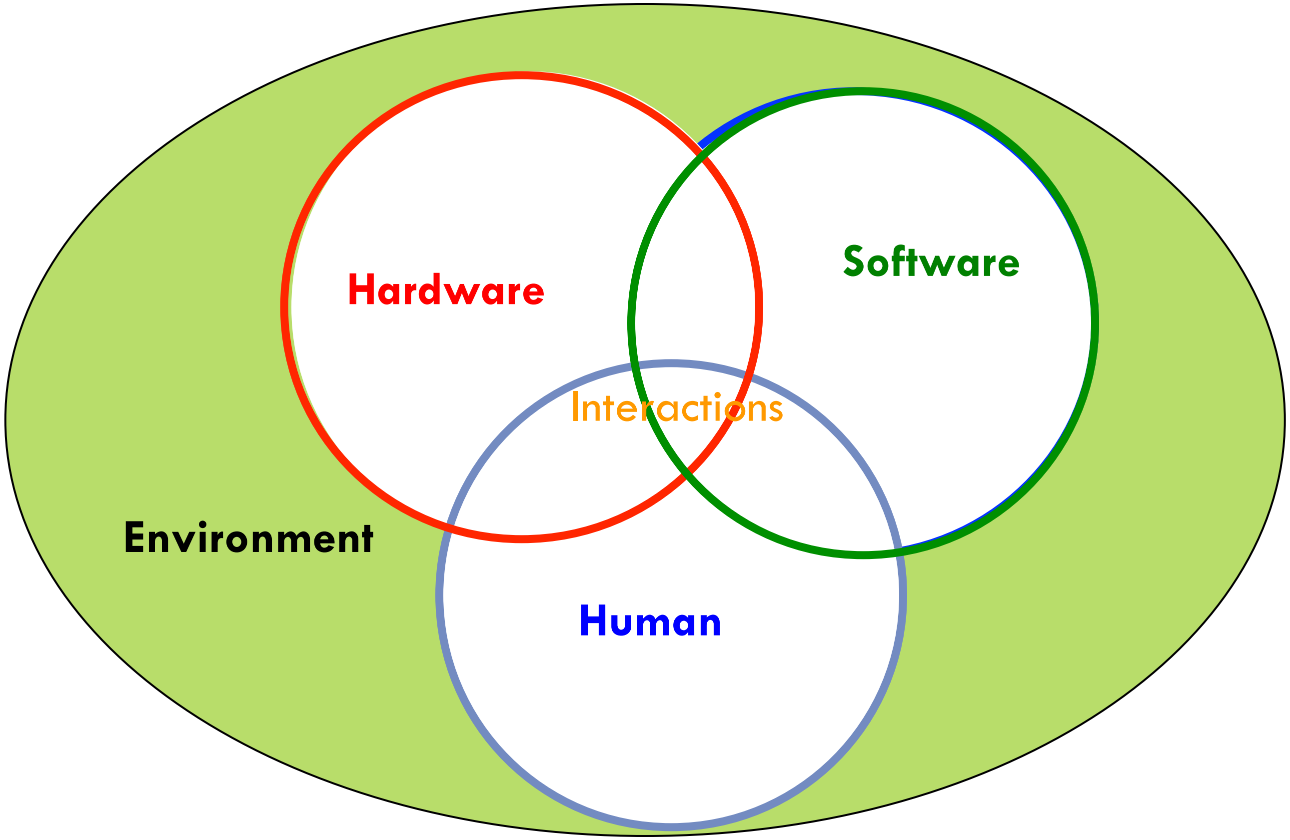
Risk Analysis

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

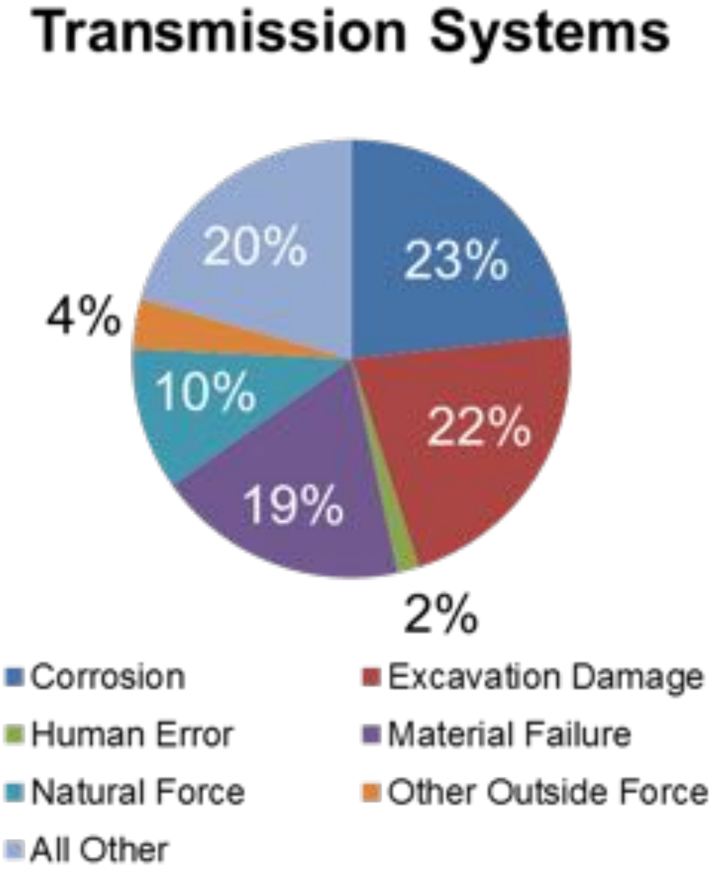
Scope

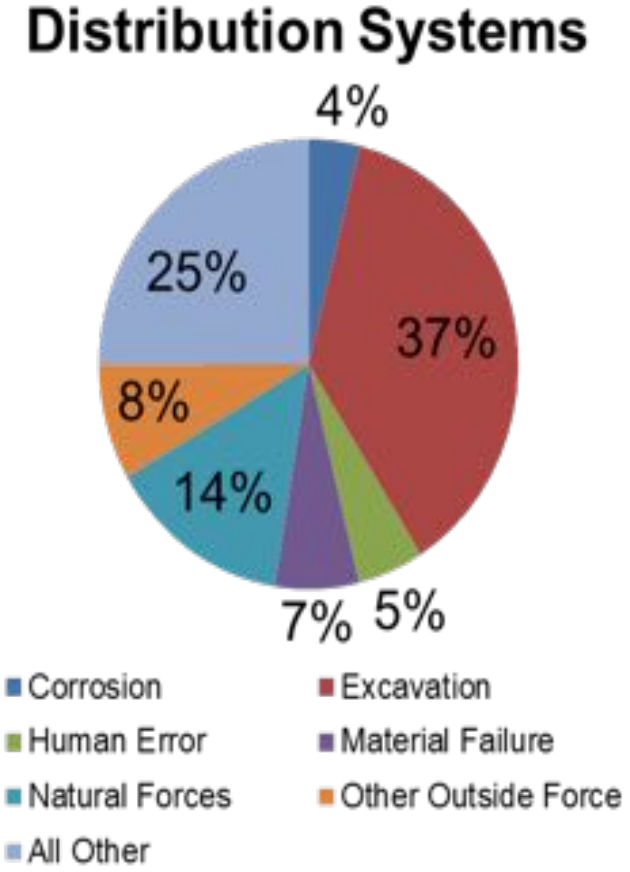

Socioeconomic Environment
Regulatory Environment
SYSTEM
Maintenance
Operation
ORGANIZIATION
Physical Environment

Dimensions



Gas Pipeline Risk Contributors*





*** Significant Incidents 1988-2008 Source: National Statistics PHMSA; Baker 2008**

Methods of Reliability Engineering

- Understanding why and how things fail
  - "science of of failure"
  - Materials, Code, Human Behavior
- Probabilistic Physics of Failure
- Life Prediction/Statistical and Probabilistic Methods
- System Logic Modeling and Failure Path Identification, e.g.,
  - Fault Tree
  - Event Sequence Diagrams
- System/Process Probabilistic Simulation

Methods for Reliability Improvement

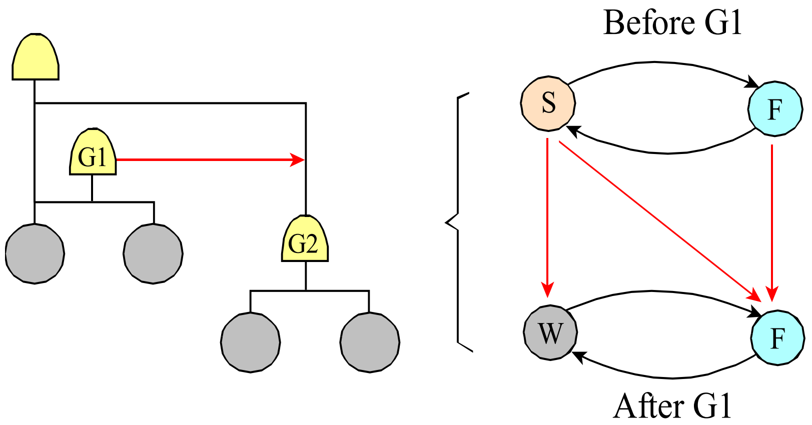
- Design for Reliability
  - Failure Mechanism Prevention
  - Redundancy and Functional Diversity
  - Fault Tolerance
- Preventive Maintenance
- Health Monitoring

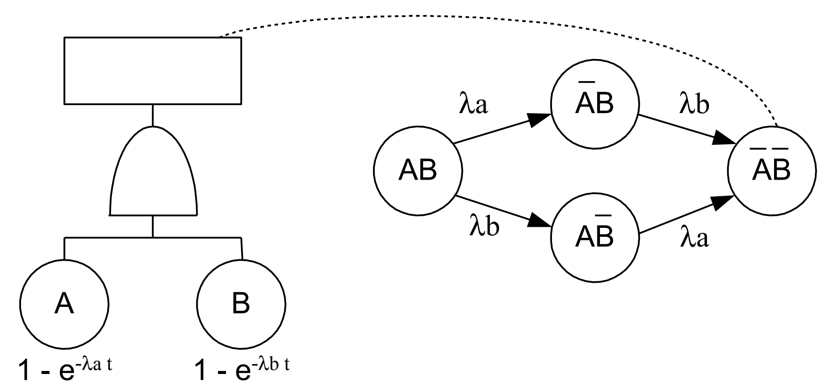
Frontiers…

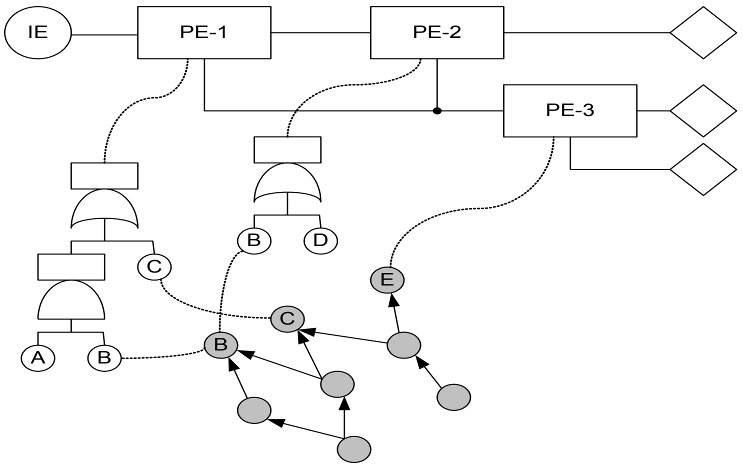
- Integrated Probabilistic Simulation (for design and operational phases)
- Probabilistic Physics of Failure
- X-Ware Systems Reliability
  - Hardware/Software/Human
  - Interface Failures
  - Soft Causal Models
- Hybrid Methods
- Advanced Inference Methods (doing more with less)
- Model-Based System Engineering w/ embedded Reliability or Risk Models
- Model-Based System Health Management
- HAL-9000 
- Resilience Engineering

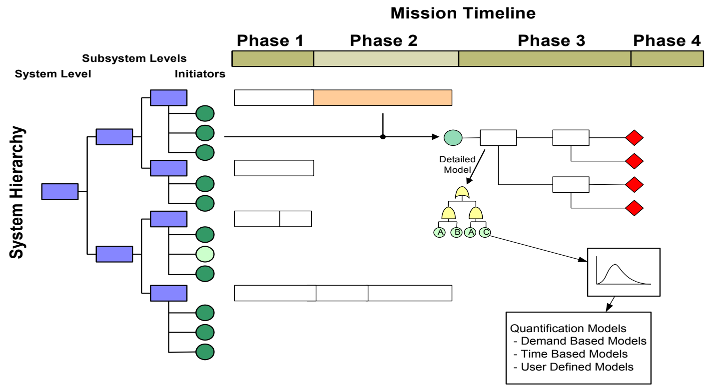
Highlights of a Few Advanced Methods

Hybrid Modeling Techniques

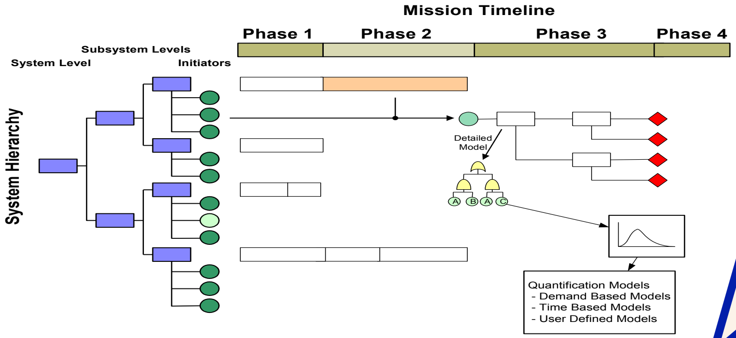






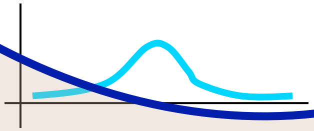


“Continuous Models”-Probabilistic Simulation



"Lambda Line"

At a given stress S

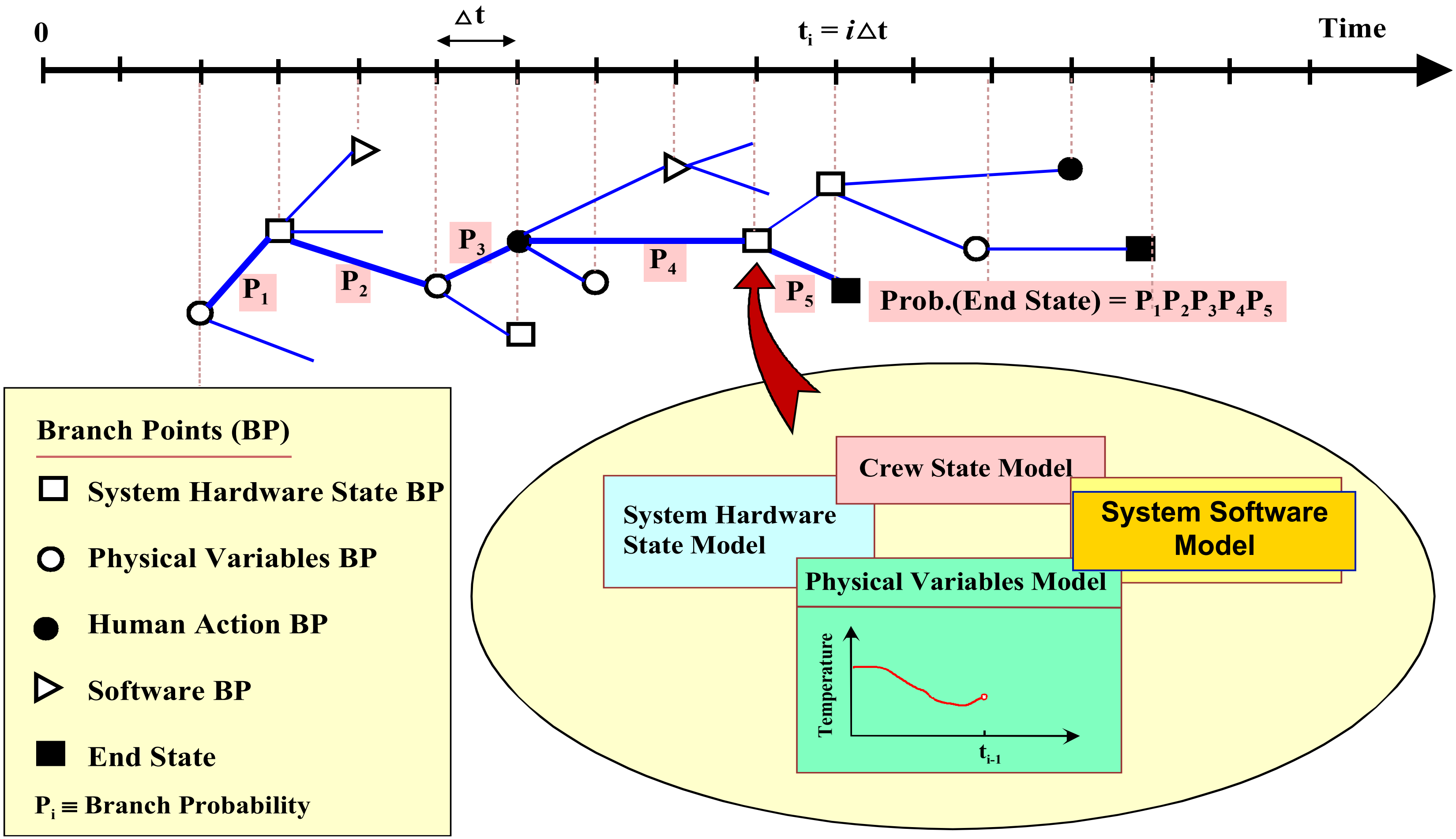


$f(t, S/K, n, \beta)$

Stress-Life Joint Distribution:

Where K, n and b are parameters

Simulation Approaches
(Discrete Dynamic Event Tree)



$\text{Prob.(End State)} = P_1P_2P_3P_4P_5$

Branch Points (BP)

- □ System Hardware State BP
- ○ Physical Variables BP
- ● Human Action BP
- ▷ Software BP
- ■ End State

$P_i \equiv$ Branch Probability

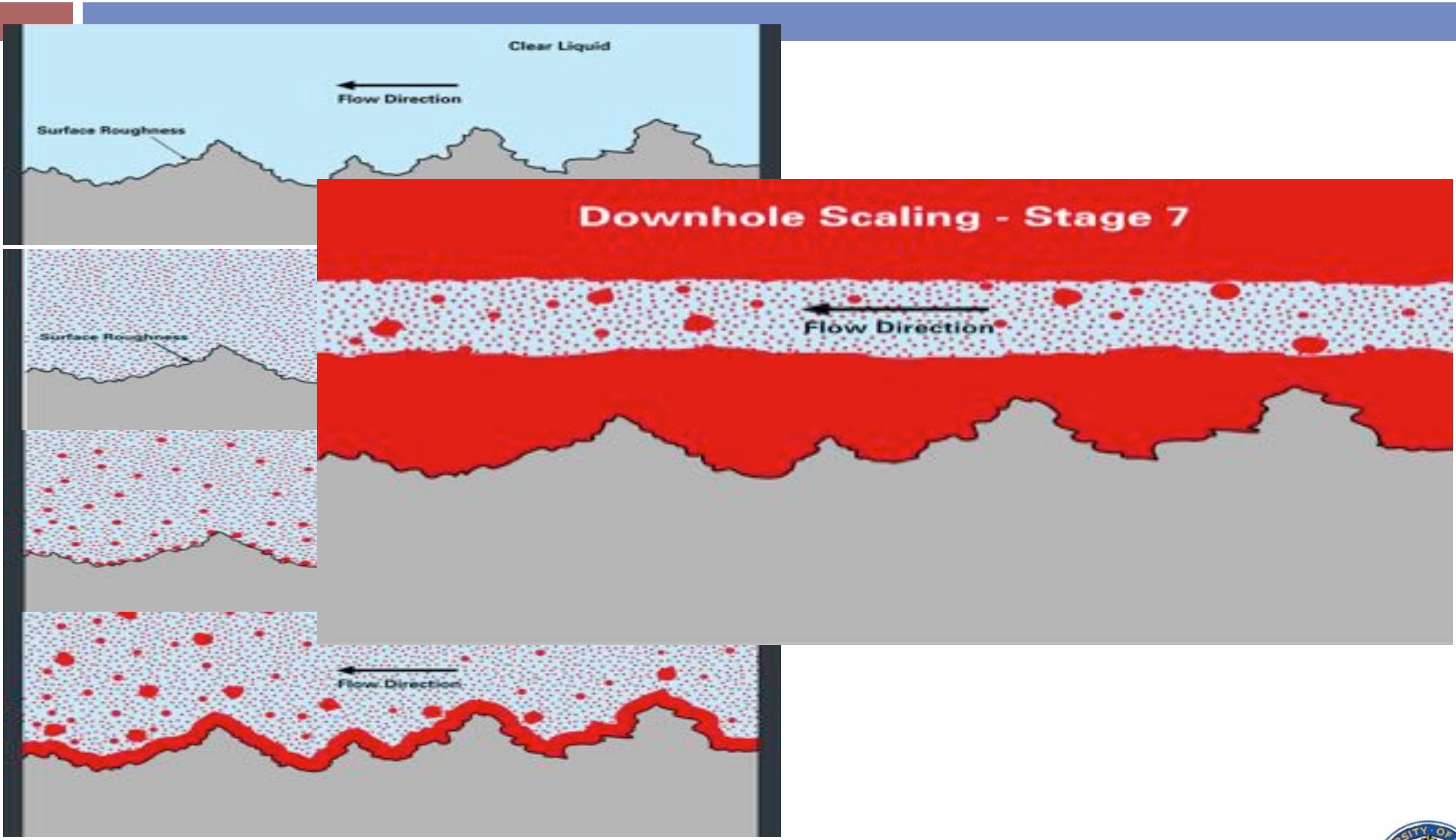
Advanced Regression Models

Degradation Prognostics Based on Hybrid Physics of Failure and Support Vector Regression

Inorganic (CaCO3) Scale Deposition in Intelligent Control Valves

- Reduce production rates by blocking valves, tubing and flow lines
- Prevent equipment of properly actuating
- Cause undesirable consequences:
    - Shortening of times between condition-based maintenances
    - Unscheduled equipment shutdowns
    - Complete interruption of oil production

Stages of Scale Formation



Degradation Prognostics Based on Hybrid Physics of Failure and Support Vector Regression

- Predict scale *built up rate* to determine proper maintenance interval for Intelligent Control Valves (ICV)
- Lack of predictive model due to complexity of phenomenon, geometry, and variability of the controlling parameters
- Used a Hybrid Physics of Failure and Support Vector Regression
- Used data from small scale experiments and tests with a real ICV

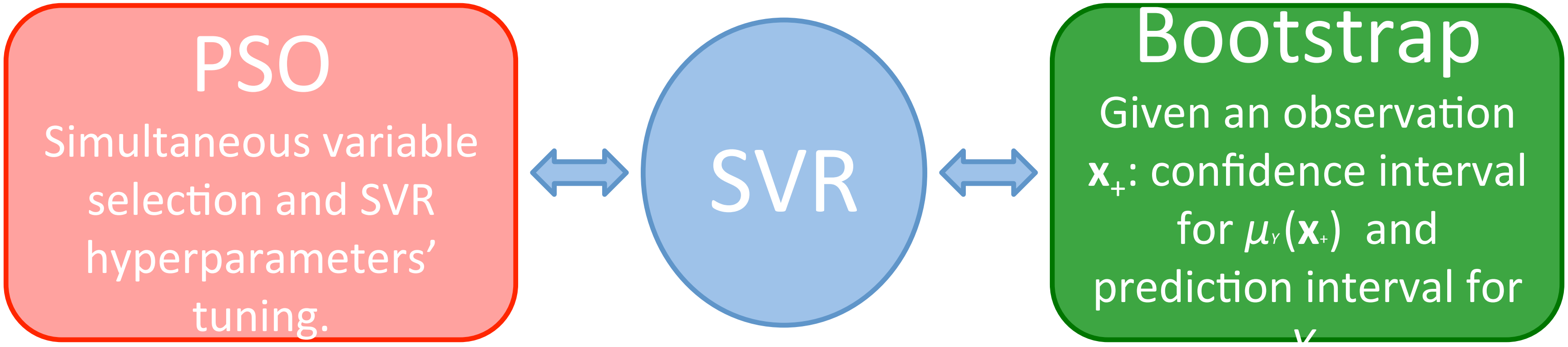
Scale Formation Experimental Setup

- **Estimate Scale Growth**
- **Based on:**
  - Surface Finish
  - Material Type
  - Temperature
  - Pressure
  - Brine Concentration
  - Flow Velocity
  - Time

Support Vector Regression: Approach and Challenges

Non-parametric regression: $Y = \mu_Y(x) + u(x)$

Estimate of $\mu_Y(x)$ via $D = \{(x_1, y_1), \ldots, (x_l, y_l)\}$



PSO

Simultaneous variable selection and SVR hyperparameters' tuning.

SVR

Bootstrap

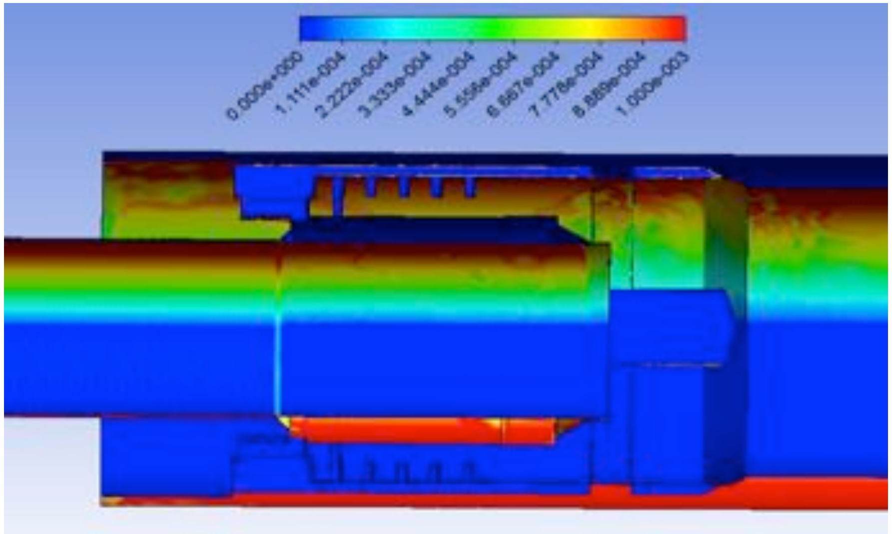
Given an observation $\mathbf{x}_+$: confidence interval for $\mu_Y(\mathbf{x}_+)$ and prediction interval for Y

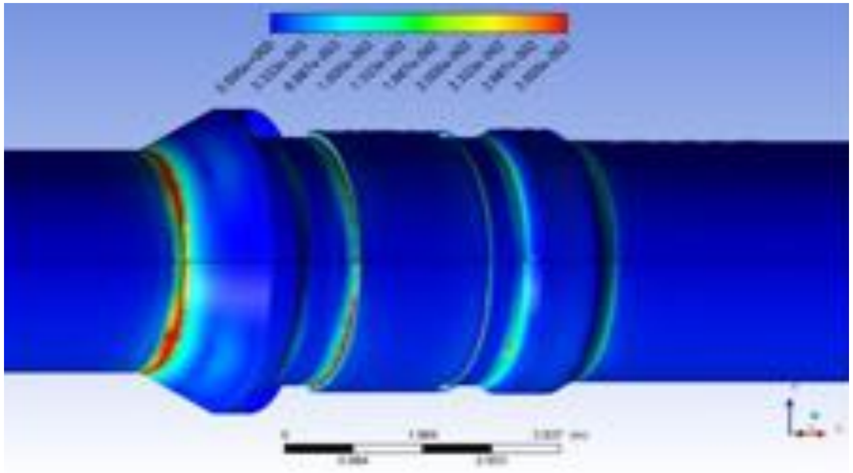
Performance is influenced by its hyperparameters.

Often not all available input variables are necessary to describe Y: modification of the training set and of the hyperparameters.

Point estimates for the response: Uncertainty?

ICV – 2000m^3/day, 7000 psi, 150C, 30% Valve Opening





- Scale growth rate:

$$\hat{y}_+ = 0.08\, in / day$$
$$CI[\mu_Y(x_+);10\%] = [0.04, 0.12]$$

- Prognostics: Plugging of the valve ID $\hat{t}_+ = 67\, days$

$$CI[\mu_t(\mathrm{t}_+);10\%] = [39, 132]$$

Doing More with Less:

Making Reliability and Integrity Decisions with Limited Information

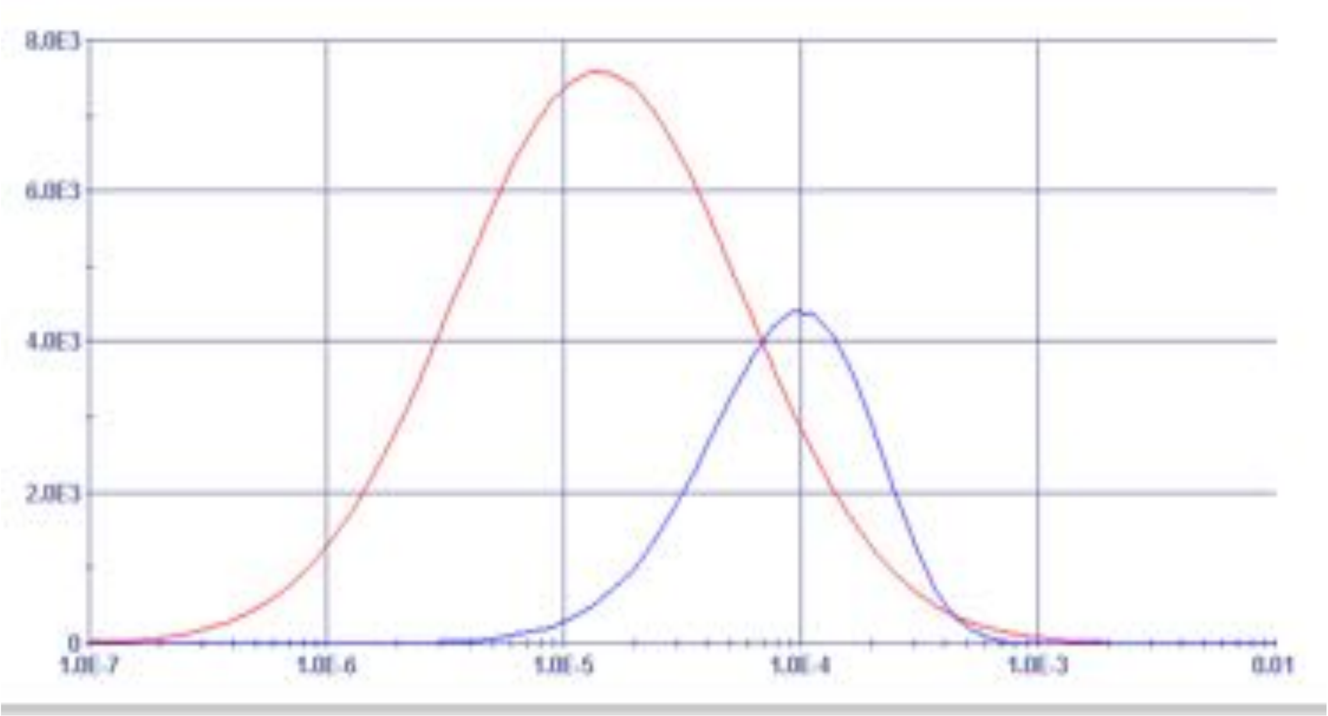
Advanced Inference Methods

- Can’t get the data we like to have

- More advanced use of surrogate data
  - Expert Opinion
  - Uncertain or Partially Applicable Data
    - Degraded State of a Component
    - Uncertainty in Observation and Data Interpretation
    - Effectiveness of Design or Failure Mode Fix Credit
    - Data Relevance (Use of Heritage Data)

Bayesian Inference Method

$$\pi(\mathrm{x}|\mathrm{D}) = \frac{\mathrm{L}(\mathrm{D}|x)\,\pi_0(x)}{\int \mathrm{L}(\mathrm{D}|x)\,\pi_0(x)\,dx}$$



Advanced Bayesian Methods

- Generalized methods for use of Uncertain or Partially Relevant Evidence

Any new information

$$\Pr\left(X \middle| \enclose{circle}{E}\right) = \frac{\Pr\left(E \middle| X\right)\Pr\left(X\right)}{\Pr\left(E\right)}$$

- Soft Causal Modeling (BBN)
- Inference Infusion of data at lower levels
  - Supplementing physics of failure models

Uncertain or Partially Relevant Evidence

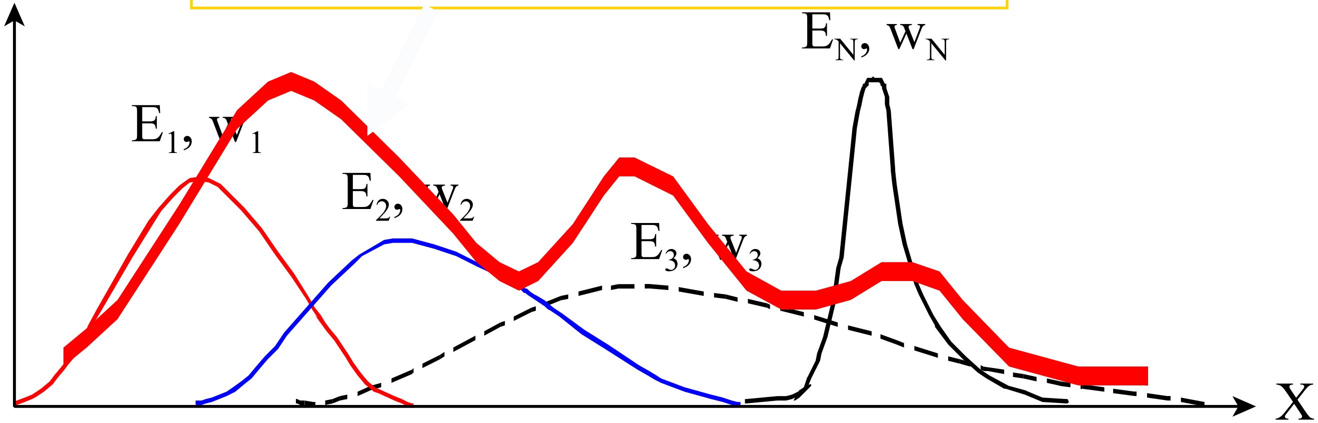
- **Degraded State of a Component**
  - $0<p<1$ level of degradation of a component
- **Uncertainty in Observation and Data Interpretation**
  - $0<p<1$ the probability that the observed event was a failure
- **Effectiveness of Design or Failure Mode Fix Credit**
  - $0<p<1$ the degree of confidence that the design modifications has eliminated the possibility of reoccurrence of an observed failure mode
- **Data Relevance** (Use of Heritage Data)
  - $0<p<1$ degree of relevance of a data item from other applications to the system or environment of interest

