Resilience and Sustainability of Infrastructure Assets through Risk-Based Adaptive Incremental Revolution

Presented at the

International Workshop on Performance-based Infrastructure Asset Management

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Questions

- **Why do we need *Incremental Adaptive Revolution?***
- **What are the challenges?**
- **Why do we need systems engineering and risk modeling, assessment, and management?**
- **What research is needed?**

My Message

To manage emergent forced changes and to ensure resilience and sustainability of infrastructure assets,

we need to develop theory and methodology that integrate scientific, technical, socioeconomic, and normative dimensions in an encompassing business case for infrastructure maintenance and maintainability.

Structure of the Presentation

The need for sustainable and resilient infrastructure assets in the face of **emergent uncertain forced changes** and thus for an **adaptive incremental revolution** to:

a. **move from probability and reliability to risk-based planning**, design and construction of infrastructure systems

b. **adapt a culture of "six-sigma" quality** throughout the **lifecycle of infrastructures** and across the organization

c. **Embrace systems engineering and risk-informative decisionmaking** in infrastructure and asset management

d. **Identify research needs** for an **integrated** management of the complex **interdependent system of systems** of infrastructure assets

From Sustainable Development…to

"We know that we cannot continue to damage our life-support systems without eventually paying a price, but how will we be affected? What will be the price? Is it likely to be a build up of carcinogens in the environment so severe it increases the incidence of cancer, dramatically raising death rates? Or will the rising concentration of greenhouse gases make some regions of the planet so hot that they become uninhabitable, forcing massive human migration? Or will it be something we cannot even anticipate yet?"

State of the World: A Worldwatch Institute Report on Progress Toward a Sustainable Society [L. R. Brown et al. 1990, W. W. North, New York]

Sustainable Infrastructure Assets

"We know that we cannot continue to damage our life-support systems without eventually paying a price, but how will we be affected? What will be the price? Is it likely that our vital critical infrastructure assets (water supply and treatment plants, bridges, levees, railroads, etc.) keep deteriorating to dramatically raising death rates? Or will the rising sea-level makes some regions of the planet so hot that they become uninhabitable, forcing massive human migration? Or will it be something we cannot even anticipate yet?"

Modified: ***State of the World: A Worldwatch Institute Report on Progress Toward a Sustainable Society*** [L. R. Brown et al. 1990, W. W. North, New York]

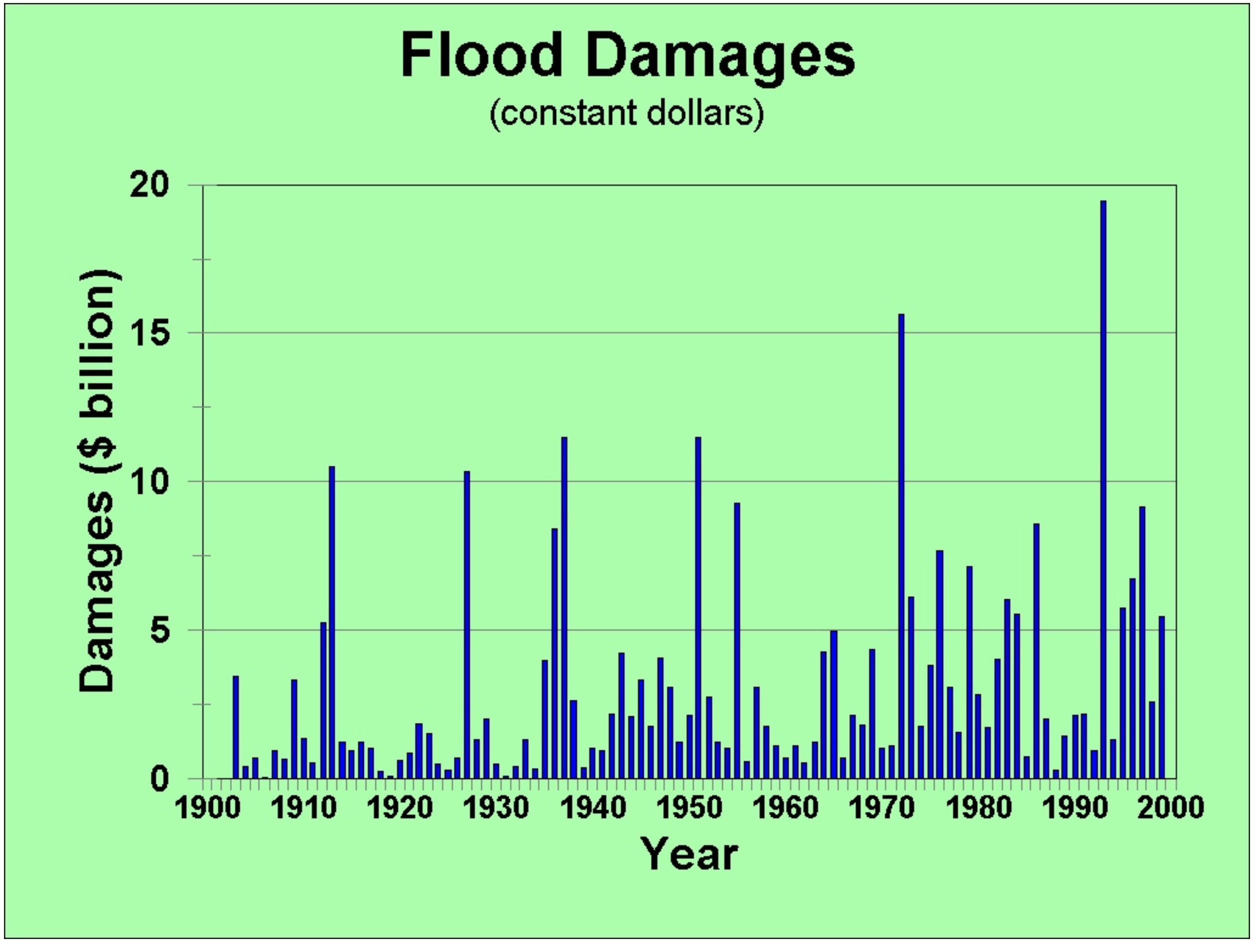
An Example of Anticipated Forced Changes: Impacts of Climate Variability

