On the Centrality of the States Space in the Definition and Quantification of the Vulnerability and Resilience of and the Risk to Infrastructure Systems of Systems

Presented at the NSF Workshop

University of Illinois, Urbana-Champaign

Yacov Y. Haimes, haimes@virginia.edu

L. R. Quarles Professor of Systems and Information Engineering

and Founding Director (1987),

Center for Risk Management of Engineering Systems

University of Virginia

16 November 2011

WHY?

Why must we understand

the *fundamental*,

the *epistemological*,

the *roots,*

of what the terms:

Vulnerability, Resilience, and Risk

of a system mean?

Because

Only then would we understand

Why

infrastructure systems of systems

behave and respond to

our actions, or to the lack thereof, the way they do.

WHY?

Why must we understand the *fundamental*, the *epistemological*, the *roots* of what the terms:

Vulnerability, Resilience, and Risk

of a system mean?

Because,

Only then would we understand why infrastructure systems of systems behave and respond to our actions, or to the lack thereof, the way they do.

My Message

To highlight and explain the complexity of the epistemological definitions and quantifications of the multidimensional vulnerability and resilience of and the risk to systems of systems

Y. Y. Haimes, *Risk Modeling, Assessment, and Management*, Third Edition, Wiley & Sons, 2009.

Y. Y. Haimes, On the Complex Quantification of the Risk Function..., *Risk Analysis*, **31**(8), 1175-1186, 2011

Y. Y. Haimes, "Modeling Complex Systems of Systems with Phantom System Models," *Systems Engineering*,
15(2), 2012 (in press).

Also in *Risk Analysis Journal*
Y. Y. Haimes:
on the Definitions of Risk (2009)
on the Definitions of Resilience (2009)
on the Definitions of Vulnerability (2007)

Uniqueness of Systems-Based Approach to Decisionmaking and to Risk Analysis

(i)Philosophical holistic mind-set, avoiding dogmatic thinking;

(ii)Always questioning and asking why we are doing what we are doing?

(iii)The complex process of risk modeling, assessment, management, & communication must be holistic, comprehensive & repeatable;

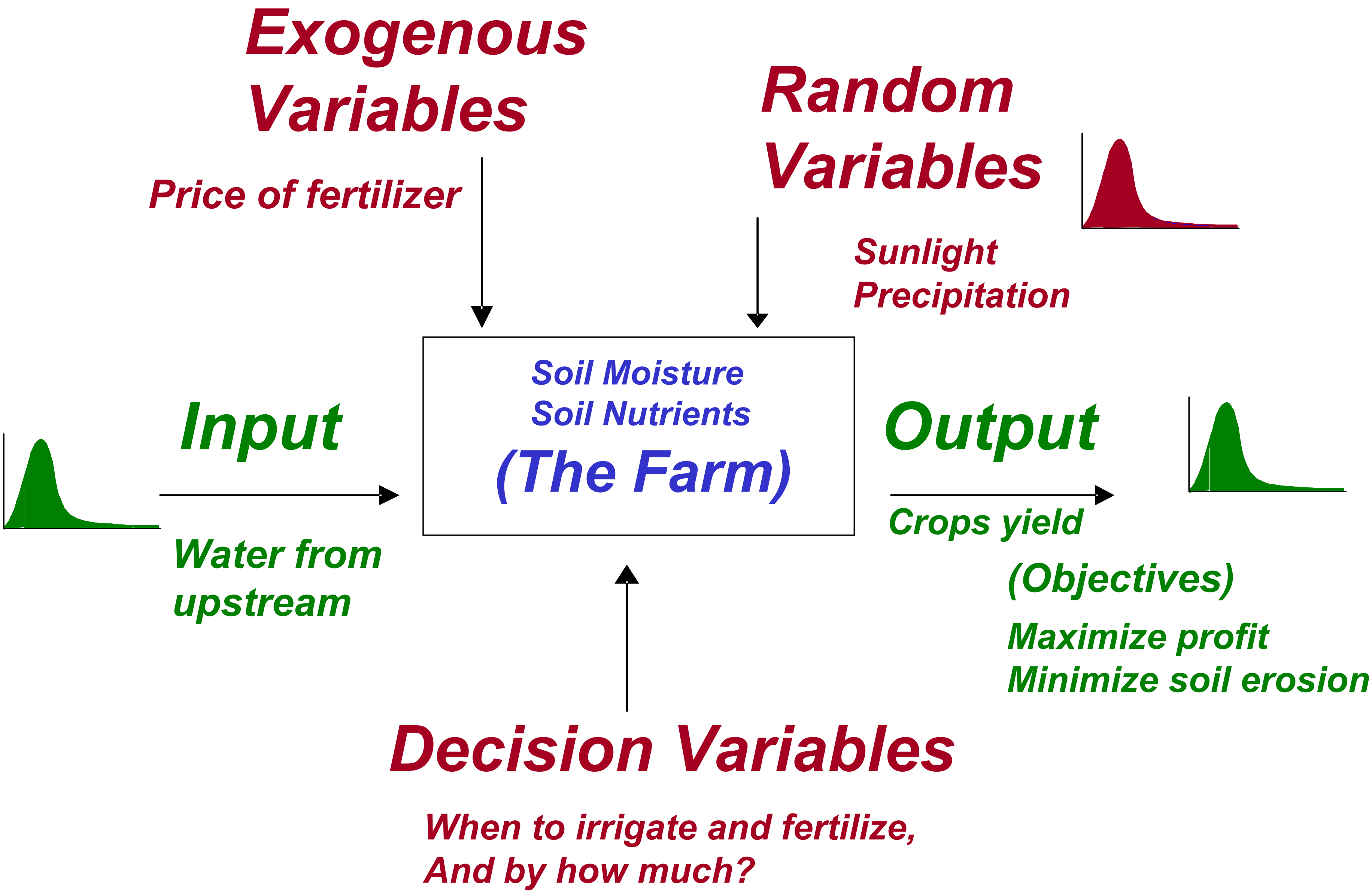
Uniqueness of Systems-Based Approach to Decisionmaking and to Risk Analysis (cont'd)