Bayesian Weighted Posterior Method

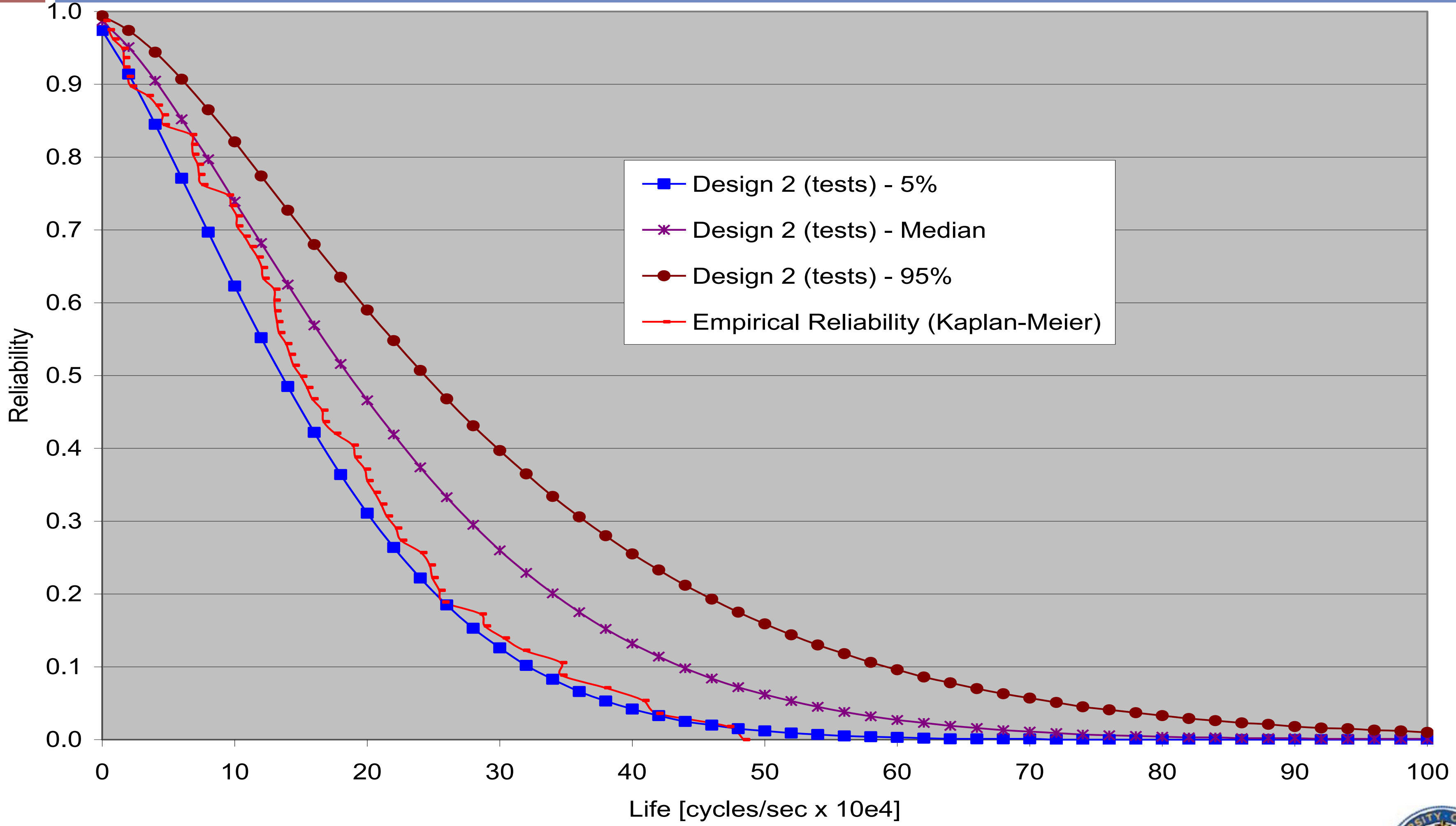
- Uncertain evidence: $E = \{E_i\ ,\ w_i\}$ $i = 1, 2, \ldots, N$

$$\pi\left(x \middle| E_i\right) = \frac{L\left(E_i \middle| x\right)\pi_0(x)}{\int L\left(E_i \middle| x\right)\pi_0(x)\,dx}$$

$$\boxed{\pi\left(x \middle| E\right) = \sum_{i=1}^{N} w_i\ \pi\left(x \middle| E_i\right)}$$



Reliability Prediction of Advanced Medical Diagnosis System



Use of Expert Opinion & Engineering Judgment

- ELICITATION
  - How to select
  - One expert or many
  - How to elicit the opinion
- USE
  - How to use

    a) expert information, and

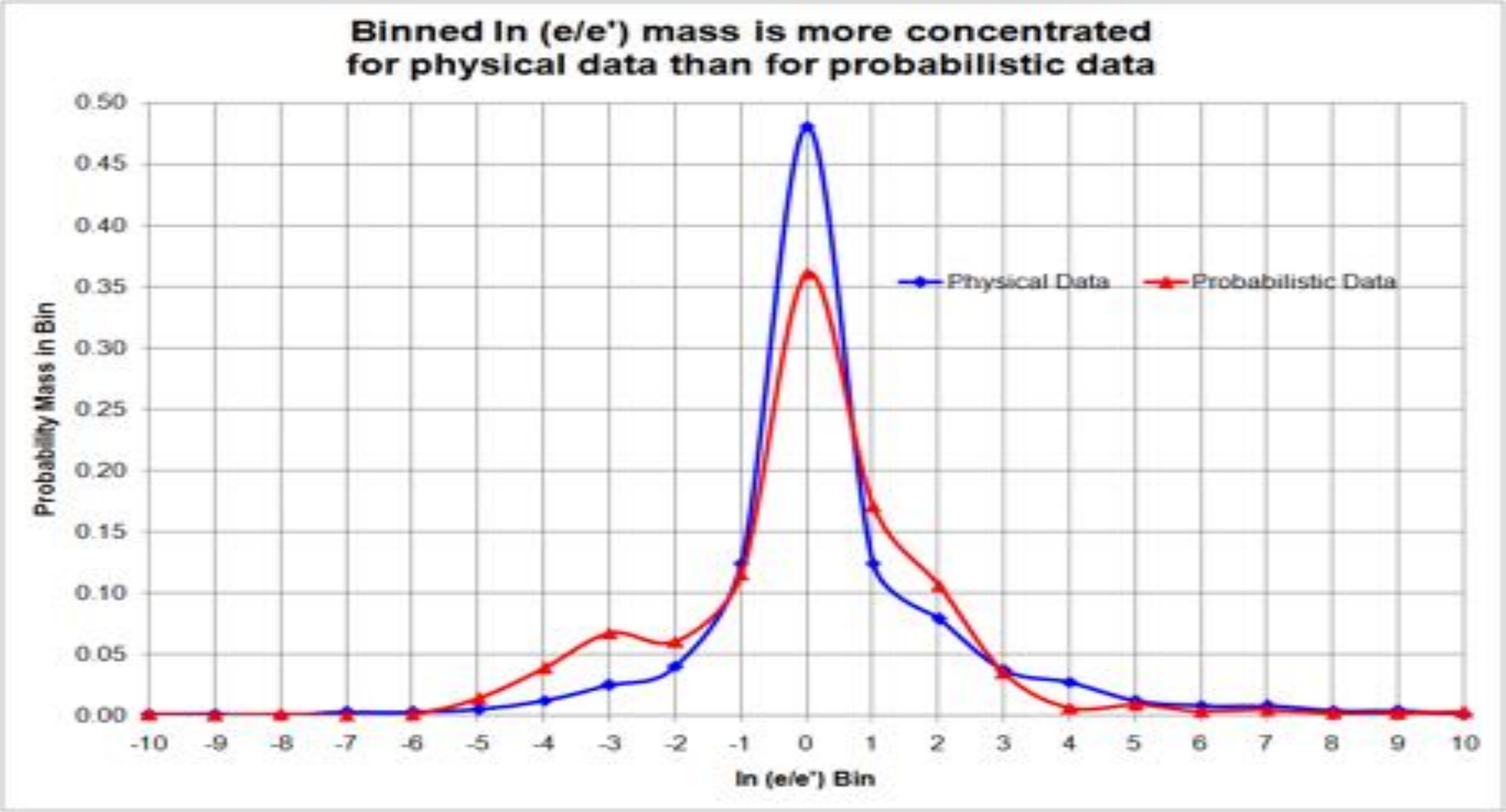
    b) information about the expert,

    to estimate the unknown quantity.
  - In case of multiple experts, how to aggregate the opinions.

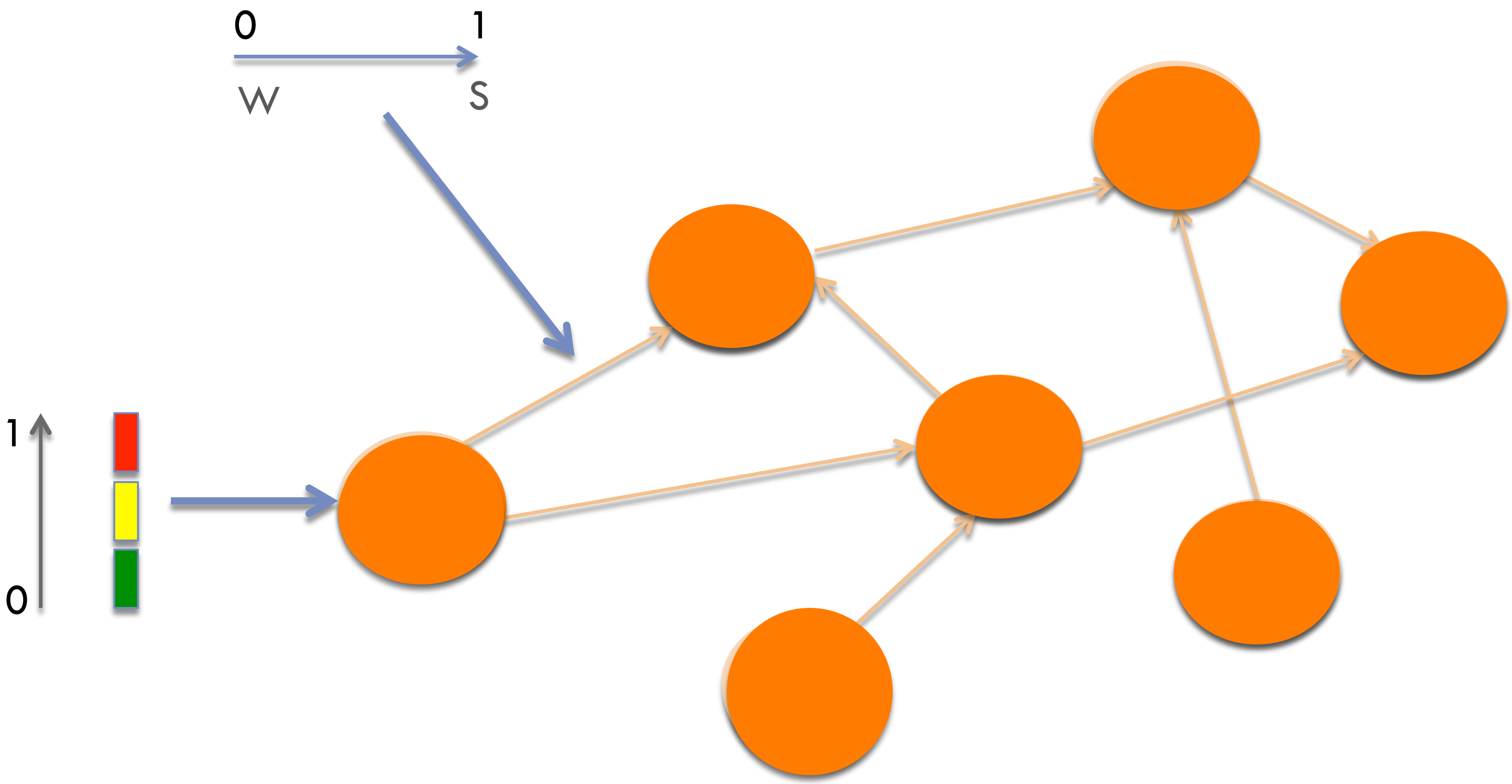
Expert Opinion: Encouraging Findings and Trends

- Increasing sophistication of elicitation methods
  - Selection, attributes
  - Elicitation process
- Progress in generic calibration
  - Domain specific
- Studies on
  - Performance and effectiveness of aggregation methods
  - Understanding and dealing with sources of dependencies

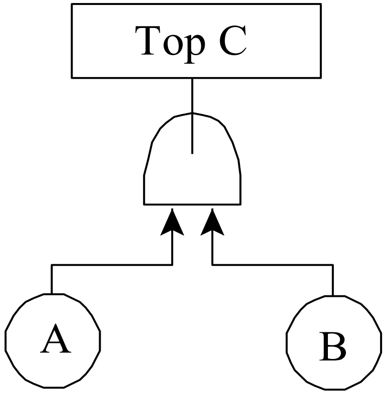
Generic Calibration of Experts



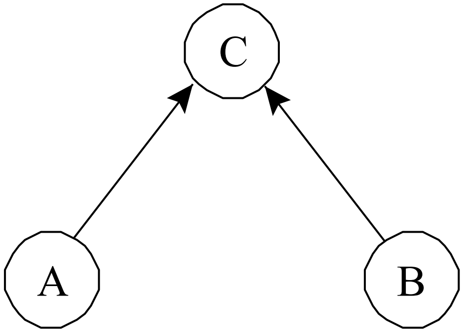
Bayesian Net (BN) as a Modeling and Analysis Tool



Deterministic and Probabilistic Causal Models



$$\Pr(c) = \Pr(A)\Pr(B)$$



$$\begin{aligned}\Pr(C) &= \Pr(C \mid A,B)\Pr(A,B) + \Pr(C \mid \overline{A},B)\Pr(\overline{A},B) \\ &\quad + \Pr(C \mid A,\overline{B})\Pr(A,\overline{B}) + \Pr(C \mid \overline{A},\overline{B})\Pr(\overline{A},\overline{B}) \\ &= \Pr(A,B)\end{aligned}$$

$$\Pr(C=1 \mid A=0, B=0) = 0$$

$$\Pr(C=1 \mid A=0, B=1) = 0$$

$$\Pr(C=1 \mid A=1, B=0) = 0$$

$$\Pr(C=1 \mid A=1, B=1) = 1$$

Human Element

Significance of Human Error

- A significant factor in risk and reliability for a number of industries; Power, Aviation, Petro-Chemical, Manufacturing, Transportation
- Accounts for more than 50% of the industrial accidents
- An issue in different phases of a system life cycle
  - Design
  - Construction
  - Operation
  - Management
  - Maintenance
  - Decommissioning/Disposal

Human Role in Petro-Chemical Accidents

EPA: **234** recordable accidents at Refineries (2000-2010) → **more incidents in that time period than any other Industry!**

MARS (Europe) 1985-2002 [1]

32% - chemical

17%

Petrochemical

Industrial Accidents

3916

585

1995-2000

22%

Petrochemical

FACTS database (TNO) [6]

2012 alone → the **CSB** tracked 125 significant process safety incidents at US petroleum refineries

1992 – 2007 **(OSHA)**

36 FAT/CAT

HHC release in refining industry

250 employee injuries

52 employees death

More than the combined total of the next three highest industries over the same period

34% of these accidents were due to human errors

38% were due to inappropriate maintenance of equipment

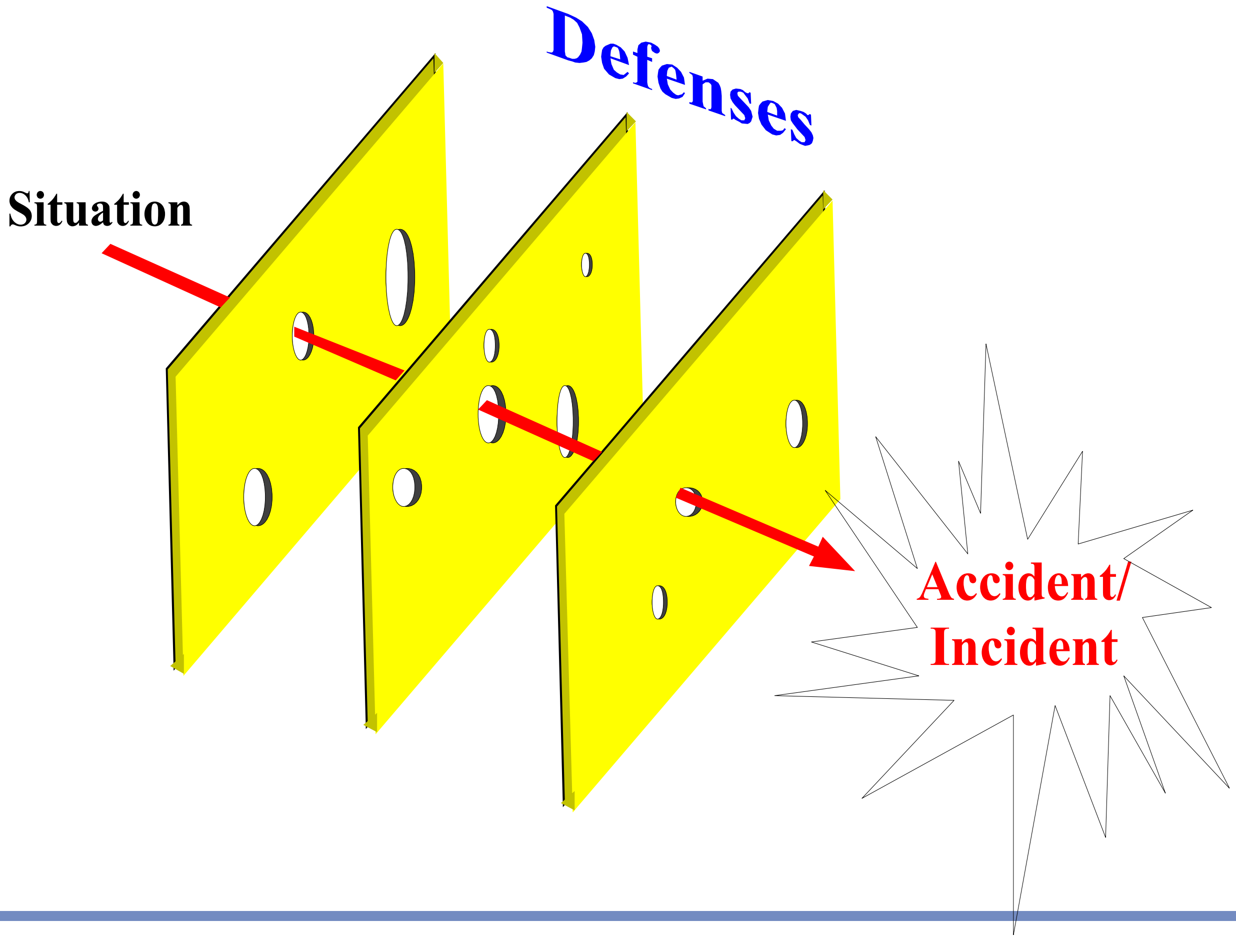
Human Reliability Analysis (HRA)