Increased storm intensity may lead to increased **service disruption and infrastructure damage over the next 50-100 years**

"**64 percent of Interstates, 57 percent of arterials, almost half of the rail miles, 29 airports, and virtually all of the ports are below 7 m (23 feet)** in elevation and subject to flooding and possible damage due to hurricane surge"

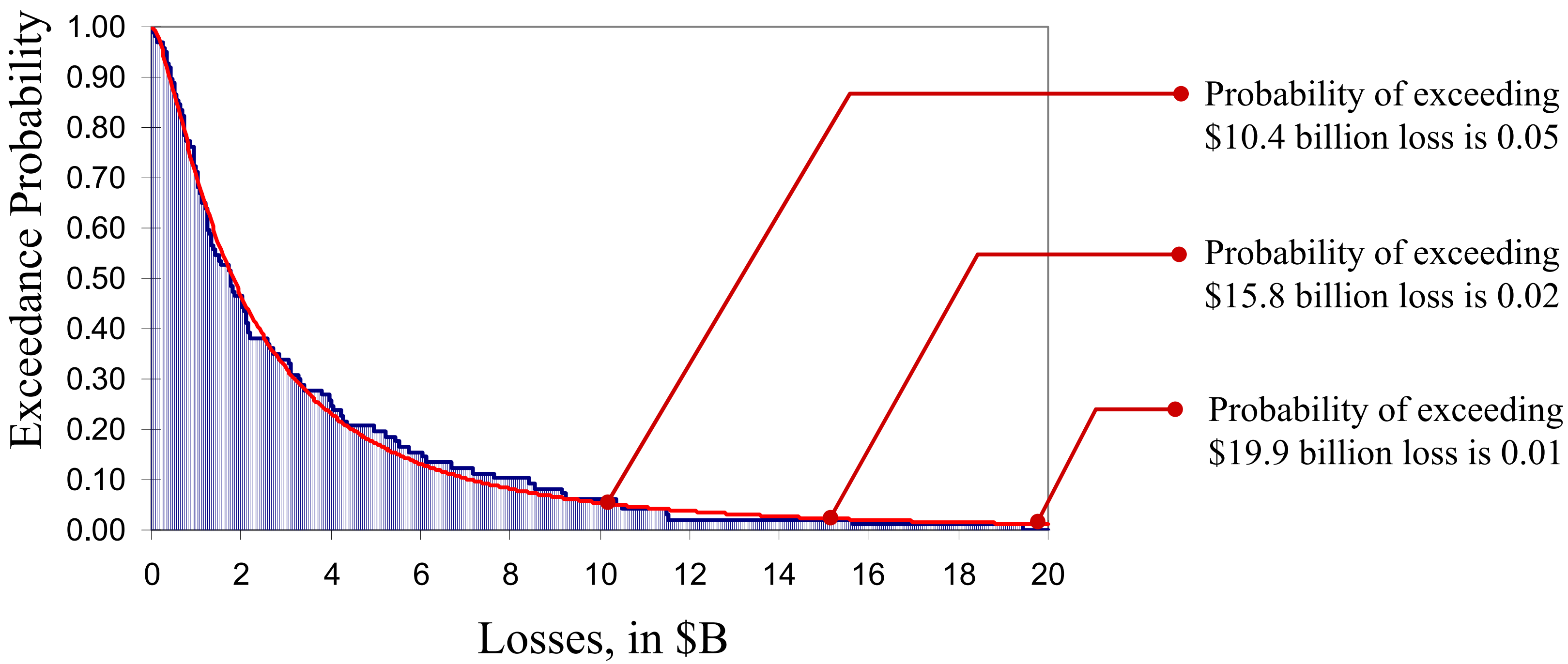
USDOT 2008

Historical Economic Losses Due to Flooding
[National Oceanic and Atmospheric Administration (NOAA)]



Source: http://www.nws.noaa.gov/oh/hic/flood_stats/flood_trends.JPG

Incremental adaptive revolution in the maintenance of infrastructure assets can protect against risks of extreme losses