(iv) Embracing the imperative need for pluralistic multi-models to study complex systems of systems

(v) Multiple non-commensurate, conflicting, and competing, objectives characterize all systems of systems

Why do farmers irrigate their crops in non-rainy seasons?

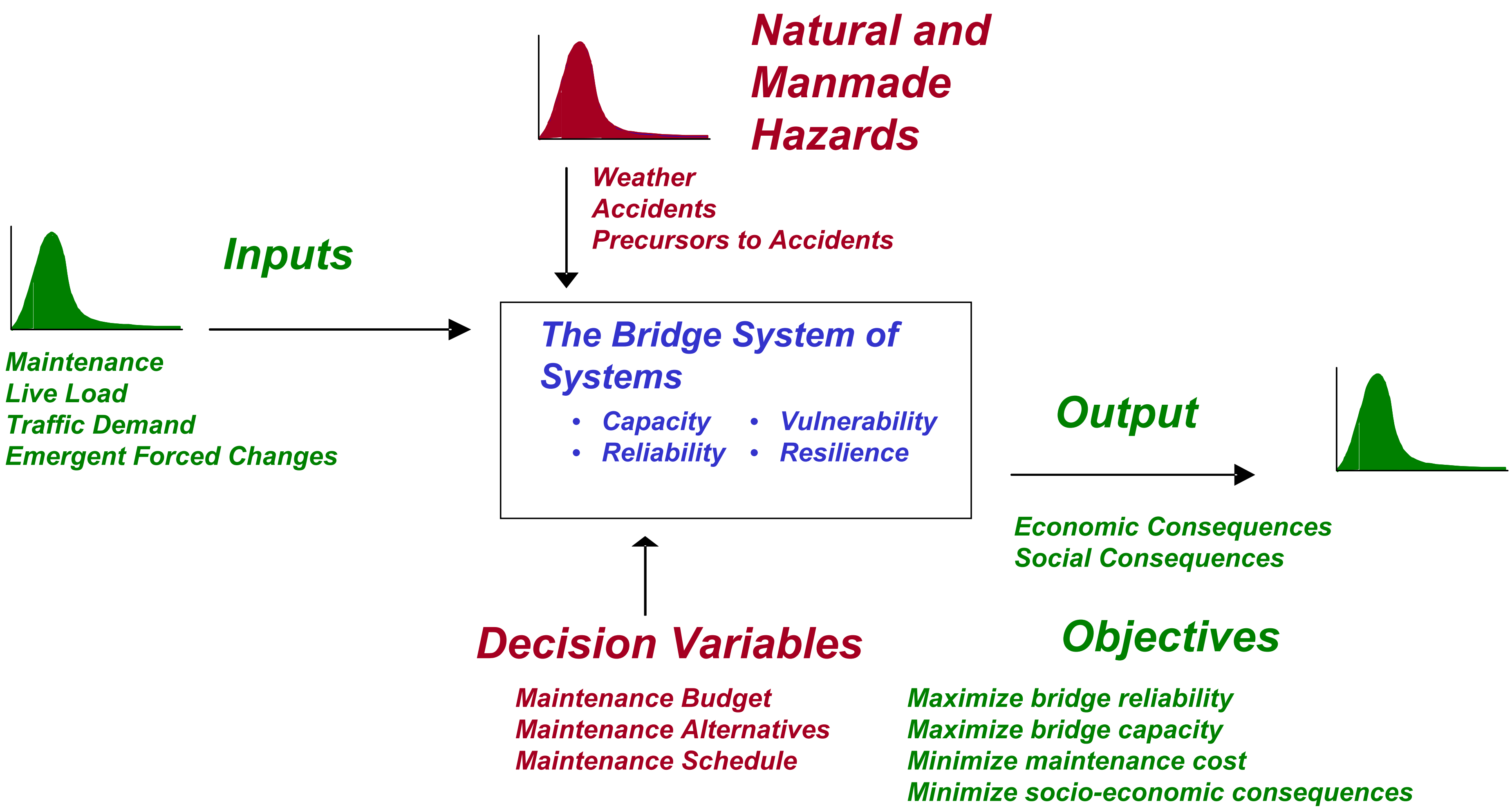
The answer is fundamental to modeling and understanding the definitions of vulnerability and resilience of, and thus the risk to, a system.