- Objective
  - Identify human response (errors are the main focus)
  - Estimate failure (error) probabilities
  - Identify causes of errors to support development of preventive or mitigating measures
- Over 40 methods at different levels of sophistication and complexity, mostly developed for nuclear power industry

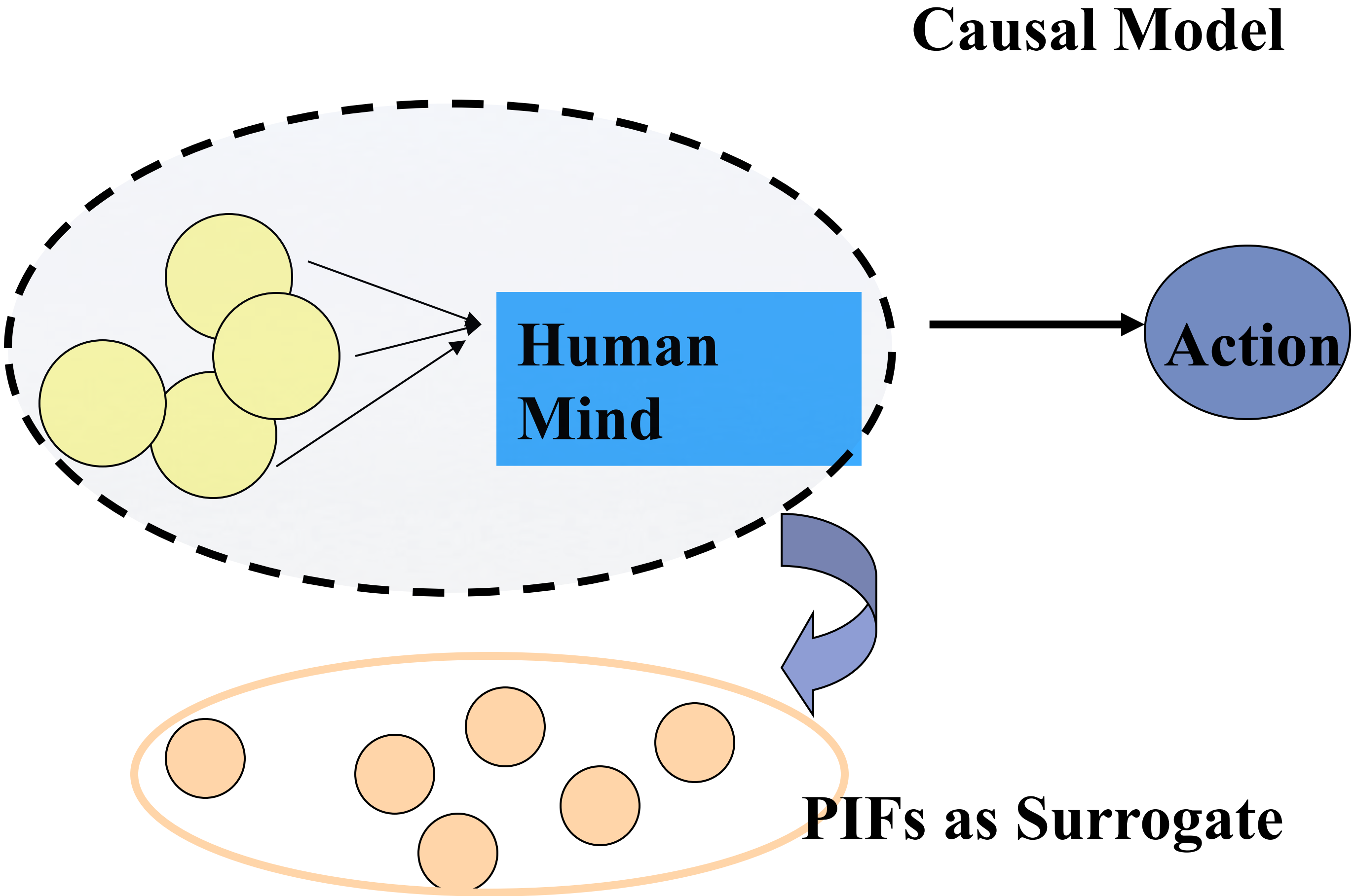
Three Types of Human Response

- An individual responses to a situation normally has three dimensions:
  - **Cognitive:** mental activities to understand the situation and plan/decide on action
  - **Emotional:** conscious and non-conscious feelings
  - **Physical:** the physical responses to the situation (movement, sound, etc.)
- These three types of activities are inter-dependent

Swiss Cheese Model



Performance Influencing Factors (PIF)



Causal Model

Human Mind

Action

PIFs as Surrogate

Main Elements of Typical HRA Method

- Task Analysis
- Identification of Error Modes and, if possible, Error Mechanisms
- Identification of Performance Influencing Factors (PIFs)
- Quantification of Error Probability and Uncertainty
- Incorporation of Results into Risk or Reliability Models
- Ranking of Contributors for Cost Effective Improvements

Chevron Richmond Refinery Fire - 2012

- Cause: ***Catastrophic pipe failure*** in the Crude Unit releasing HC, which vaporized into a large cloud that engulfed 19 employees and ignited (all escaped). The large plume of particulates and vapor travelled across Richmond. 15000 people sought medical treatment**. Estimated 1-2 Billion $ cost**

Sulfidation
Corrosion

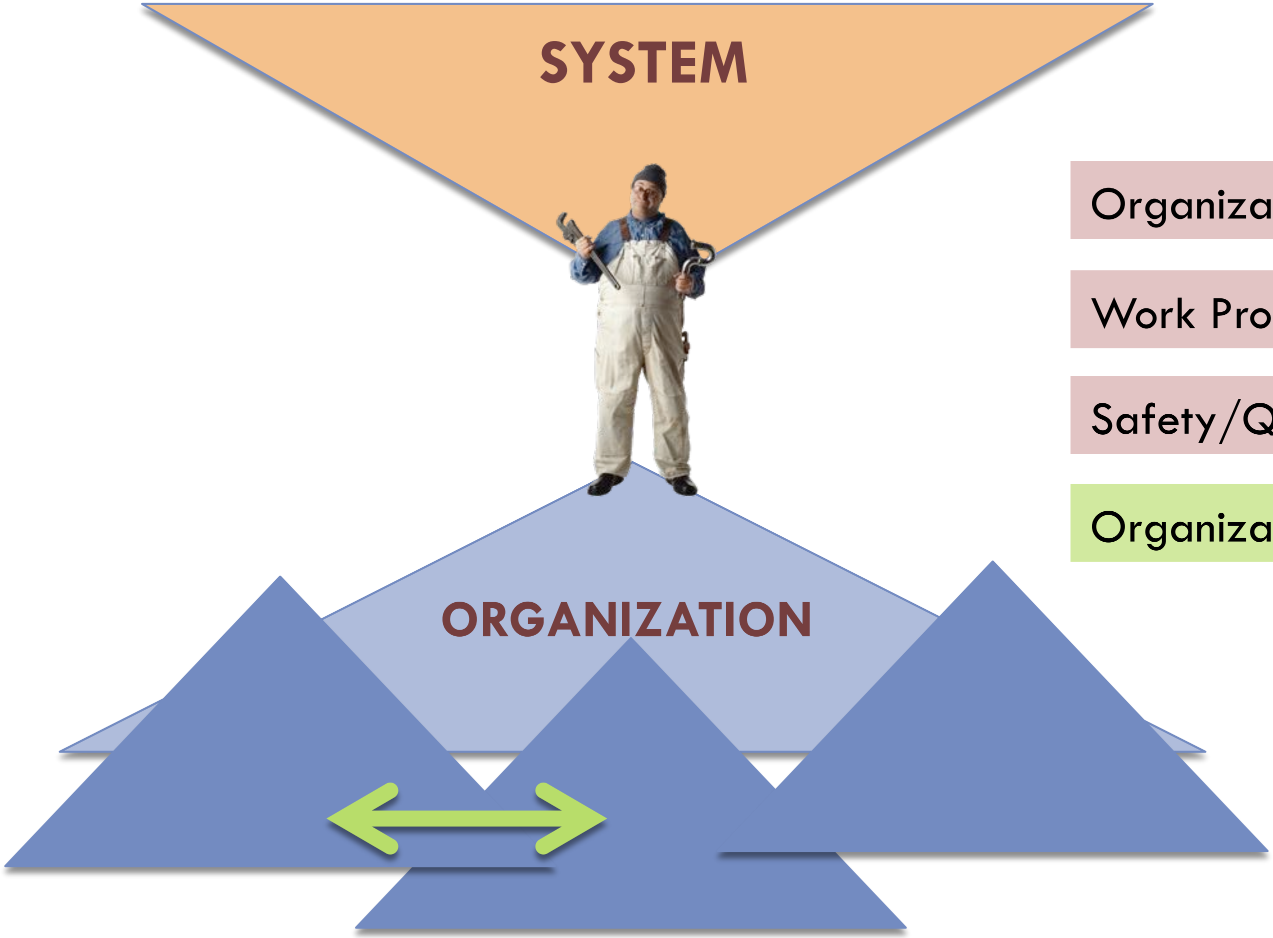
Technical Findings

- - 2002 – sulfidation corrosion in Crude Unit in Utah. Chevron performed inspection in the #4 sidecut at Richmond → accelerated thinning, failure in 2012. Replacement recommended.
  - Not implemented. The piping was never inspected again
- - 2007: the same kind of incident. Chevron upgraded the piping metallurgy only in the piping spool that have failed
- - 2009: Chevron experts recommended that every segment of high risk carbon steel piping be inspected for corrosion
  - Not implemented

- Each and every segment of the piping should have been inspected
- The pipe should have been replaced much earlier

- Had the Crude Unit been shut-down when the leak as first noticed the massive fire likely would not have occurred

Organization and Organizational Interface Failures



Organizational Structure

Work Processes

Safety/Quality Culture

Organizational Interface

Getting More Out of the Same Data:

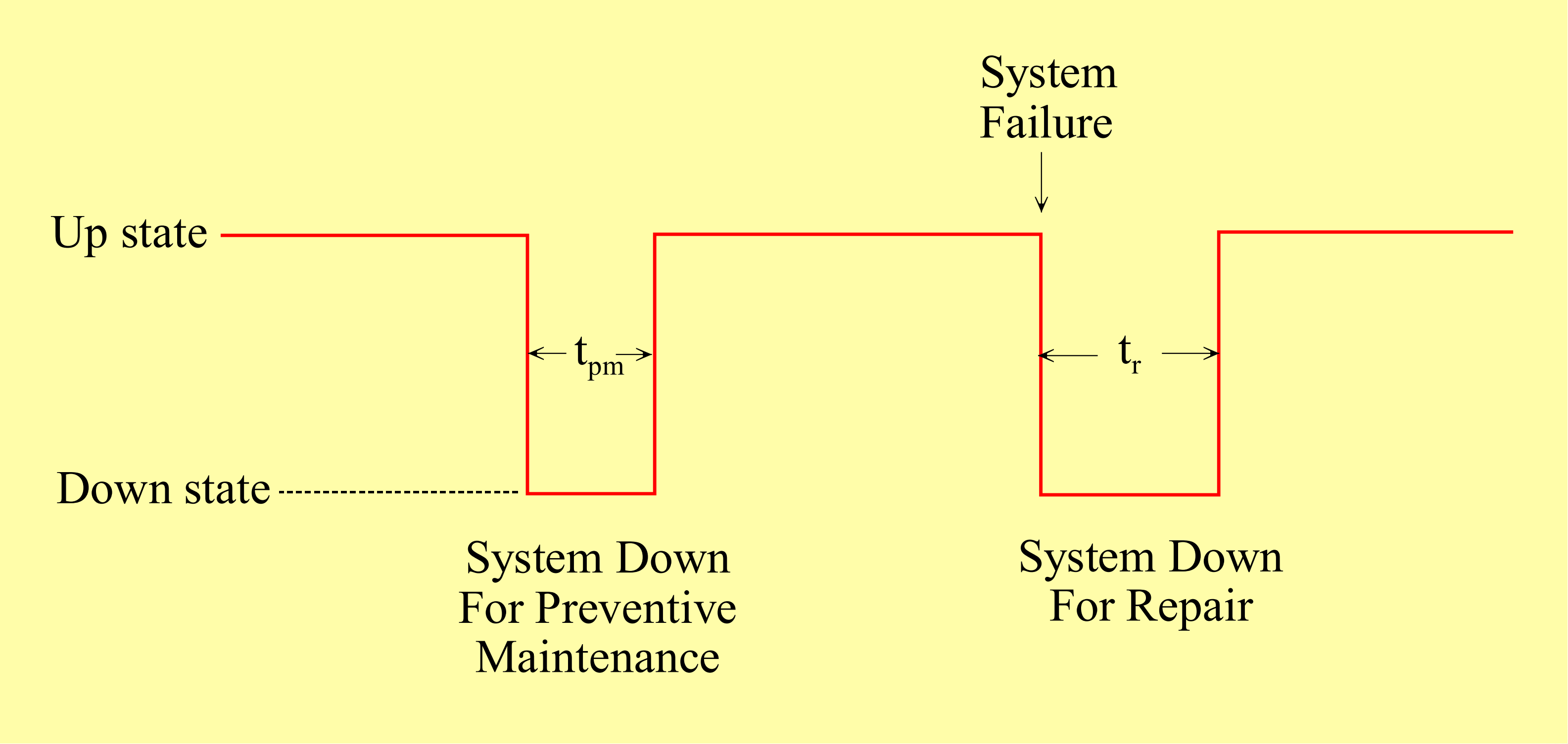
Renewal Theory and

Application to Maintenance Models

IMPCT OF MAINTENANCE

- Corrective Maintenance
- Preventive Maintenance

$$\lim_{t \to \infty} A(t) = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}}$$