Probability of Exceedance of Economic Losses Due to Flood

Fragile Foundations: A Report on America's public Works. February 1988

Report Card on the Nation's Public Works

Highways	C+
Mass Transit	C-
Aviation	B-
Water Resources	B
Water Supply	B-
Wastewater	C
Solid Waste	C-
Hazardous Waste	D

ASCE progress report 2003

Revisiting the Report Card of the Nation's Public Works

Roads	D+
Bridges	C
Transit	C-
Aviation	D
Schools	D-
Drinking Water	D
Wastewater	D
Dams	D
Solid Waste	C+
Hazardous Waste	D+
Navigable Waterways	D+
Energy	D+

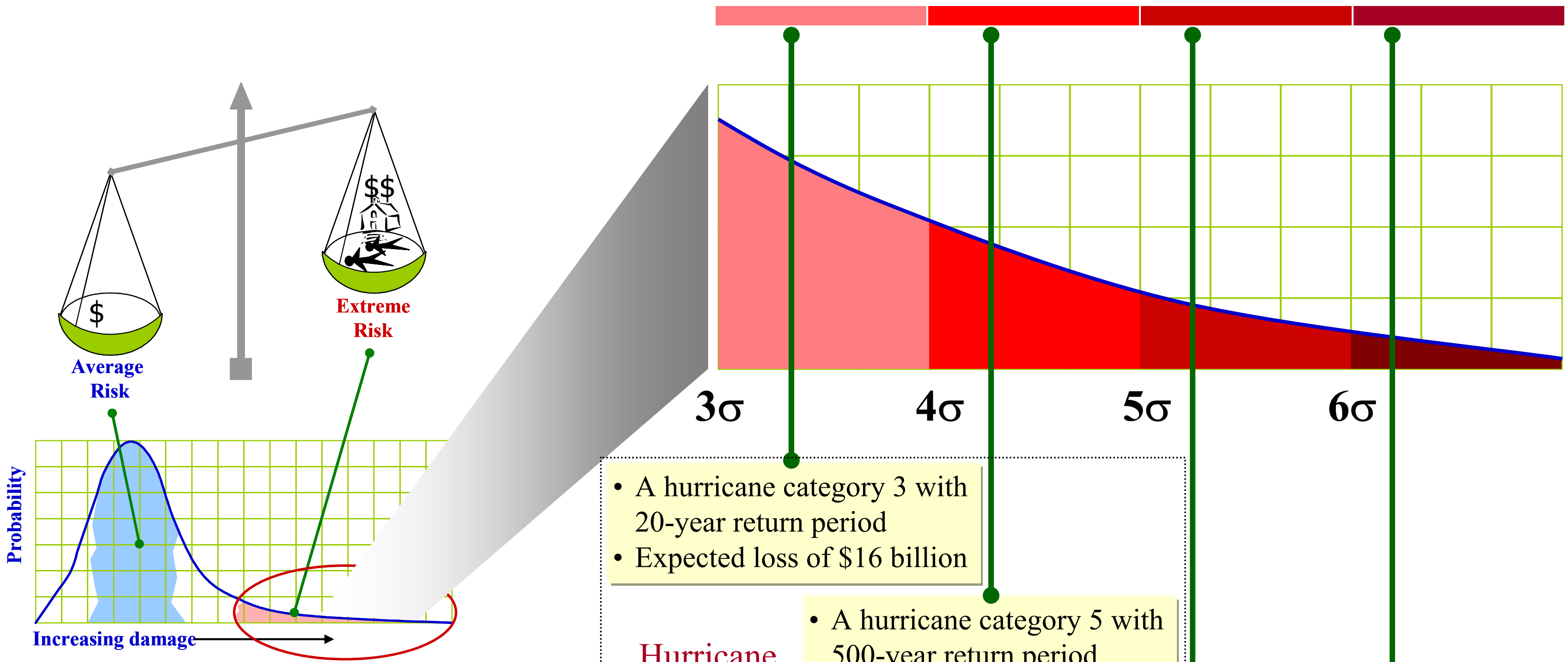
How would the previous graphs and reports look, given the anticipated forced changes (including emergent climate change)?

What new advances in systems theory, modeling, and risk analysis do we need to develop to manage these forced changes and ensure resilience and sustainability of infrastructure assets?

We need better models and decision tools to:

- Prioritize Infrastructure Maintenance
- Budget and allocate financial resources
- Measure progress on the need for change
- Integrate databases from several potentially disparate sources
- Educate a new cadre of engineering professionals who understand the complexity and interdependency of infrastructure asset management
- Communicate the above needs with all stakeholders

The need for unified metrics for maintenance



Hurricane

- A hurricane category 3 with 20-year return period
- Expected loss of $16 billion

- A hurricane category 5 with 500-year return period
- Expected loss of $48 billion