Exogenous Variables
Price of fertilizer
Random Variables
Sunlight
Precipitation
Soil Moisture
Soil Nutrients
(The Farm)
Input
Water from upstream
Output
Crops yield
(Objectives)
Maximize profit
Minimize soil erosion
Decision Variables
When to irrigate and fertilize,
And by how much?

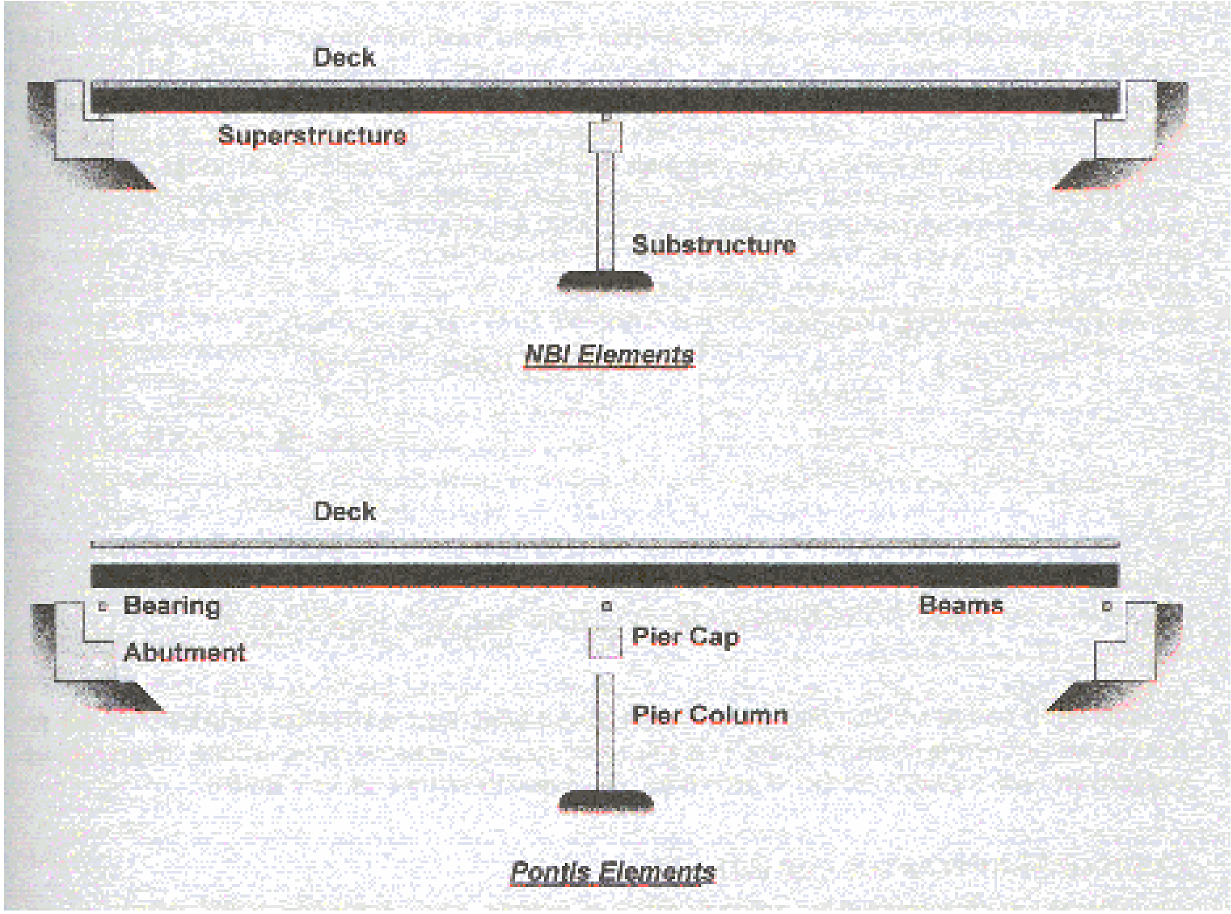
Essential States of the System

All decisions are made to control (retain or change as appropriate) the levels of the essential states of the system to meet specific desired outputs (goals and objectives)

Building Blocks of a Bridge infrastructure System



Essential States and sub-States of a Bridge Infrastructure Sub-Systems (Components)



Excerpt from Bridge Safety and Reliability (Dan M. Frangopol, 1999)

States of:

- ***Superstructure***
  - ***Beams***
  - ***Bearing***
- ***Substructure***
  - ***Pier***
  - ***Column***
  - ***Abutment***
- ***Deck***
  - ***Deck Joints***
  - ***Drainage***
  - ***Deck Appurtenances***
  - ***Signing and Lighting***

States of a System

*Given a system's model, **the states of a system are the smallest set of independent system variables** such that the values of the members of the set **at time t_0** along with known inputs, decisions, random and exogenous variables **completely determine the value of all system** variables for all*

$t \geq t_0$ (under certain conditions).

States of a System

The selection of the appropriate number of state variables to represent the essence of the multiple perspectives of the system is among the most challenging and important tasks of systems modelers.

Emergent Forced Changes

The term emergent forced changes connotes:

external or internal sources of risk to a system that may adversely affect or enhance specific states of that system, and consequently, affect the system as a whole.

Emergent Forced Changes