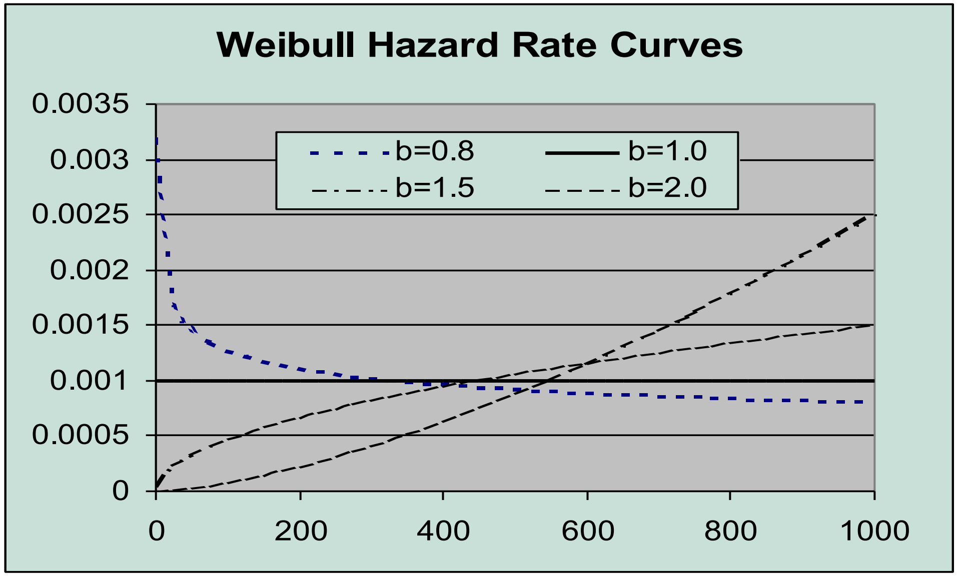


WEIBULL TIME-TO-FAILURE MODEL

- The Weibull model

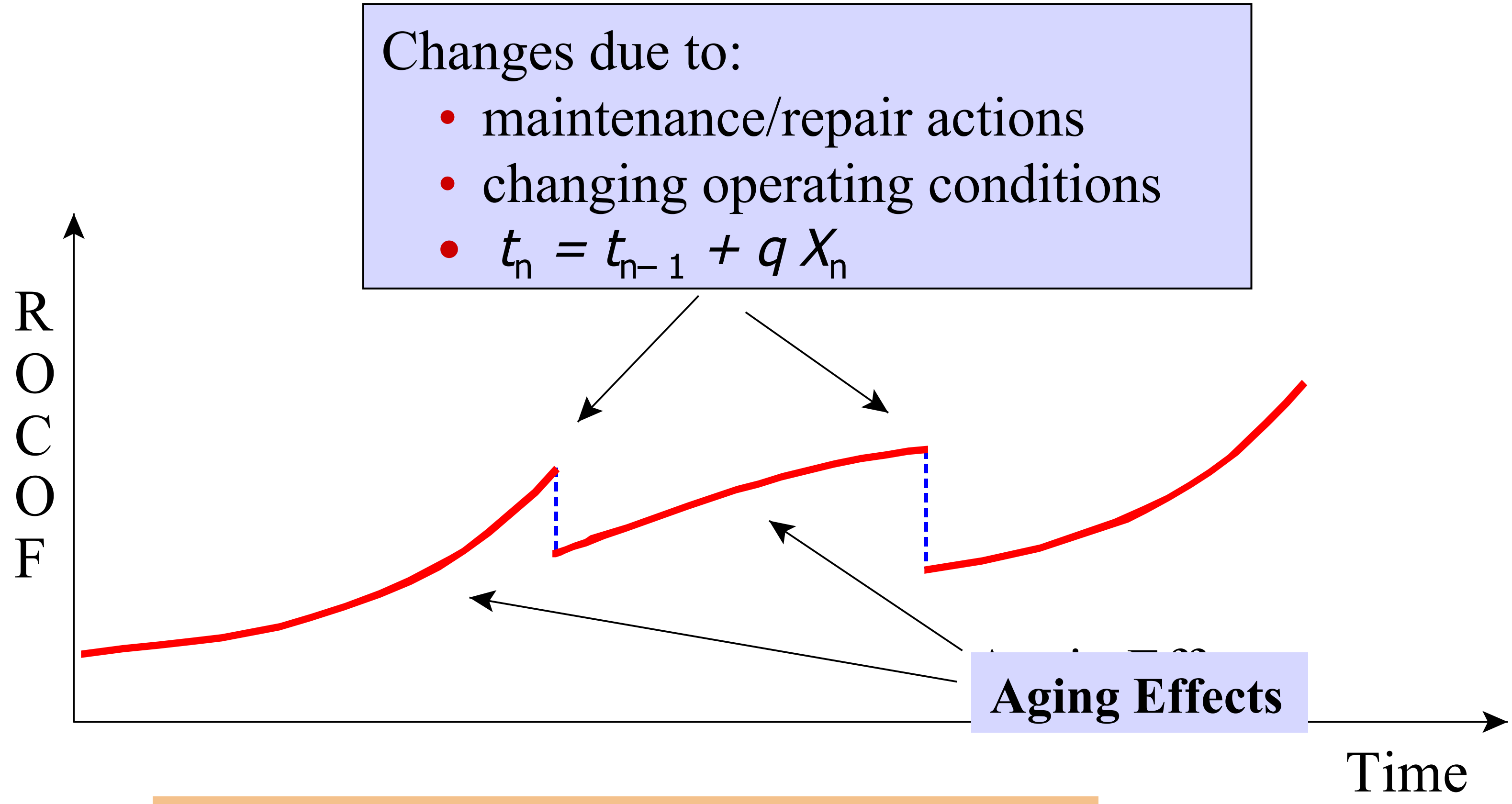
$$h(t) = \frac{\beta}{\alpha^{\beta}} t^{\beta-1}$$

$$R(t) = e^{-(t/\alpha)^{\beta}}$$



- Provides a basic capability to model aging effects, since depending on the value of β, it can describe both decreasing (β < 1), or increasing (β > 1) failure rates.

GENERALIZED RENEWAL PROCESS

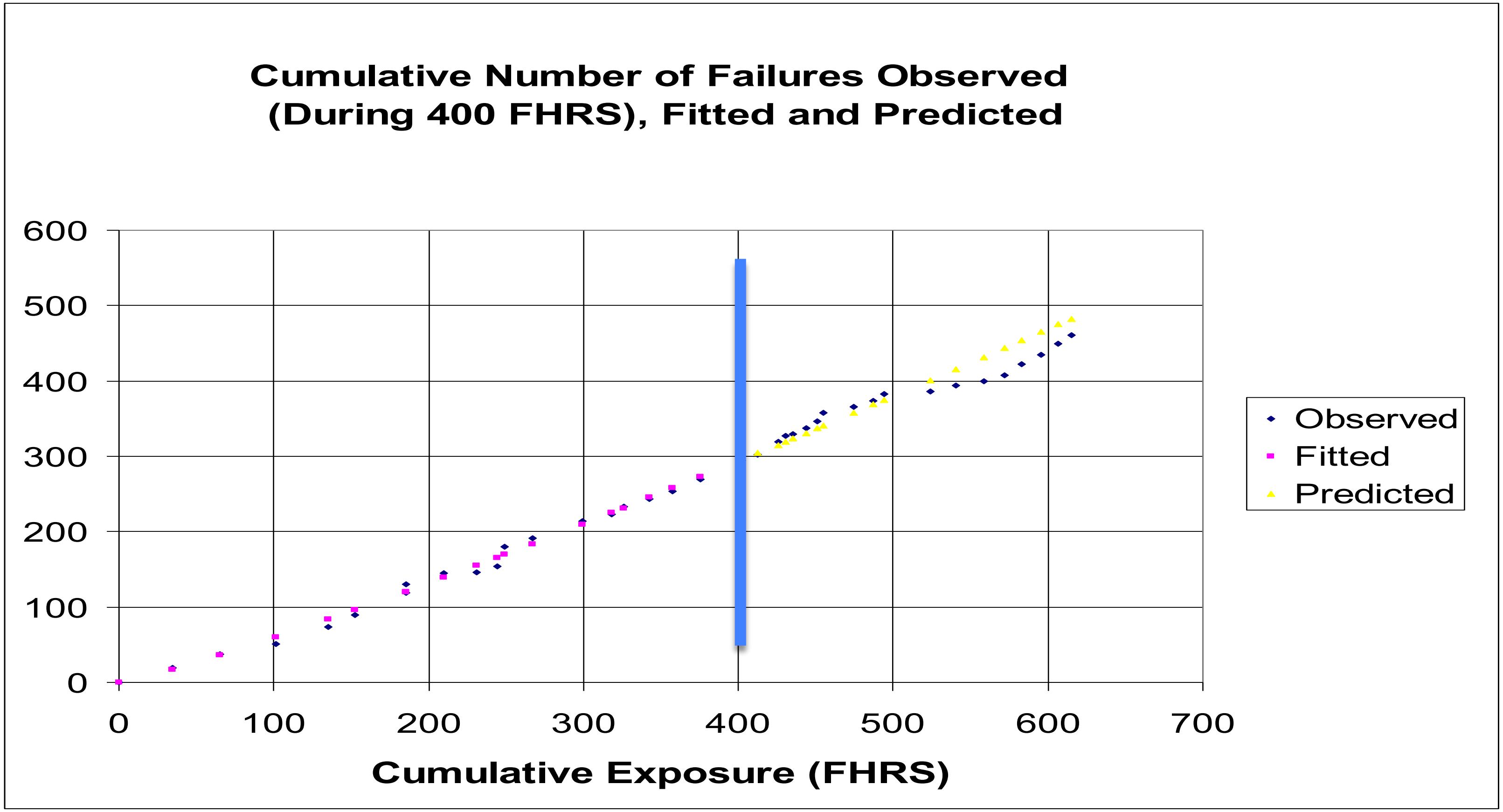


Changes due to:

- maintenance/repair actions
- changing operating conditions
- $t_n = t_{n-1} + q X_n$

“q” quantifies the impact of quality

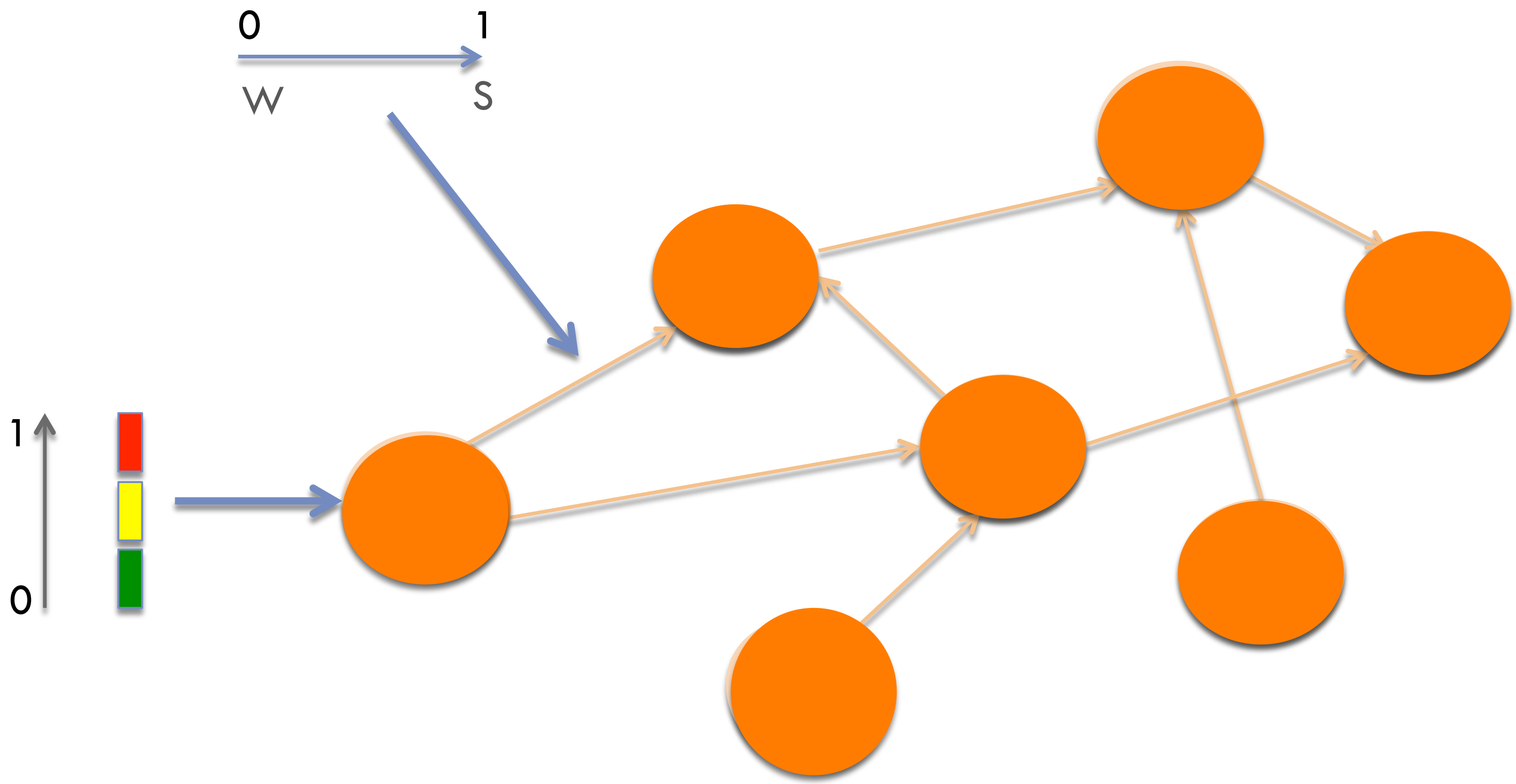
An Application and Insights



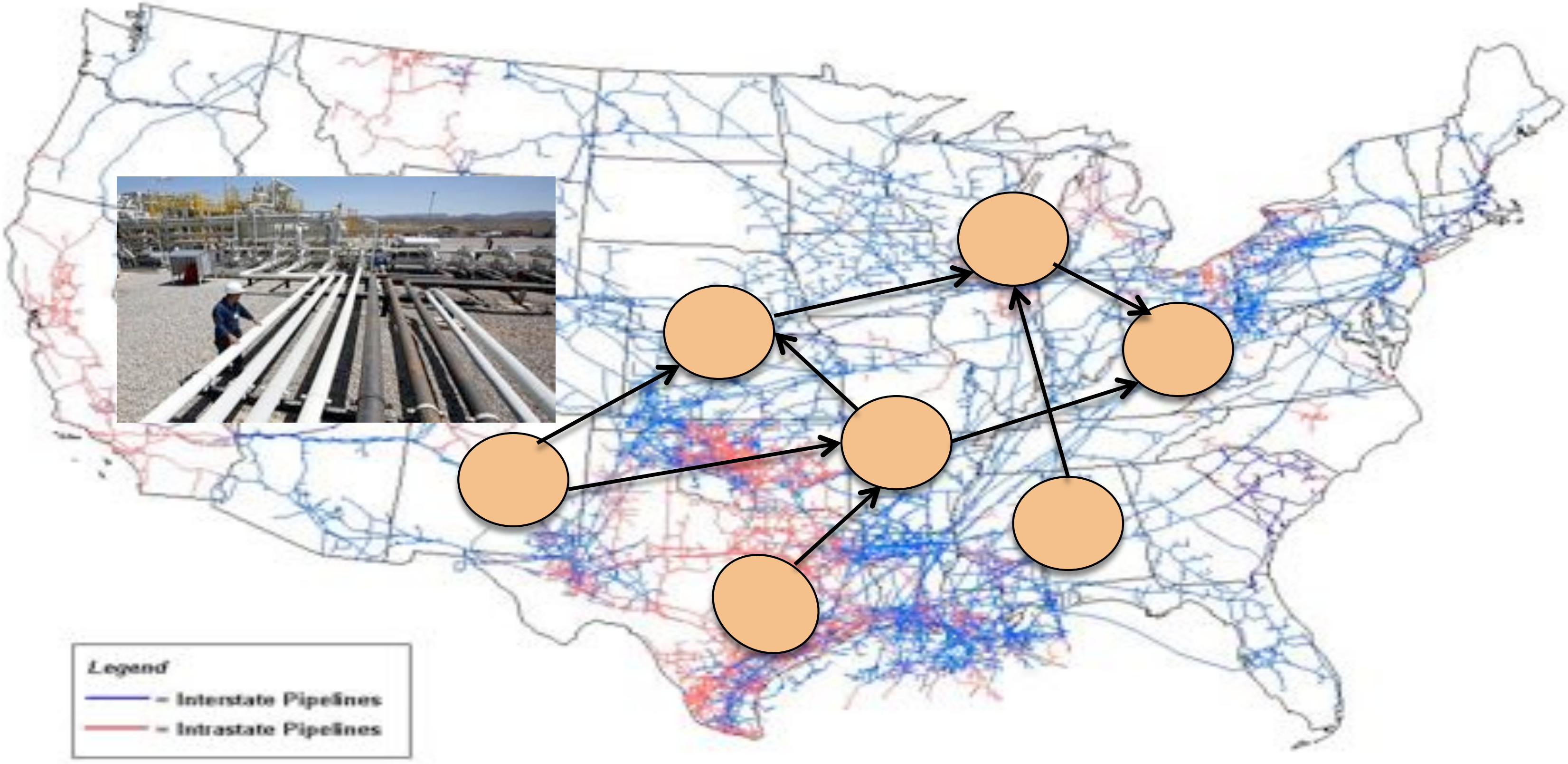
(Scale Parameter α = 2.86 hours, Shape Parameter β = 1.16, **Repair Effectiveness q = 0.6**)

Model-Based Approach to Integrity Management : An Example

Bayesian Net (BN) as a Modeling and Analysis Tool



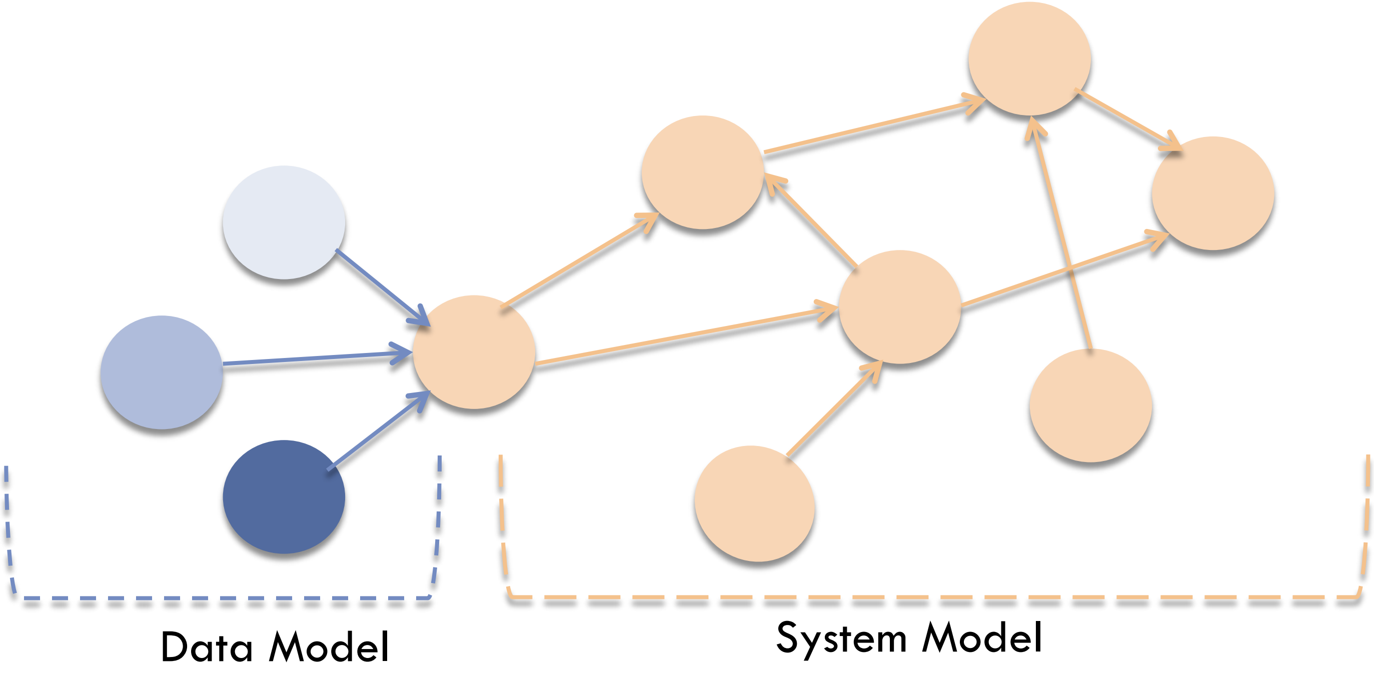
Distribution Network Abstraction with BN