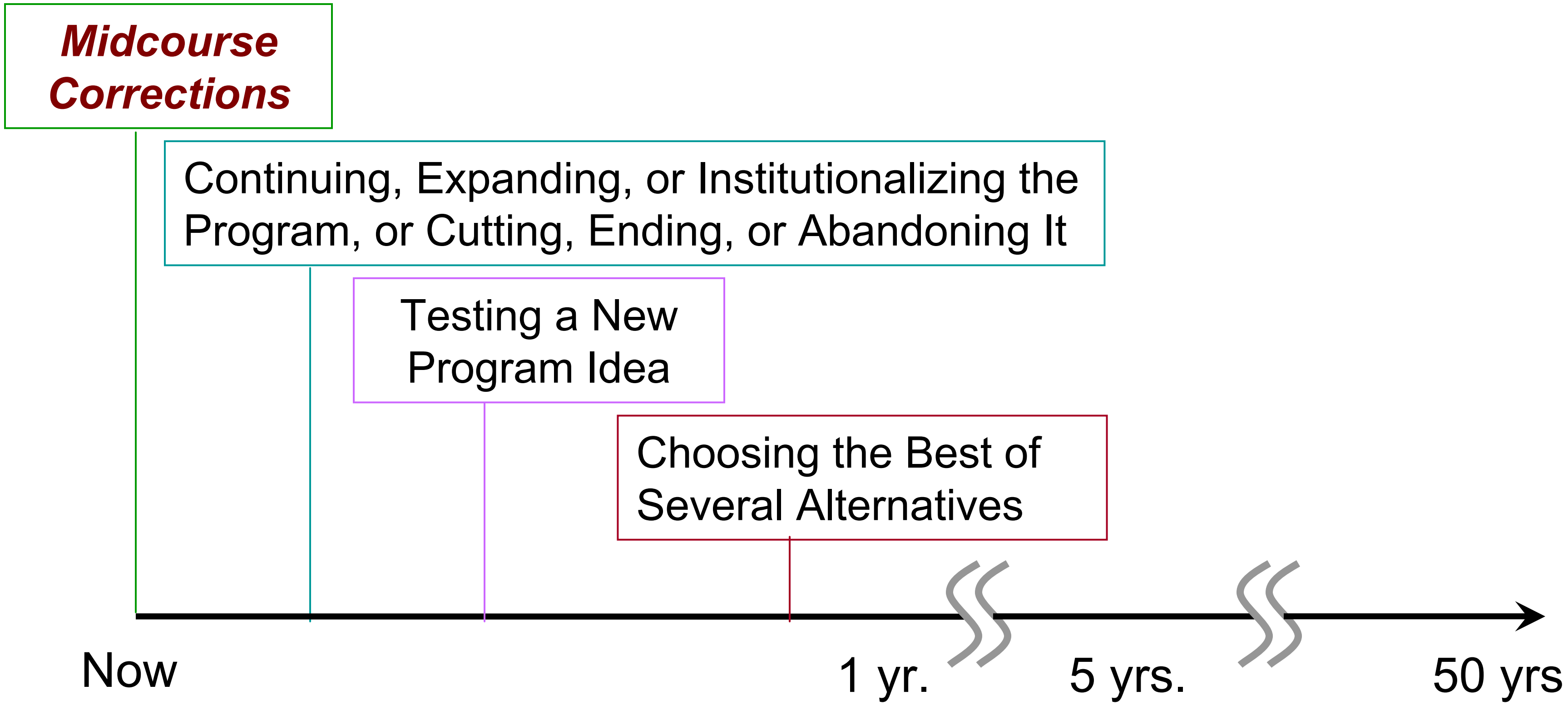
Flood

- PMF of 1 in 10^4 years
- Expected loss of $24 billion

- PMF of 1 in 10^6 years
- Expected loss of $28 billion

Relating Extreme Events and Six Sigma

What Do We Mean by Adaptive Incremental Revolution?
It is a mind-set cultural philosophy



* Adapted from Carol H. Weiss, *Evaluation*, 1998, Prentice Hall Inc.

Educational Dimension of Resilience and Sustainability of Infrastructure Assets

Versatile, knowledgeable, well-informed, and well-trained cadre of **professionals with technical capability** are essential to **maintain sustainable operation** of critical infrastructure assets.

This **knowledge must transcend the entire life cycle** of an infrastructure system, from planning, design, construction, operation, maintenance, and replacement.