Government agencies, the military, the private sector, and major corporations—all seek to understand the trends of risks associated with forced changes that affect the states of their systems, in order to prevent, mitigate, or prepare for undesirable future occurrences.

Emergent Forced Changes

Unanticipated, undetected, misunderstood or ignored emergent forced changes, whether they originate from within or from outside a system, are likely to affect a multitude of states of that system with potentially adverse consequences.

Therefore, it is imperative to be able--through scenario structuring, modeling and risk analysis--to envision, discover, and track emergent forced changes.

Precursors to Emergent Forced Changes, the Time Frame, Measurements, and Data Collection

Prudent risk management calls for a continuous process of measuring the performance of a system, assessing whether observed changes are sufficiently significant, design a data-collection mechanism, and developing metrics with which to measure performance—all are requisites for effective risk modeling, assessment, management, and communication

What is Vulnerability?

Vulnerability is the manifestation of the inherent states of the system (e.g., physical, technical, organizational, cultural) that if exploited by an adversary, or affected by a harmful initiating event, can result in adverse consequences to that system.

The vulnerability of a system is a vector that is a function of the specific initiating event (or threat) and the time frame.

The Epistemology of Vulnerability as Manifestation of the States of the System

Knowledge of the state (vector) $x(t_0)$ of a system at time t_0 together with the input (emergent forced changes) $u(t)$, for $t \geq t_0$, determines the vulnerability $v(t, u)$ of the system for all

$t \geq t_0$.

