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# **Challenges in disaster mitigation of large infrastructure by engineering design**

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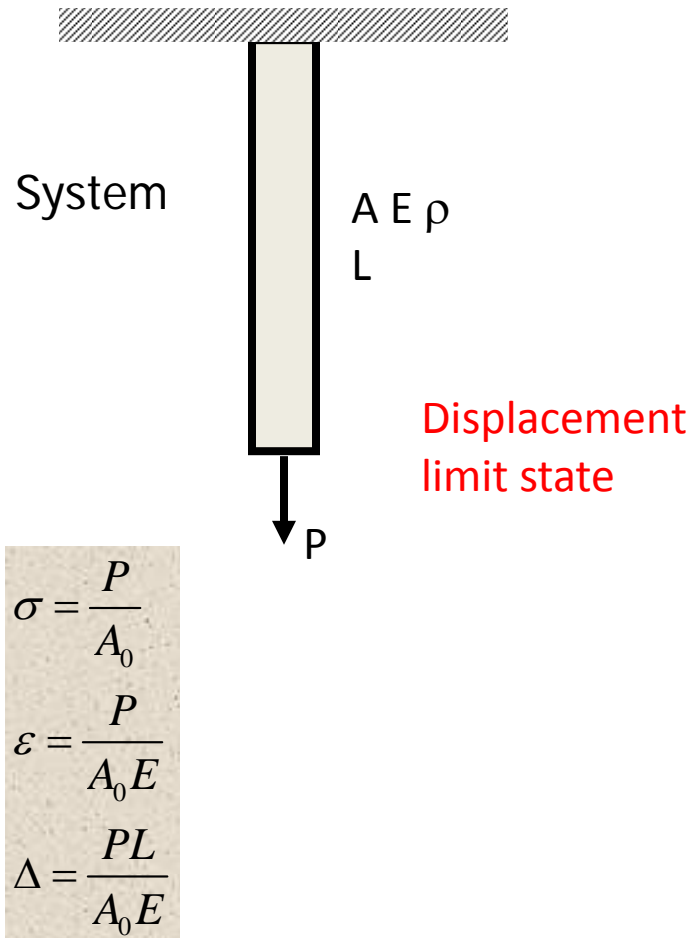
# Outline

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- Civil infrastructure systems
  - Uncertainty and reliability
  - Evolution of engineering design
- Current challenges: thinking beyond failure
  - Uncertainty analysis: **Load modeling**
  - System modeling: **Efficient simulations**
  - Risk quantification: **Acceptable risk**

# The engineer's work

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- System
  - System properties (A,E,ρ,L)
  - Input (P)
  - Response (Δ)
  - System (I/O) model:  $\Delta = f(P;A,E,...)$
  - System capacity:  $\Delta_{\max}$
- Failure
  - Response exceeds capacity
  - Multiple performance requirements
- Presence of uncertainties
  - Model, input, properties
- Compute probability of failure
  - Is it acceptably low?
- Is it economical?
- Done! (Good luck and take care)

# Compute probability of failure

$C > D$  : Safe  
 $C < D$  : Failed

Reliability formulation

Limit state eqn:

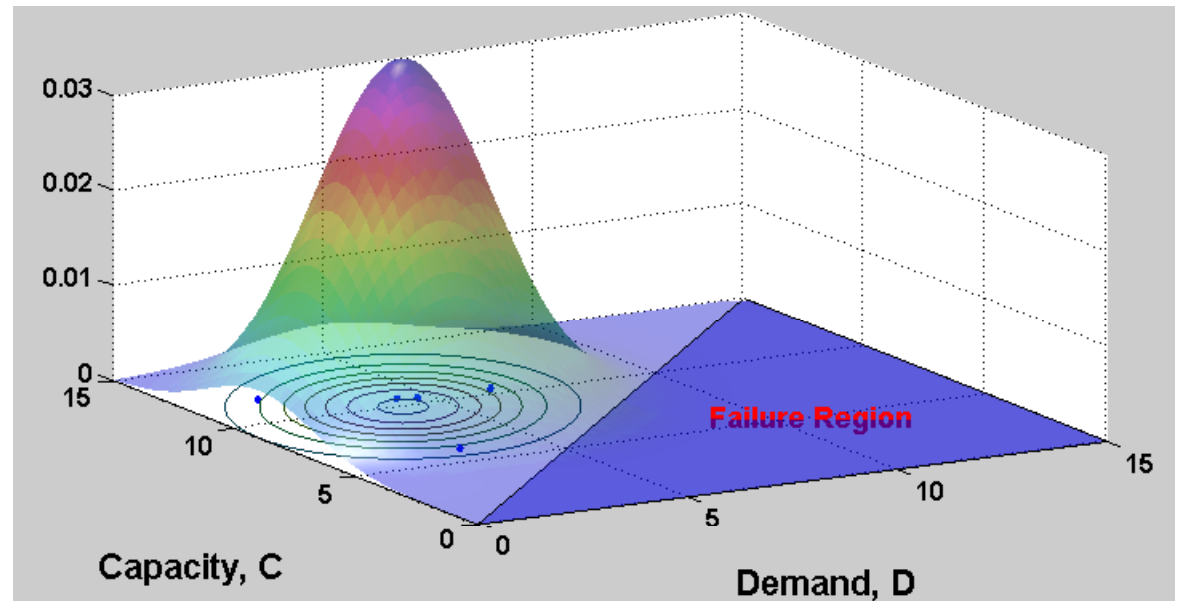
$$C - D = 0$$

Failure probability:

$$P_f = P[C - D < 0]$$

Reliability:

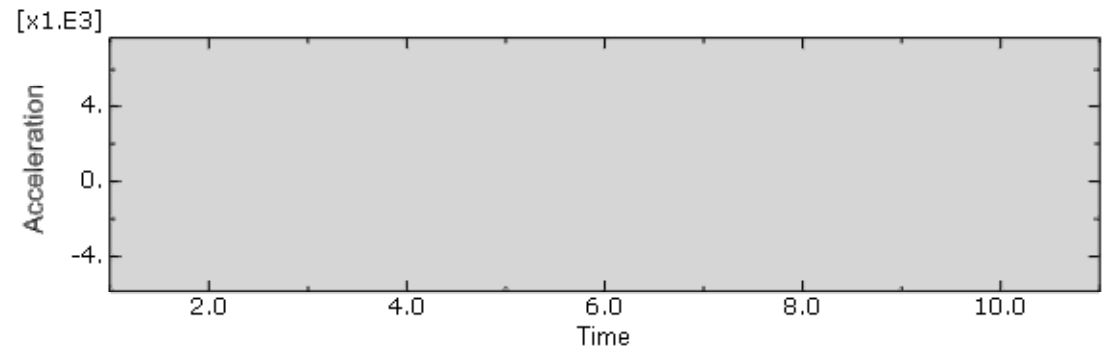
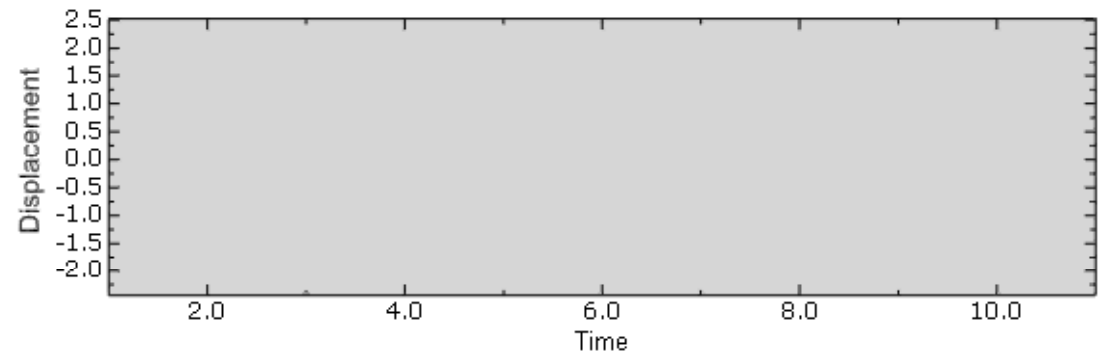
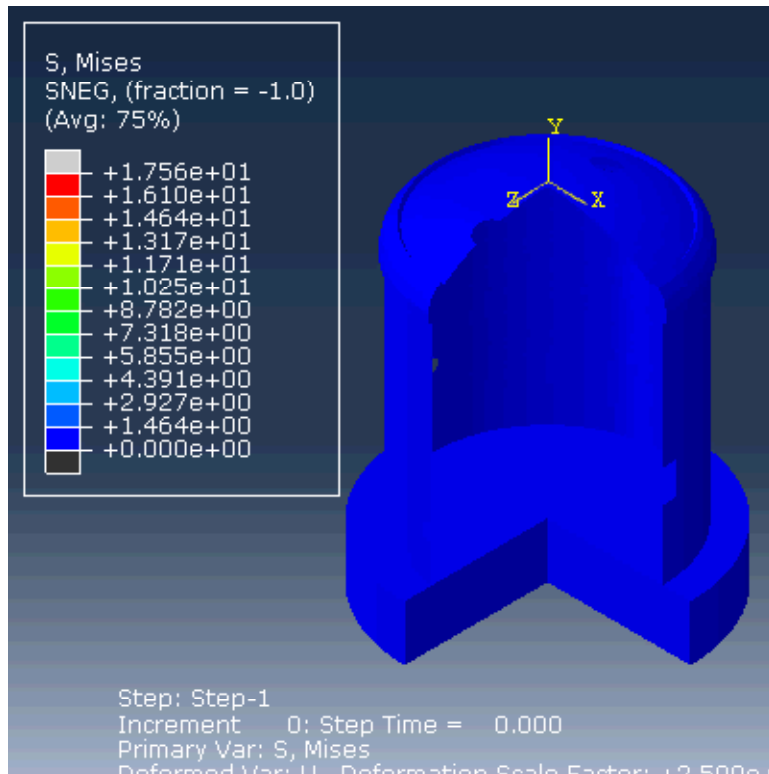
$$\text{Rel} = 1 - P_f$$