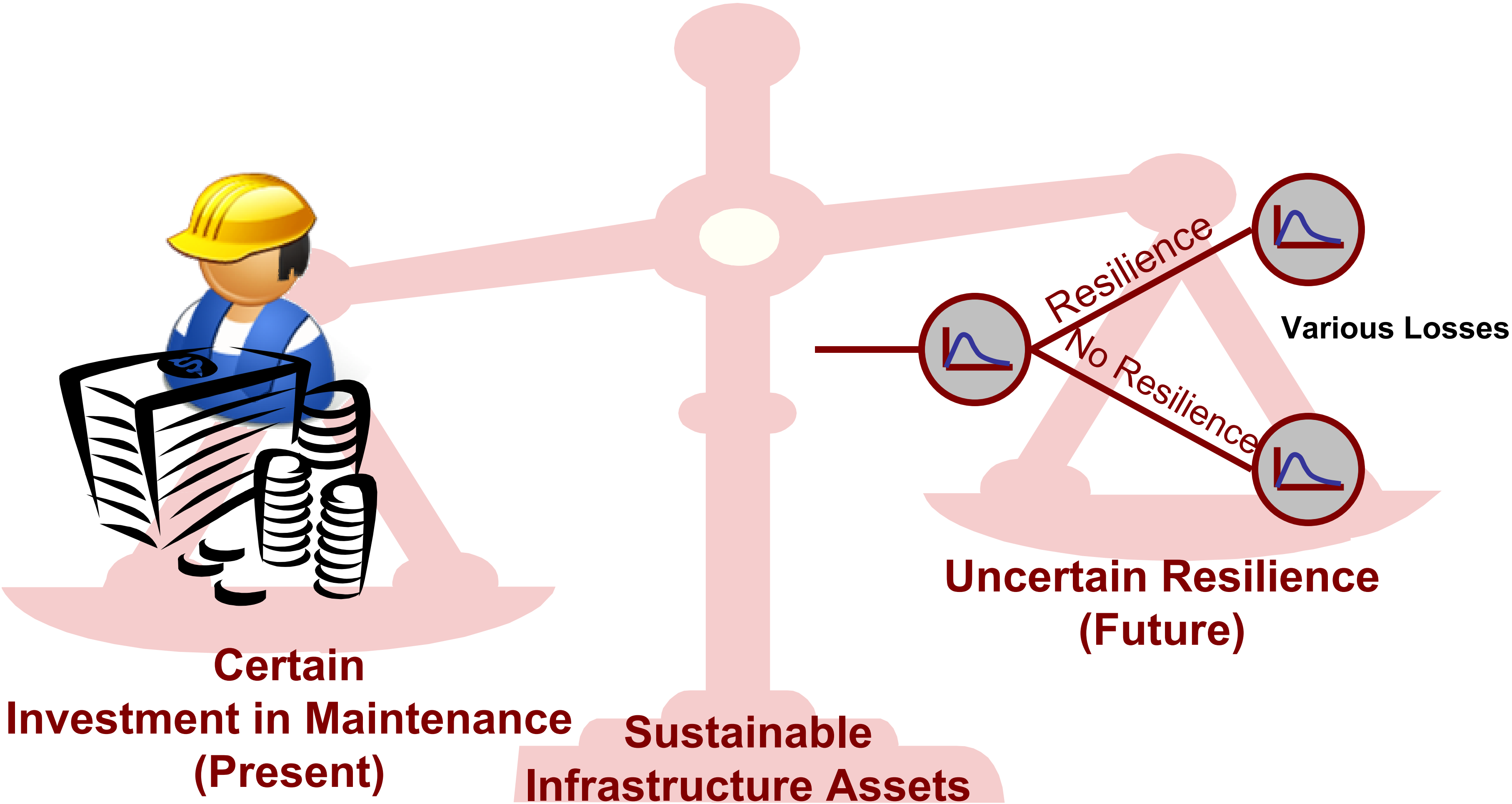
Systems engineering and risk-informative decisionmaking are requisites for adaptive incremental revolution in infrastructure asset management

Strategic Infrastructure Asset Management

- **Strategic infrastructure asset management** (in this talk) refers to a **sustainable state** that builds on **maintenance and resilience** that results from **decisions and associated actions** implemented during the **entire lifecycle** of infrastructure assets, aimed at **reducing likelihoods of failures and consequences** to an acceptable level (in terms of response/recovery time and cost).

- **Adaptive incremental revolution** requires the: Development of **decision support methodologies** and tools to support the sustainability of physical infrastructure assets

Harmonizing Maintenance with Strategic Resilience for Sustainable Infrastructure Assets