Vulnerability: An Example

The human body is vulnerable to infectious diseases. Different organs are continuously bombarded by a variety of bacteria, viruses, and other pathogens.

***However, only a subset of the human body is vulnerable to the threats from a subset of the would-be attackers, and due to our immune system only a smaller subset of the body would experience adverse effects*.**

Vulnerability: Another Example

Consider a sample of states of an airport: (a) technological capabilities, (b) personnel quality, (c) situational awareness, and (d)congestion.

All are manifestation of the airport's vulnerability to external or internal sources of risk to the airport, and may adversely affect any or all of the above states of the system, and consequently, affect the airport system as a whole.

What is Resilience?

The resilience of a system is also a manifestation of the states of the system. It is a vector that is time and initiating-event (or threat) dependent.

Resilience represents the ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable composite cost and time.

The Epistemology of Resilience as Manifestation of the States of the System

Knowledge of the state (vector) $x(t_0)$ of a system at time t_0 together with the input (emergent forced changes) $u(t)$, for $t \geq t_0$, determines the resilience $R_e(t, u)$ of the system for all

$$t \geq t_0$$

Vulnerability and Resilience

The questions:

"What is the vulnerability of the water system in Urbana-Champaign?"

"What is the resilience of the water system in Urbana-Champaign?"

These questions are uninformative and, thus, are unanswerable.

Vulnerability and Resilience

The questions:

"What is the vulnerability of the water system in Urbana-Champaign?"

"What is the resilience of the water system in Urbana-Champaign?"

These questions are uninformative and, thus, are unanswerable.

To answer them we need to know the specific emergent forced changes (threat) and the states of the water system at time t.

In Sum:
The vulnerability and resilience of a system

both as manifestations of the states of the systems

are two sides of the same coin

This discussion leads us to the

Theory of Scenario Structuring,
and thus, to the process of
Risk Assessment, Management, and Communication

Theory of Scenario Structuring

Theory of Scenario Structuring (TSS)
[Kaplan and Garrick 1981]
and
Hierarchical Holographic Modeling (HHM)
[Haimes 1981]

Both address the multiple perspectives of a system and promote the consideration of every conceivable emergent forced change.

A joint paper streamlined the TSS and the HHM [Kaplan, Haimes, and Garrick 2001].

Theory of Scenario Structuring

Hierarchical Holographic Modeling (HHM)
[Haimes 1981, 2009]

We have deployed HHM for several projects and studies supported by the following government agencies:

President Commission on Critical Infrastructure Protection (PCCIP); FBI; Army National Ground Intelligence Center (NGIC); NASA; Department of Homeland Security; Institute for Information Infrastructure Protection (I3P); Virginia Governor's Preparedness Office; Virginia DOT.

Time Frame

- ***The fundamental premise that the states of all systems are functions of time makes the time frame pivotal in the risk assessment, management, and communication process.***
- ***The vulnerability and resilience of a system, the probability of an emergent forced change, and the probability of the resulting consequences, given the emergent forced change— all are functions of the time frame.***

The Complex Risk Function

Risk is a measure of the probability and severity of adverse effects."

William W. Lowrance, Of Acceptable Risk, 1976

Is risk a measure of:

the probability of the initiating event?

OR

the probability of the consequences?