Source: Energy Information Administration, Office of Oil & Gas, Natural Gas Division, Gas Transportation Information System

Features

- Compact and seamless integration of the ***data model*** and ***pipeline network model*** into a single risk-based Integrity Management platform



Features

- Ability to utilize all available information about state of any system element (e.g., pipe segment):
  - Quantitative and Qualitative input
  - Actual operational data
  - Partially relevant evidence
  - Output of physical models
  - Subject Matter Expert knowledge

Integrity Assessment Based on Comprehensive Range of Evidence

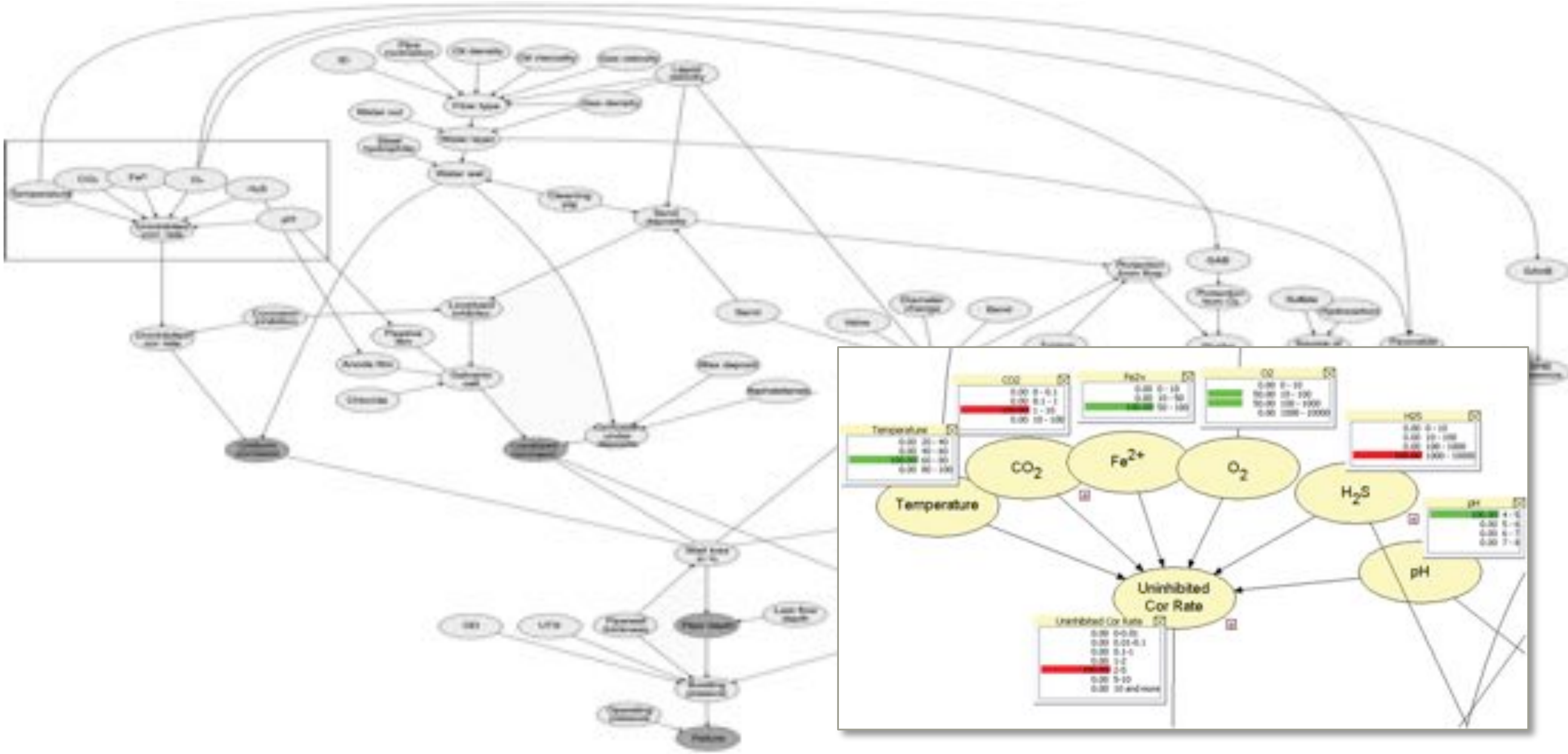
- **Instrumented, for example**
  - High definition cameras for monitoring internal and external condition of pipelines for dents, cracks and corrosion
  - Ultrasonic crack detection, corrosion detection and wall thickness measurement
- **Visual inspection**
- **Physical models and data** on failure mechanisms related to various causal factors including
  - Material
  - Environment
  - Manufacturing, installation, and inspection damage

Feature

Threat Type/Category	Description (ASME 2012)
Time-Dependent	
External Corrosion	Deterioration of the pipe due to an electrochemical reaction between the pipe material and the environment outside the pipe
Internal Corrosion	Deterioration of th material and the e
Stress Corrosion Cracking	Cracks in the pipe with a corrosive enviro
Stable (Resident)	
Manufacturing	Defects introduced spots; pipe manufactured frequency electric elds
Construction	Defects and weakn elds, wrinkle bends, strip
Equipment	Pipeline facilities ot relief equipment, gaskets
Time-Independent	
Third Party/Mechanical	Accidental or intentional excavation damage by a third party (that is, not the pipeline operator or contractor) that causes an immediate failure or introduces a weakness (such as a dent or gouge) into the pipe
Incorrect Operations	Incorrect operation or maintenance procedures or a failure of pipeline operator personnel to correctly follow procedures
Weather-Related/ Outside Forces	Earth movement, seismic events, heavy rains or floods, erosion, cold weather, lightning

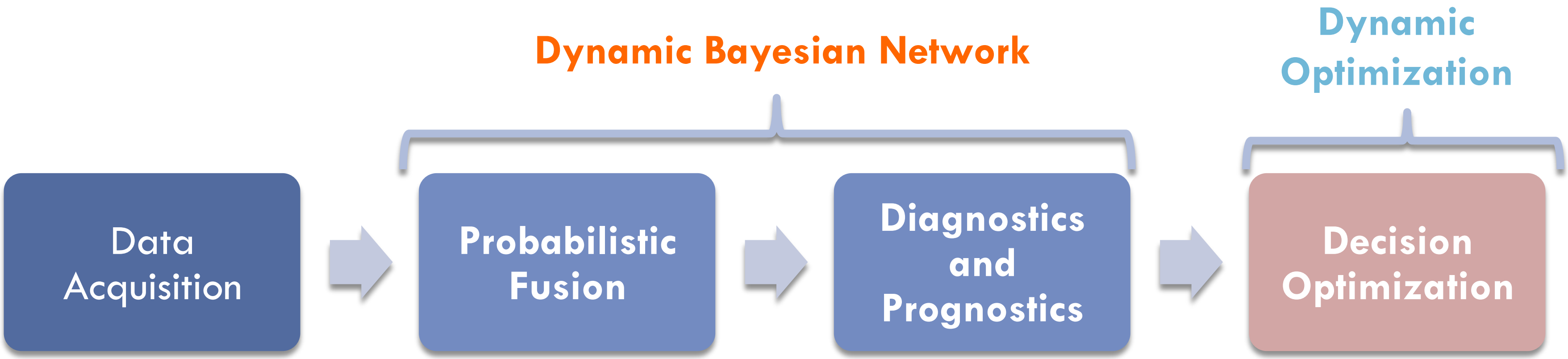
Ability to represent wide range of causal factors and functional states (failure modes) of the system and its components

Bayesian Network Created for Pipelines' **Internal Corrosion** Damage Assessment*



F. Ayello,‡,* S. Jain,* N. Sridhar,* and G.H. Koch, "Quantitative Assessment of Corrosion Probability—A Bayesian Network Approach"

Analysis and Decision Support Framework



Dynamic Bayesian Network

Dynamic Optimization

Data Acquisition → **Probabilistic Fusion** → **Diagnostics and Prognostics** → **Decision Optimization**

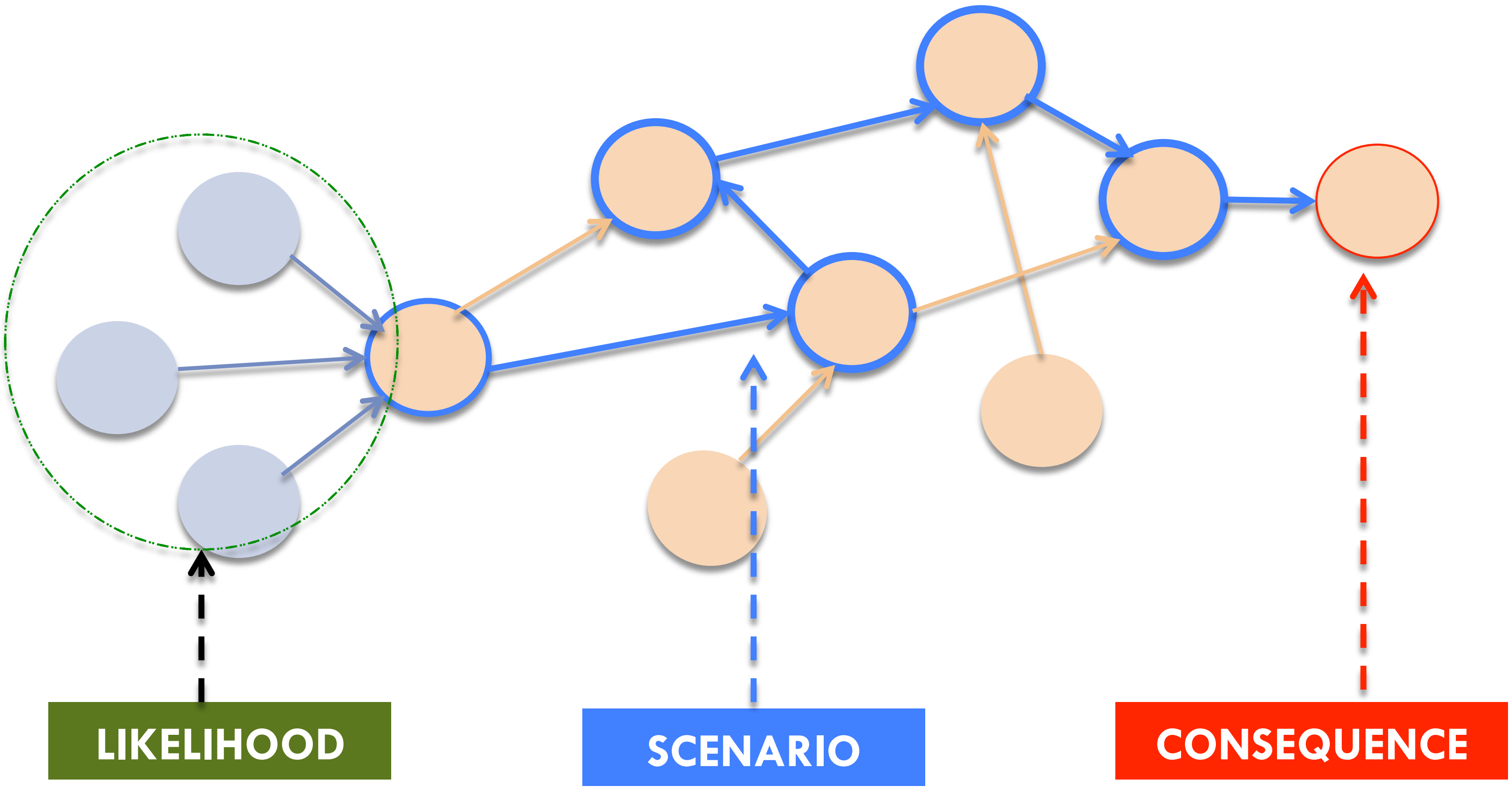
- Sensors (e.g., continuous gas leak detection)
- Inspection (e.g., high definition cameras)

- Integrate different types of uncertain information through a BN

- What is the current state of the degradation?
- What is the remaining time to failure (RUL)?

- Support cost-effective decisions on performing Inspection/ maintenance actions, and sensor placement

Capability: Model for Risk Analysis (scenarios, likelihoods, and consequences)



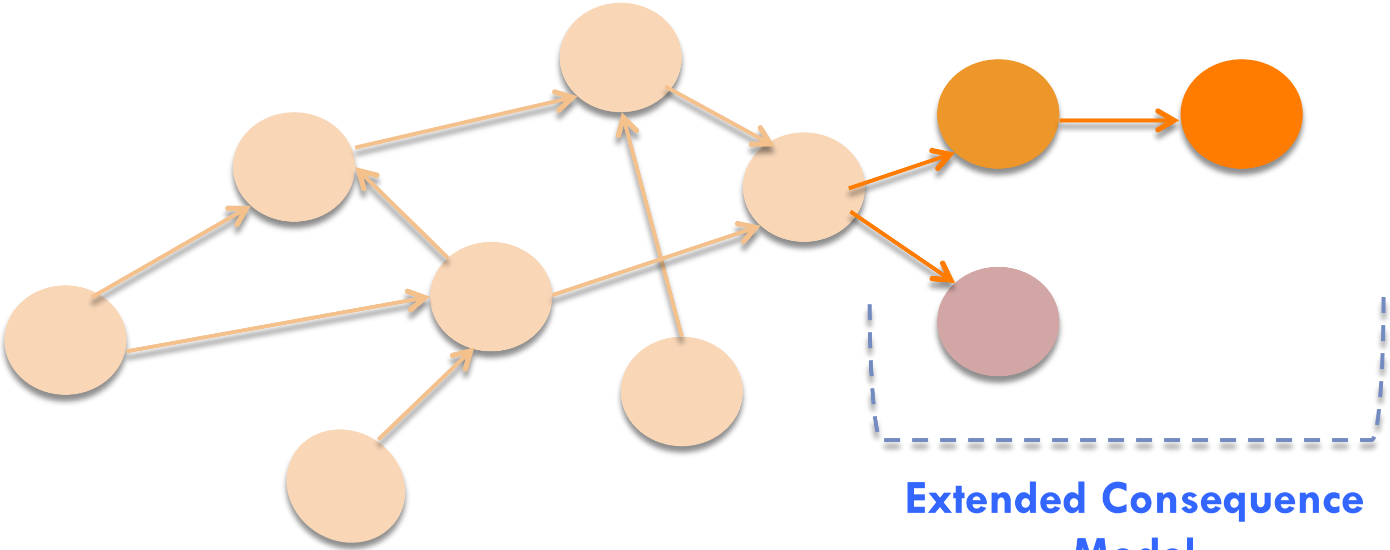
LIKELIHOOD

SCENARIO

CONSEQUENCE

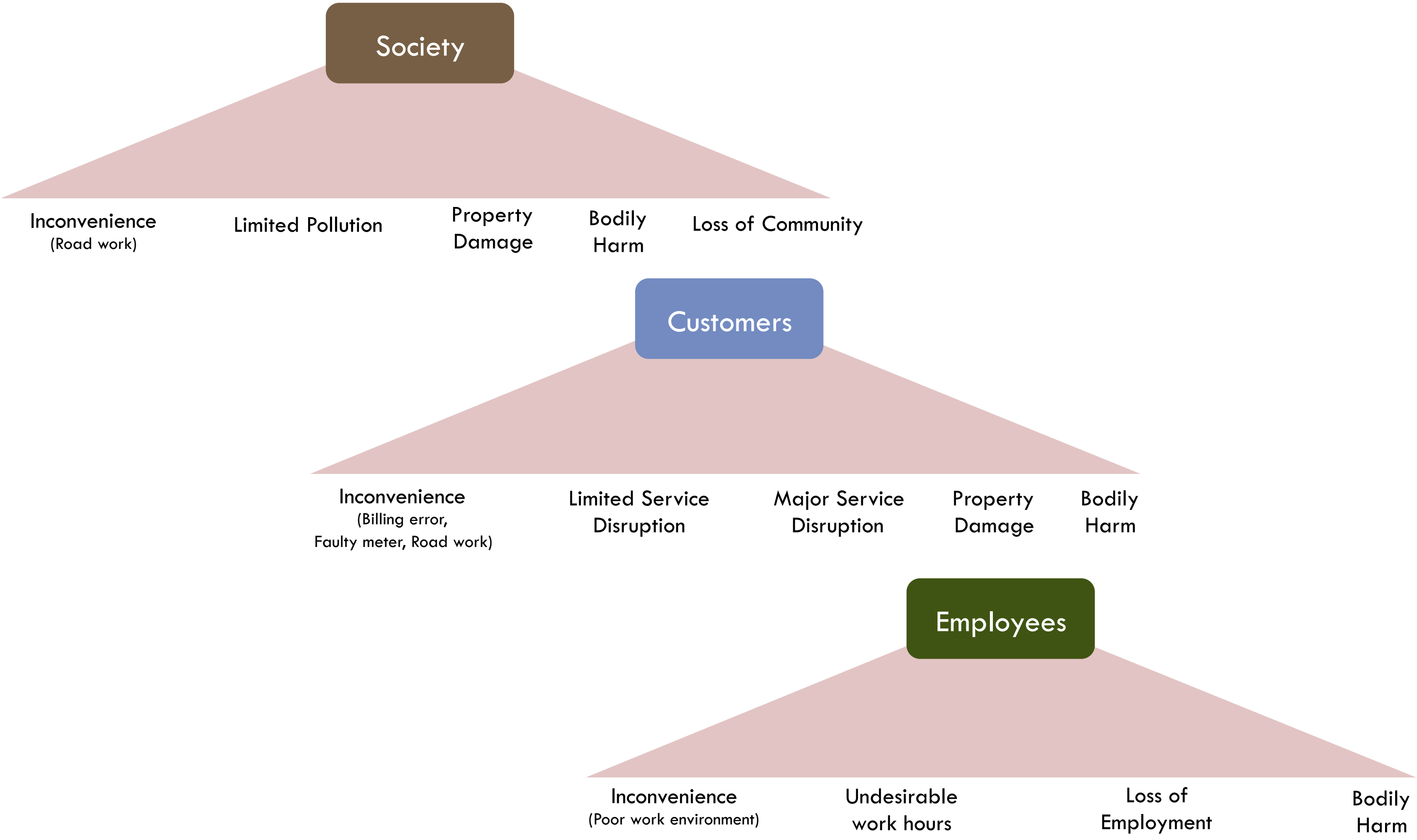
Capability: Extended Risk Scenario Consequences