RISK

A Measure of the *Probability* and *Severity* of Adverse Effects

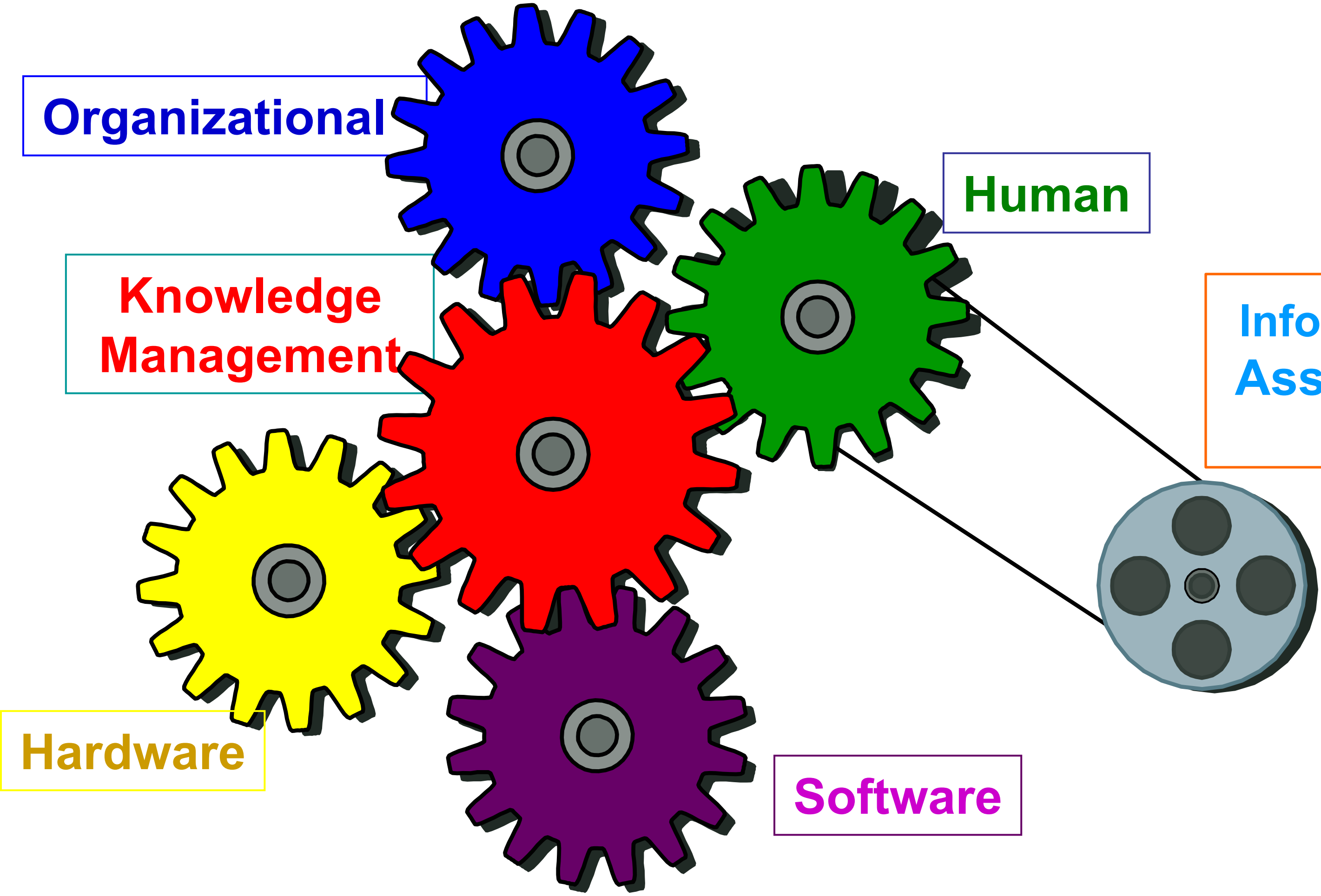
William W. Lowrance, 1976

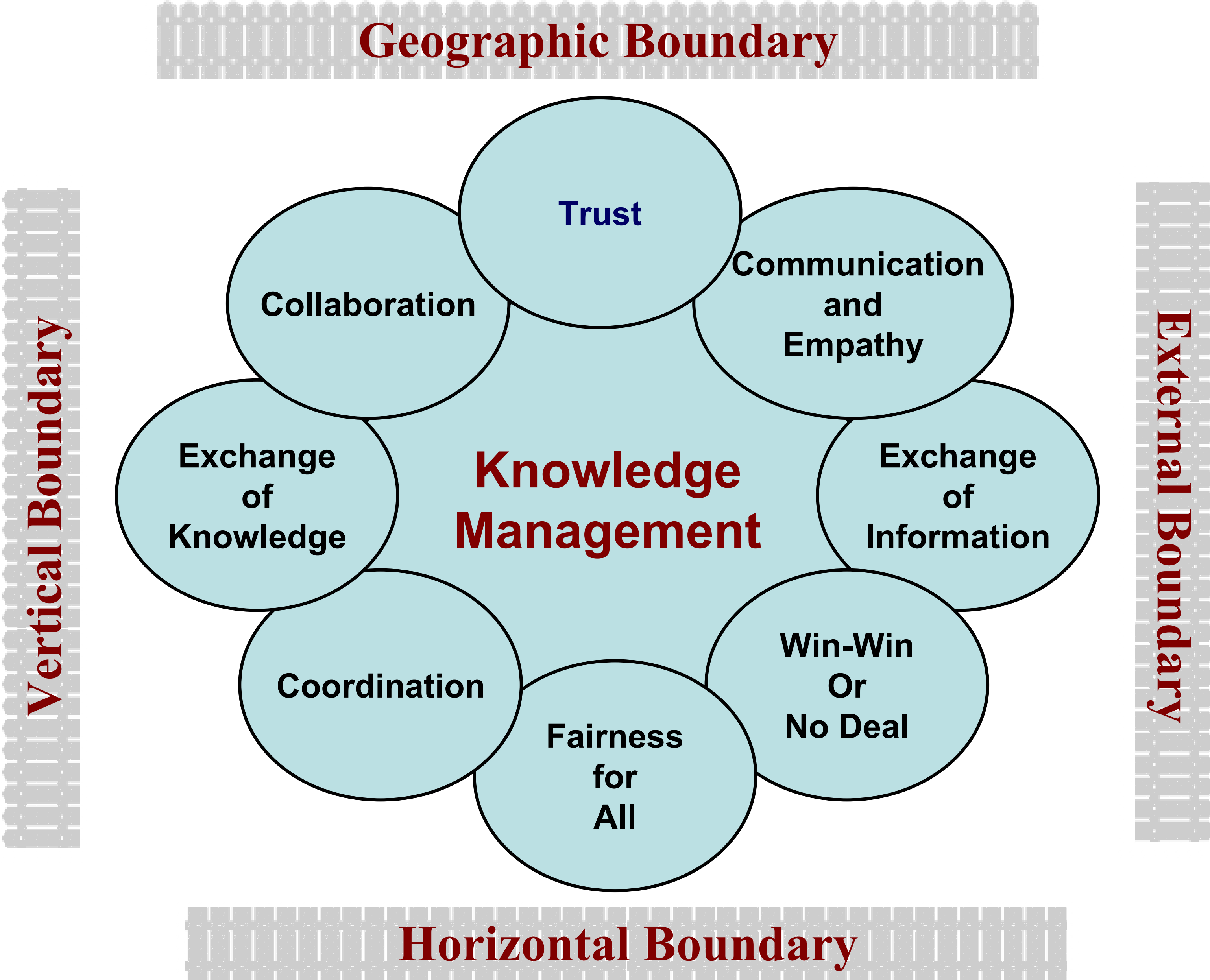
SAFETY

The level of [residual] risk that is deemed acceptable

William W. Lowrance, 1976

The Process of Risk Assessment, Management, and Communication




Geographic Boundary
Vertical Boundary
External Boundary
Trust
Collaboration
Communication and Empathy
Exchange of Knowledge
Knowledge Management
Exchange of Information
Coordination
Win-Win Or No Deal
Fairness for All
Horizontal Boundary

Four Detrimental Boundaries to Knowledge Management

- **Vertical boundaries** represent layers within an organization
- **Horizontal boundaries** exist between organizational functions, product lines, or units.
- **External boundaries** are barriers between organizations and the outside world
- **Geographic, or global, boundaries** exist when complexly structured organizations operate in different "markets" and countries.