The answer is of both

SAFETY

The level of risk that is deemed acceptable

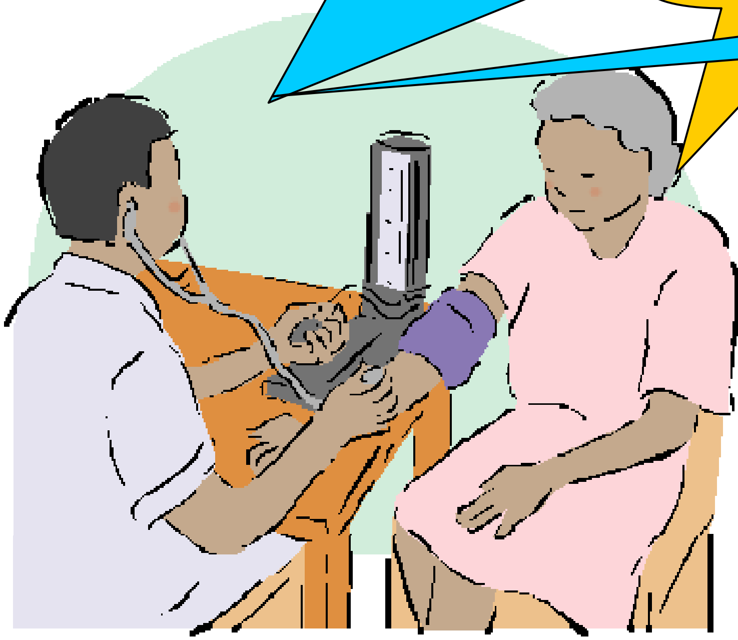
William W. Lowrance, 1976

Risk Assessment: A Physician Metaphor

Mrs. Jones, the test shows that your current blood cholesterol level and weight are much higher than the normal levels; also given that you have been smoking in the past 20 years, I believe that you are vulnerable to a heart attack.

Oh?!

So, see you next year. ***Good Bye****.*



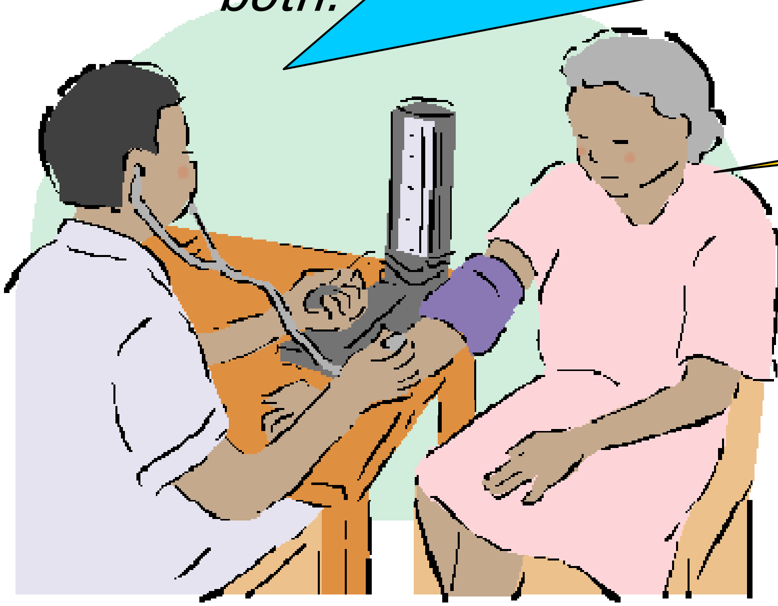
Risk Assessment Triplet Questions [Kaplan and Garrick, 1981]:

-*"What can go wrong?"*
-*"What is the likelihood?"*
-*"What are the consequences?"*
What is the time frame?

Risk Management: A Physician Metaphor

Mrs. Jones, I think you should quit smoking, exercise, and follow a healthy diet. Alternatively, I can prescribe some medications for you now, which can help bring down your blood cholesterol level more quickly, but there might be some side effects. My recommendation is to do both.

So, what shall I do?



Risk Management Triplet Questions [Haimes, 1991]:

-"What can be done and what options are available?

-"What are the tradeoffs in terms of all costs, benefits, and risks?"

-"What are the impacts of current decisions on future options?"

Components of the Risk Function

(i) The time frame

(ii) the probability of the threat (emerging forced changes) and of its specificity (probability of the consequences)

(iii) the vector of the states of the system (including its performance capability, vulnerability, and resilience)

(iv) the vector of the resulting consequences

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 frame?

Risk Modeling

Causal Relationships Among All State Variables

Risk Communication

Stakeholders and Knowledge Integration

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

Risk Communication

Risk communication bridges risk assessment and management and enables the public and the involved stakeholders to become partners to and supportive of the multi-party enterprise involved in risk management.