- ☐ The BN model of pipeline performance can be extended in a natural way to include risk scenarios and consequences associated with enterprise concerns



Extended Consequence Model

Example Metrics: Impact on Stakeholders



Society

- Inconvenience (Road work)
- Limited Pollution
- Property Damage
- Bodily Harm
- Loss of Community

Customers

- Inconvenience (Billing error, Faulty meter, Road work)
- Limited Service Disruption
- Major Service Disruption
- Property Damage
- Bodily Harm

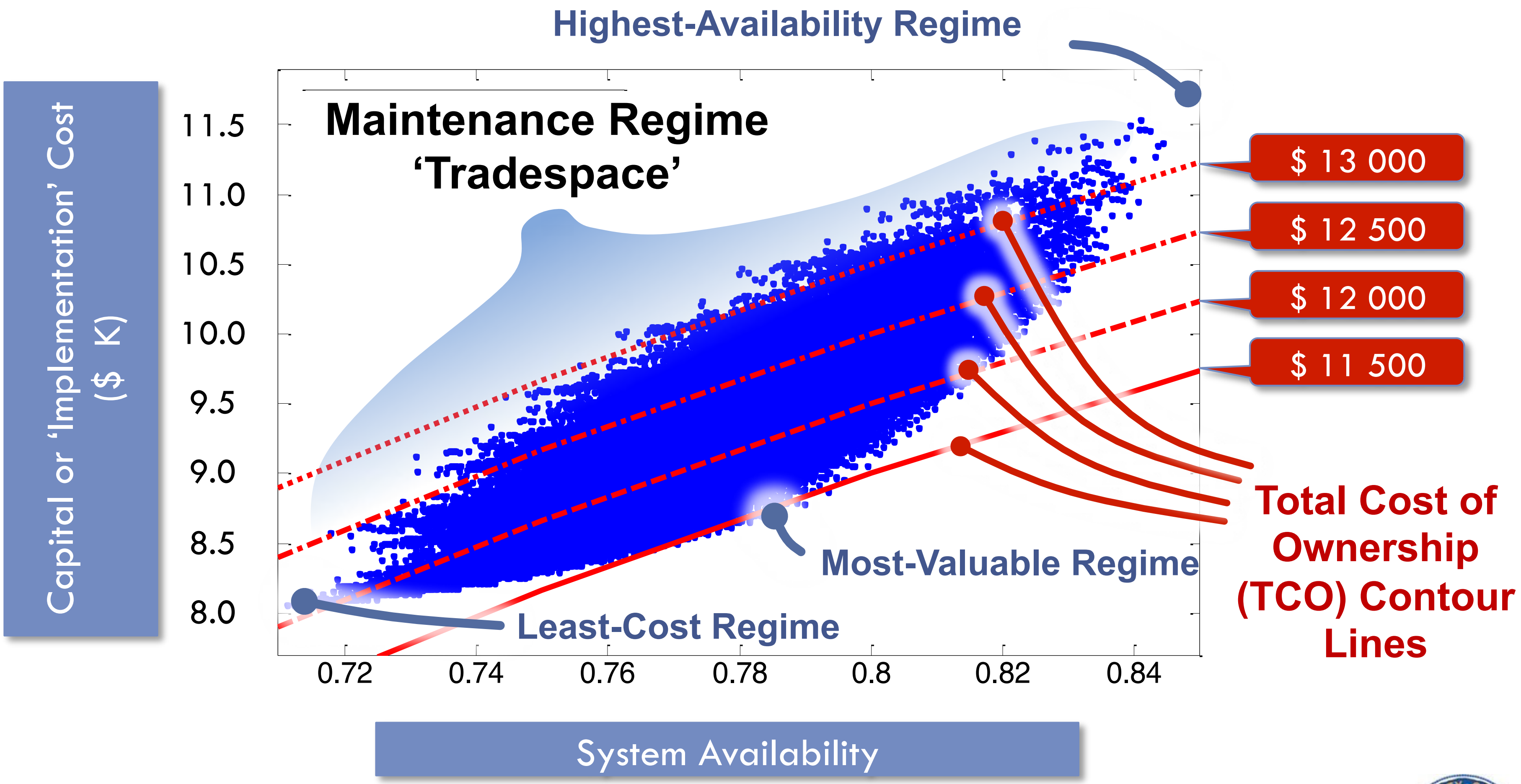
Employees

- Inconvenience (Poor work environment)
- Undesirable work hours
- Loss of Employment
- Bodily Harm

Capability:
Dynamic Maintenance and Inspection Optimization

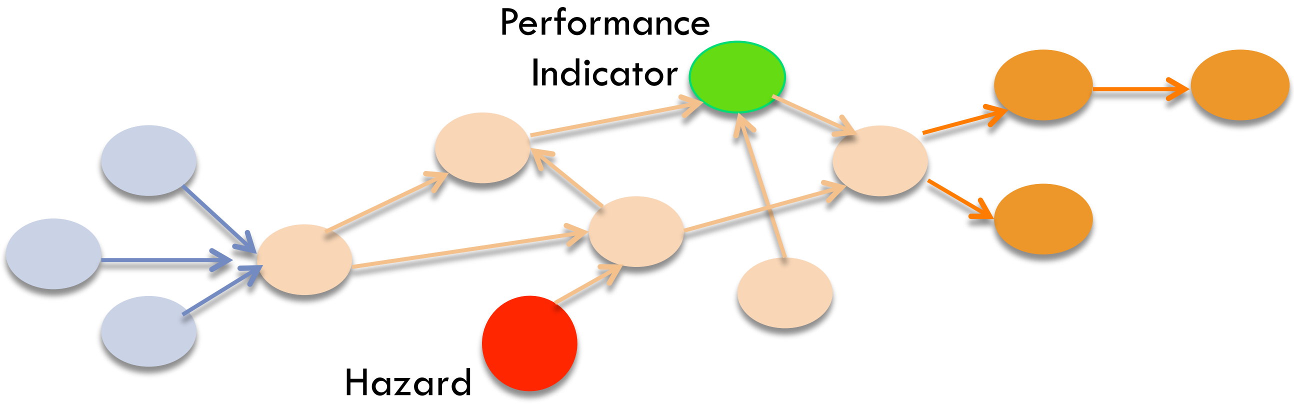
- Use of advanced multi-objective optimization techniques to find optimum
  - inspection type
  - maintenance action and
  - next inspection time
- Minimizing
  - pipeline failure rate
  - total cost over a finite planning horizon

Capability:
Dynamic Maintenance and Inspection Optimization

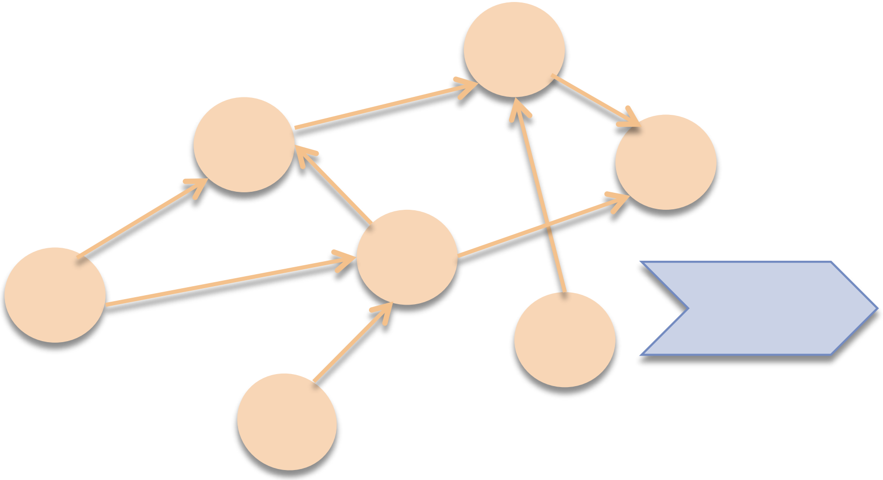


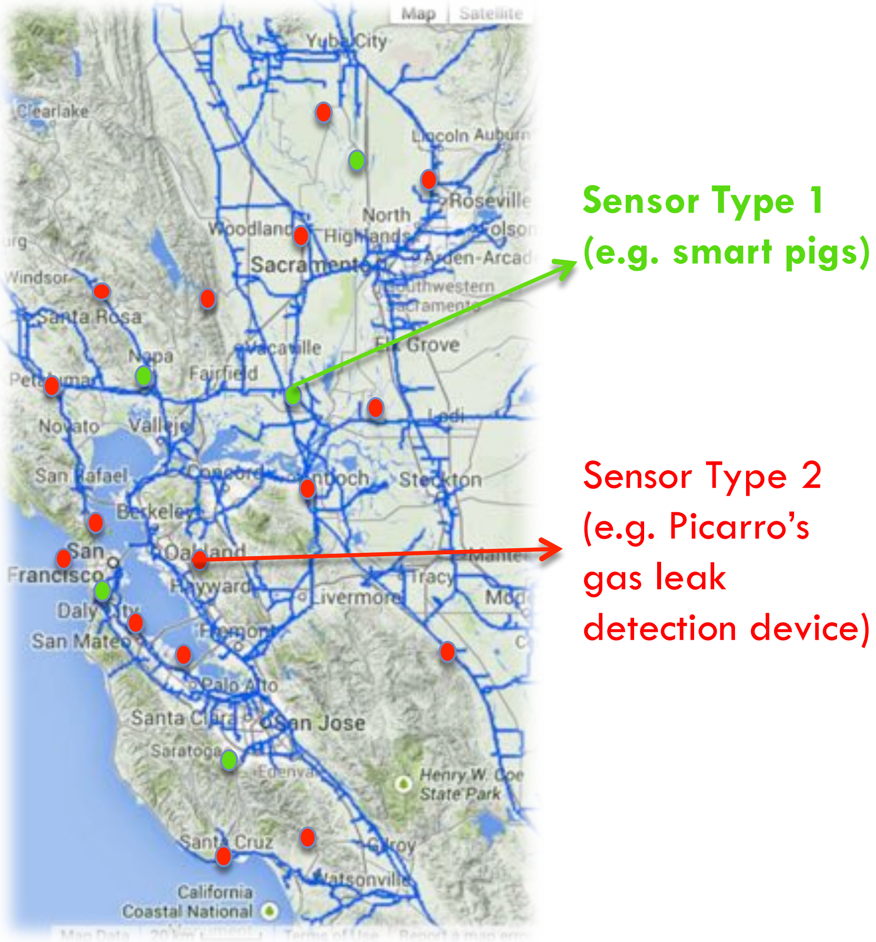
A Single Platform for Diverse Applications

- ☐ **Analysis of Hazards and Precursors**
  - Identification and ranking
- ☐ **Accident/Incident Analysis**
  - Identification of root causes
- ☐ **Identification and Quantification of Safety Indicators**
  - Calculation of conditional risk for various safety indicators



Capability:
Sensor Placement Optimization

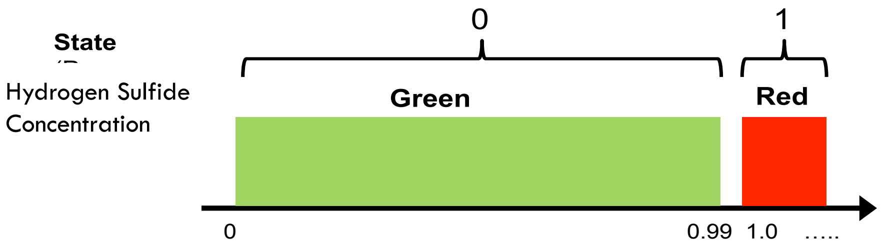


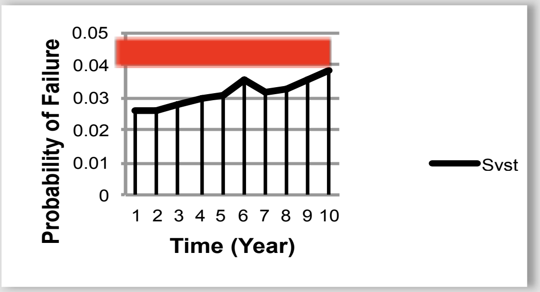


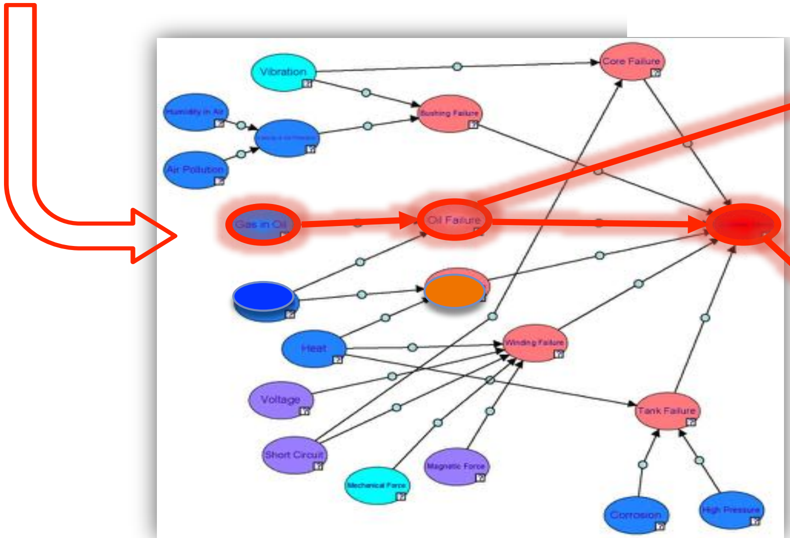
- Selecting the types and locations of sensing and monitoring instruments (e.g. Smart pigs, Picarro's gas leak detection device).
- Done by minimizing the number of sensors (and cost) and maximizing the amount of information on pipeline system condition.

System-Wide Prognostic and Health Monitoring (PHM)

BN as Underlying Model Engine





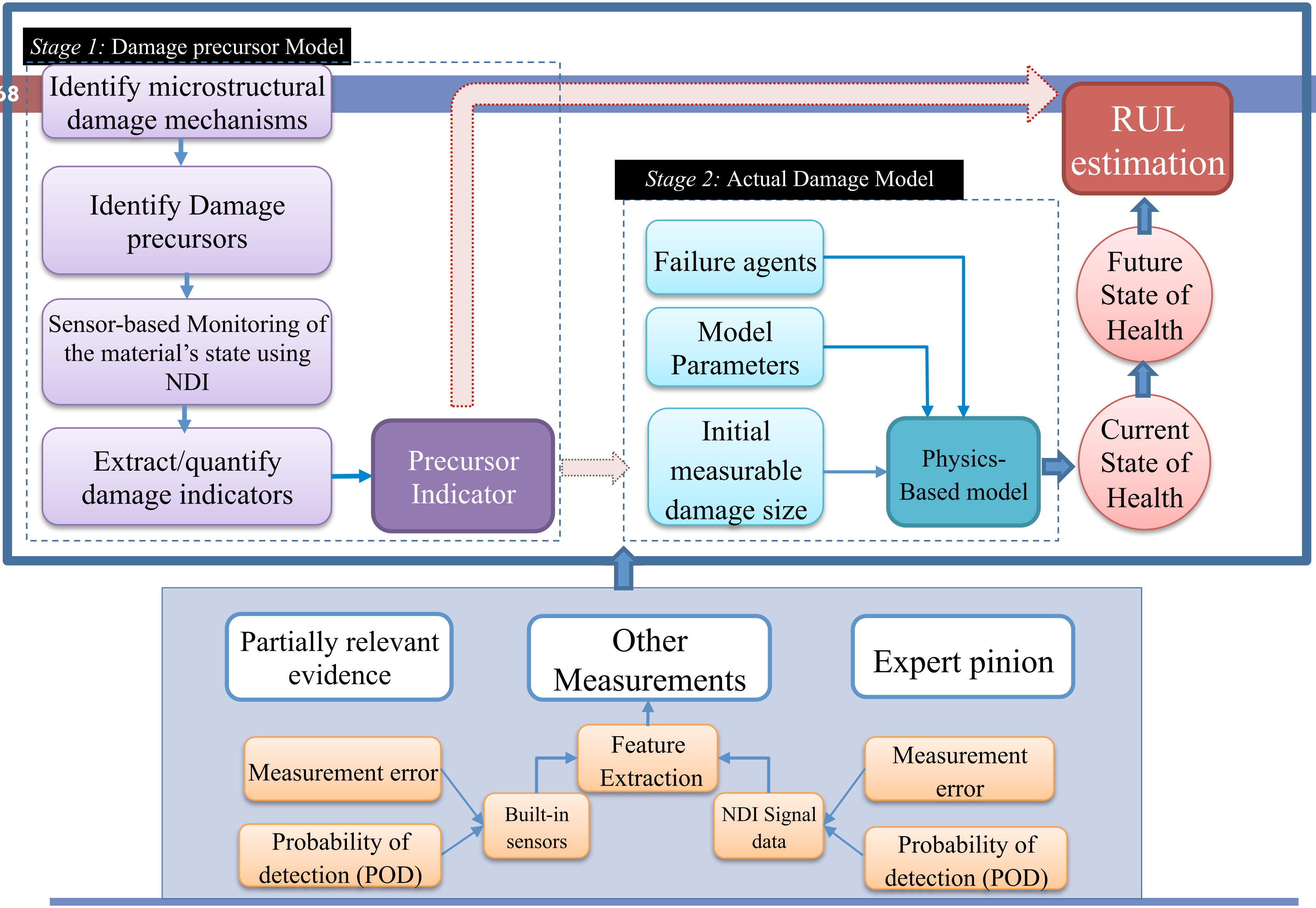


Hydrogen Sulfide	Corrosion Rate
1	%5.08
0	%0.07

Hydrogen Sulfide	Prob. of System Failure
1	%3.16
0	%2.66

Dynamic Bayesian Network

“Damage Precursor” SHM Approach



Stage 1: Damage precursor Model

Identify microstructural damage mechanisms

Identify Damage precursors

Sensor-based Monitoring of the material’s state using NDI

Extract/quantify damage indicators

Precursor Indicator

Stage 2: Actual Damage Model

Failure agents

Model Parameters

Initial measurable damage size

Physics-Based model

RUL estimation

Future State of Health

Current State of Health

Partially relevant evidence

Other Measurements

Expert pinion

Measurement error

Probability of detection (POD)