Adapted from
The Boundaryless Organization: Breaking the Chains of Organizational Structure
by Ron Ashkenas et al., 1995

The Process of Risk Modeling, Assessment, and Management through Risk Communication

Risk Assessment

1. What can go wrong?
2. What is the likelihood that it could go wrong?
3. What are the consequences?

[Kaplan and Garrick 1981]

4. What is the time domain?

Risk Communication
(knowledge management)

Risk Communication
(knowledge management)

1. What can be done and what options are available?
2. What are the associated trade-offs in terms of all costs, benefits, and risks?
3. What are the impacts of current management decisions on future options?

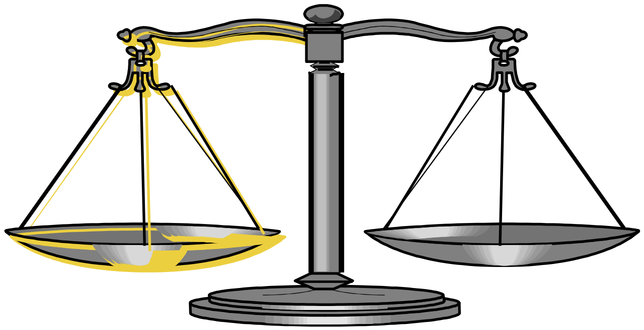
[Haimes 1991]

Risk Management

Y. Y. Haimes, *Risk Modeling, Assessment, and Management*, 2nd Edition 2004, Wiley

Risk Management

Risk Management □ Acceptable Balance



Uncertain Benefits

Uncertain Costs

Risk Management

System Management:

Human/Organization/Hardware/Software

- **Planning**
- **Design**
- **Operation**

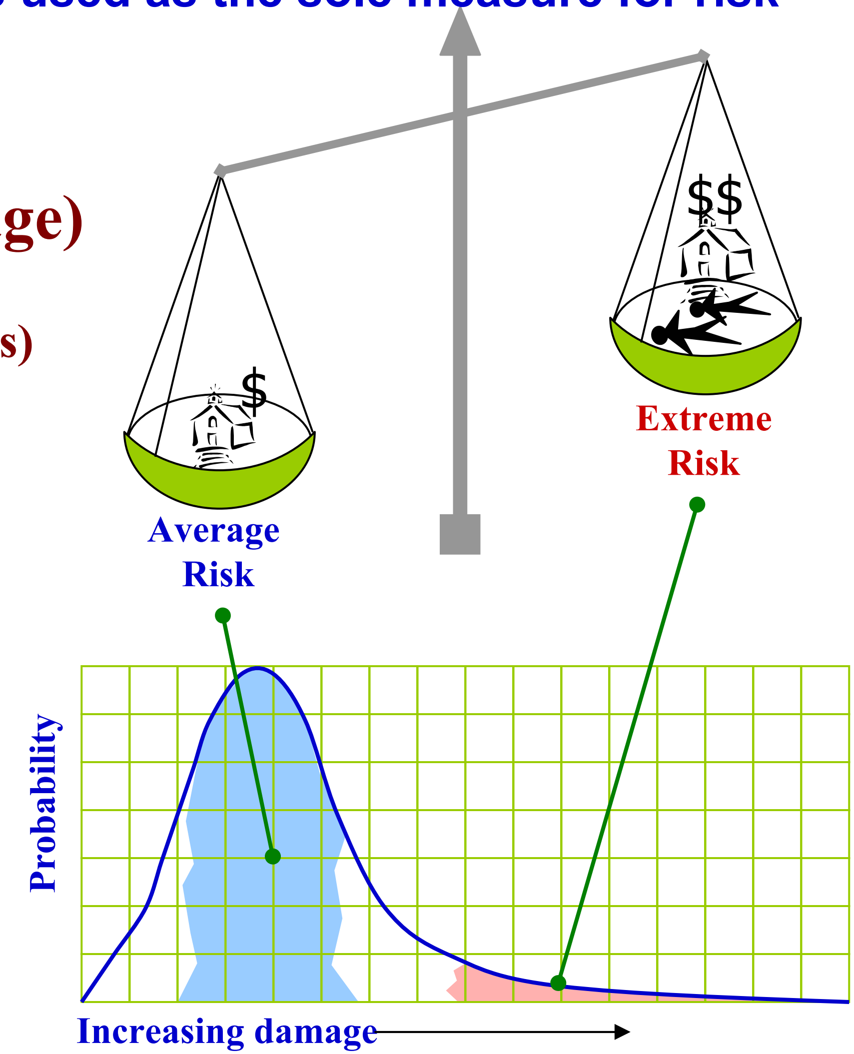
Limitation of Expected Value of Risk

and its fallacy when it is used as the sole measure for risk

Risk = *f* (Probability, Damage)

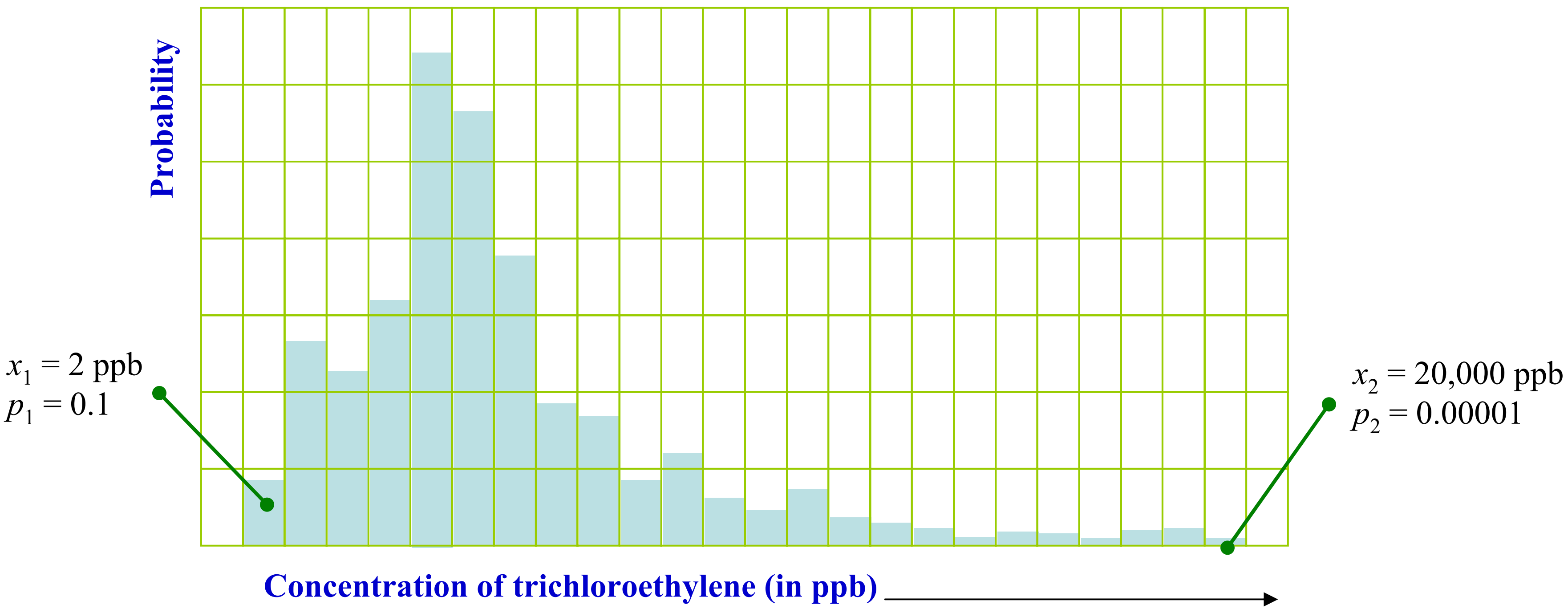
or

Risk = *f* (Likelihood, Consequences)



Limitation of Expected Value of Risk

Consider the probabilities of two particular concentrations of a groundwater contaminant



Contribution of x_1 to the expected value = $2 \cdot 0.1 = 0.2$ ppb

Contribution of x_2 to the expected value = $20{,}000 \cdot 0.00001 = 0.2$ ppb

Contributions are equal, but consequences are very different

EPILOGUE

To manage emergent forced changes and to ensure resilience and sustainability of the complex system of systems of interdependent infrastructure assets, we need to develop theory and methodology that integrate scientific, technical, socioeconomic, and normative dimensions in an encompassing business case for their maintenance and maintainability.

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