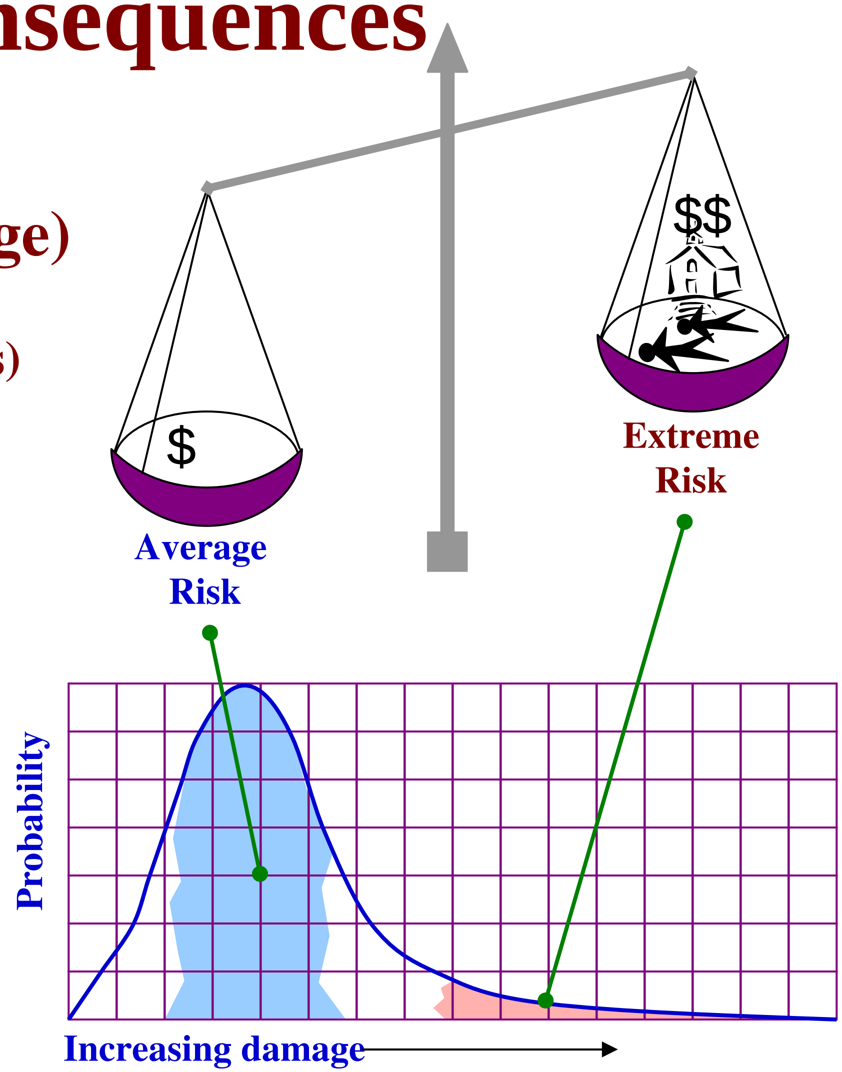
Risk of Low Probability and Extreme Consequences

Risk = *f* (Probability, Damage)

or

Risk = *f* (Likelihood, Consequences)

The fallacy of the expected value of risk as the sole metric for risk measurement



Risk Analysis Must Account for Knowledge Uncertainty and Variability Uncertainty

- ***Two major sources of uncertainty in modeling affect Risk Analysis:***
  - ***Knowledge (Epistemic) Uncertainty, e.g., the selection of model topology (structure) and model parameters.***
  - ***Variability (Aleatory) Uncertainty, which includes the incorporation into the modeling process all relevant and important random processes, and emergent forced changes.***
  - ***Both types of uncertainties markedly affect the quality and effectiveness of risk analysis effort.***

The Complex Risk Function

To assess the risk to a system facing any Emergent Forced Change (EFC), we ought to know the following:

- *The probability of the specific EFC*
- *The potency, effectiveness, and duration of the specific EFC;*
- *The vulnerability of the threatened system to the specific EFC at the time of the event;*
- *The resilience of the threatened system at the time of EFC;*
- *The assessed/projected multidimensional vector of consequences from the specific EFC; and*
- *The duration of each element of the multidimensional vector of consequences*

Epilogue

A systemic and effective process of risk assessment, management, and communication must adhere to the following guiding roadmap:

(i)A "Watch List" of emergent forced changes ought to be updated regularly and be on the agenda for risk management.

(ii)Systemic measurements and data collection ought to support the risk management of all emergent forced changes on the watch list.

(iii)Criteria ought to be developed on how to decide when evidence on an emergent forced change is sufficient to take an action.

A Most Challenging and Probably Unanswerable Question

Who should decide

On acceptability

of what risks

for whom,

and in what terms,

and why?

William Lowrence, Acceptable Risk, 1976