Built-in sensors

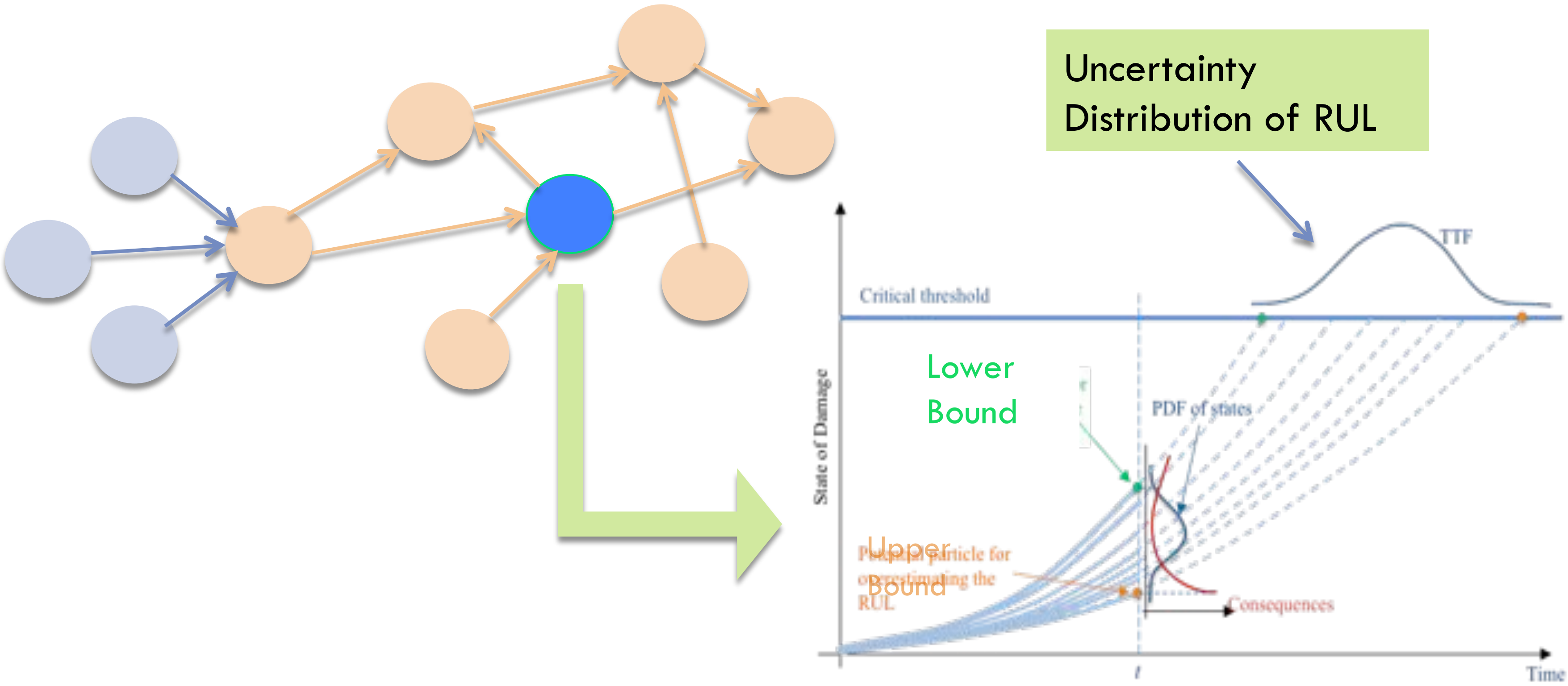
Feature Extraction

NDI Signal data

Measurement error

Probability of detection (POD)

Remaining Useful Life (RUL) Prediction

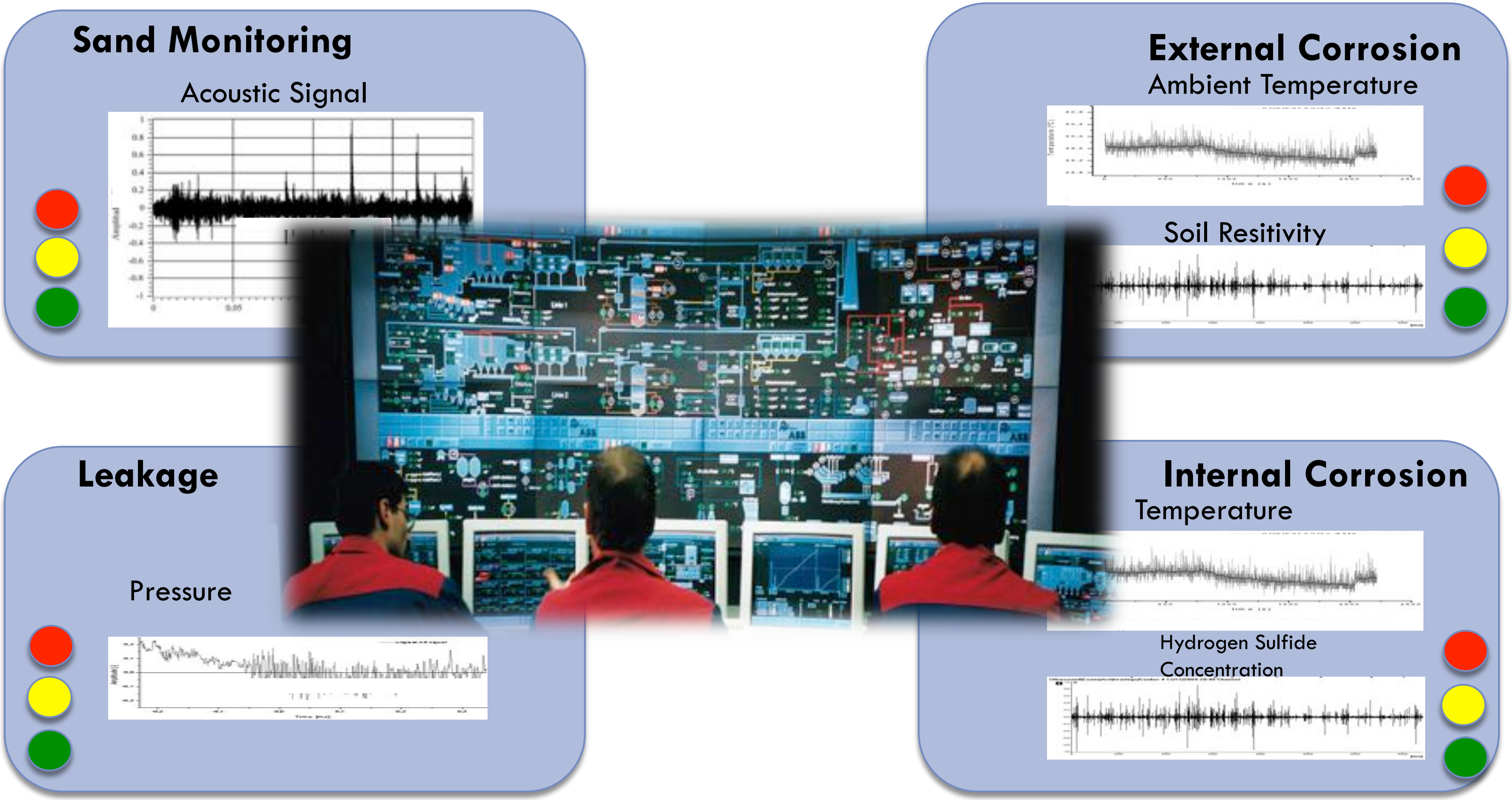


Uncertainty Distribution of RUL

Lower Bound

Upper Bound

Risk-based Dynamic Integrity Management System



Sand Monitoring

Acoustic Signal

External Corrosion

Ambient Temperature

Soil Resitivity

Leakage

Pressure

Internal Corrosion

Temperature

Hydrogen Sulfide Concentration

A Few Observations

A Numerical History of Risk Analysis

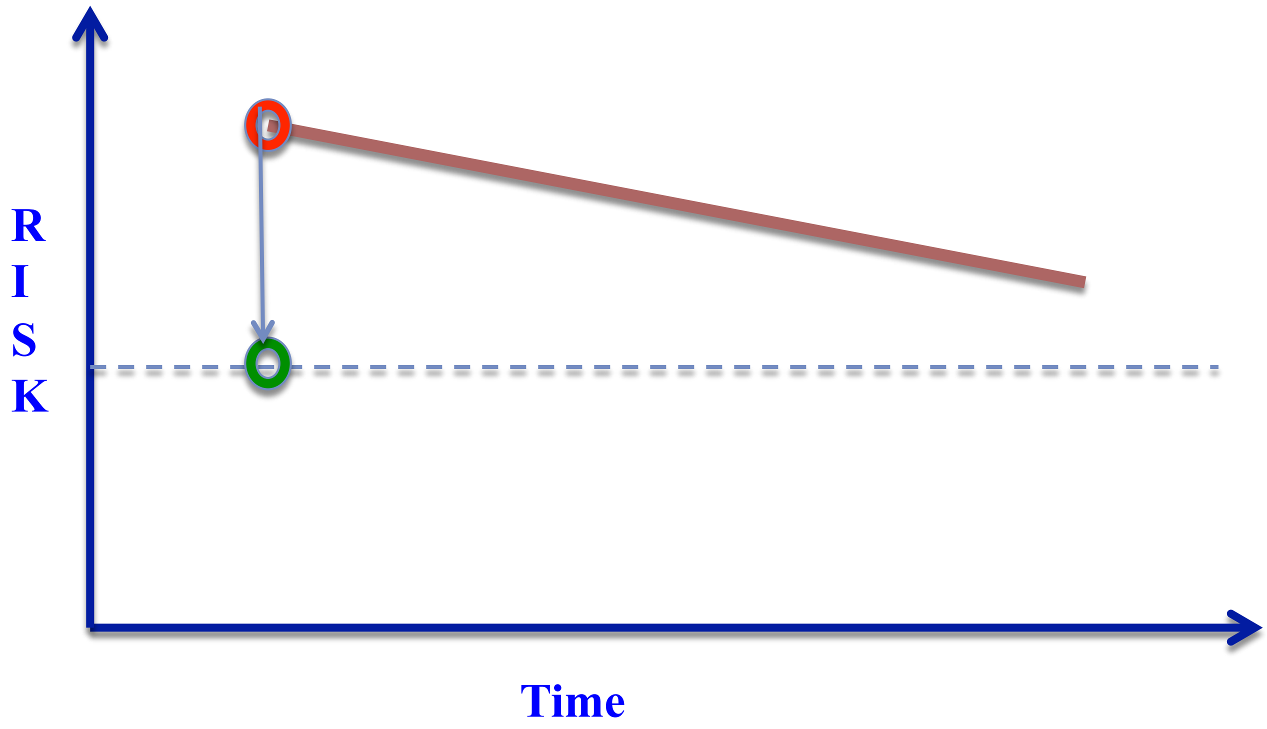
Nuclear Power Risk:

- Generic Estimate of Core Damage Frequency by WASH-1400
  - 5×10^{-5} to 5×10^{-4}
- Experience (10,000 RY)
  - $5/10{,}000 = 5 \times 10^{-4}$
- An Earlier attempt using inferior methodology:
  - 10^{-30}

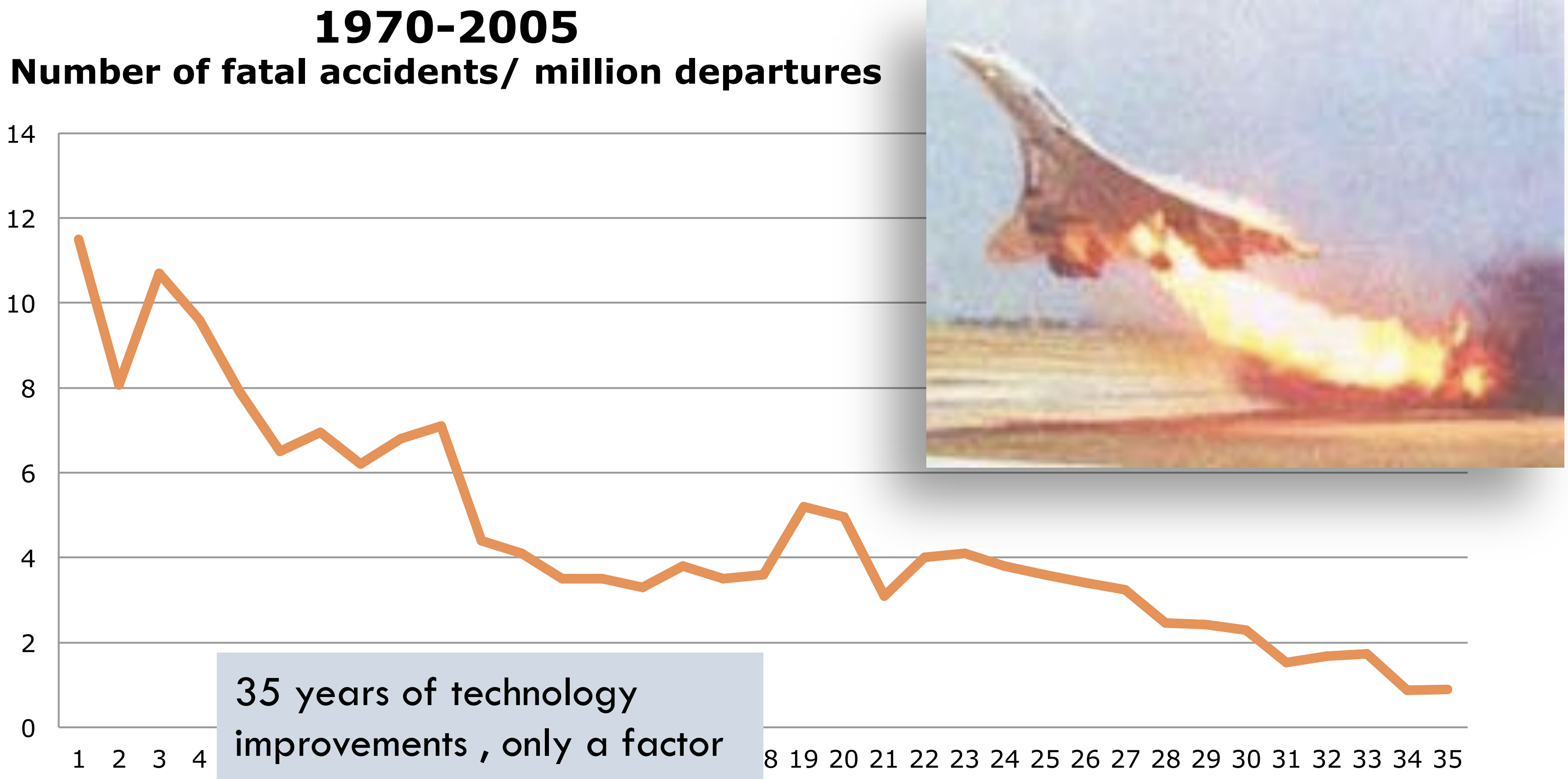
Space Shuttle Risk:

- Several PRA estimates:
  - 1/90 per mission
  - 1/112 per mission
- Experience
  - 2/134
- Earlier attempts using "rule of thumb"
  - 1/100,000

Numbers Move Faster Than Reality



Aviation Accident Rates



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

Non-Technical Challenges of Reliability, Risk, and Safety Management

- Latent or invisible impact
  - Lack of generally accepted metrics of performance, ROI
- Cultural and organizational barriers
  - “Make it first then worry about how it might fail”
  - “Tell me something I don’t know”
  - Use of probability, soft input, expert opinion
  - Not integrated with design and operational activities
  - Seen as “confirmatory analysis”
  - Short term perspective
  - Complacency with success

Other Barriers

- 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

Better and More Relevant Methods and Tools Can Help

- Improved realism, quality, and credibility
- Solve real problems, not highly abstracted or imaginary ones
- Enable easier, less resource-intensive analysis
- More timely input to design and operational decisions
- Integrative, interdisciplinary approach, covering all key dimensions at proper level

Thank You !