More generally:

$$\text{Rel}(t, \Omega) = P[C(\tau, \underline{x}) > D(\tau, \underline{x}), \forall \tau \in (0, t), \forall \underline{x} \in \Omega]$$

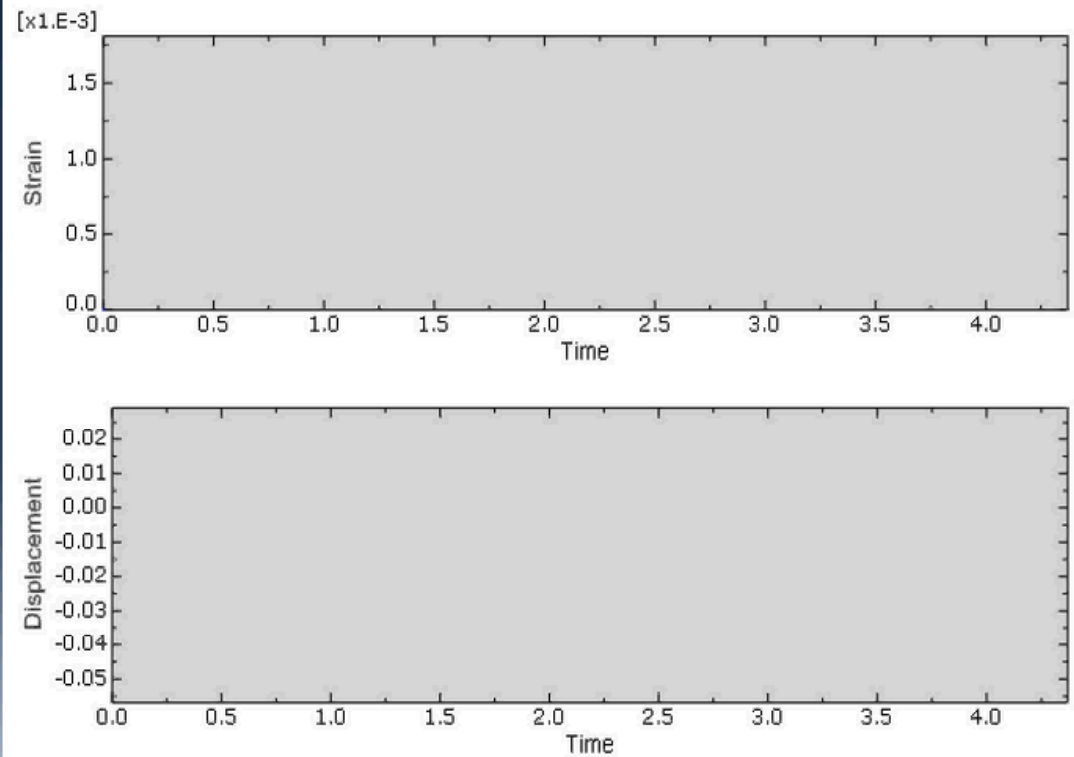
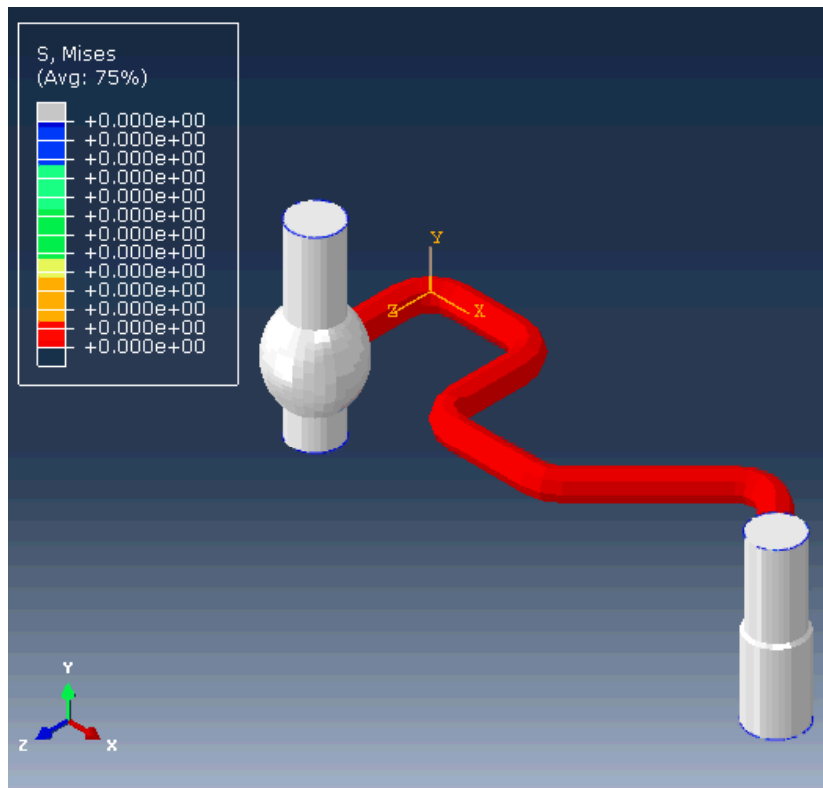
# A complex infrastructure: global response



Response of primary system

# A complex infrastructure: local response

Response of secondary systems



# A complex infrastructure: local response

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Response of secondary systems

FEMA 350

	Performance Levels	
	Immediate Occupancy	Collapse Prevention
Demand level	500 yr return period earthquake	2500 yr return period earthquake
Non structural requirements	Equipment and contents should be OK, may not work due to lack of power	Extensive damage allowed
Structural requirements	Strength and stiffness must be retained. Minor cracking allowed. Elevator and fire protection systems must be OK.	Little strength and stiffness remains. Gravity loads must be supported. Large permanent deformation allowed.

# Evolution of engineering design

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## Code of Hammurabi (Babylon, 1772 BC):

Building construction - 6 clauses, 193 words to define payment and liability

Clause: 229. If a builder build a house for some one, and does not construct it properly, and the house which he built fall in and kill its owner, then that builder shall be put to death.



## Indian Civil Nuclear Liability Act (2010)

- 14000 words, 49 major clauses
- Grades of damage (7 types)
- Determination of responsible party
- Liability is “no fault” type
  - Limited to Rs 15 Bn (USD 300m)
  - Depends on size and cause of event
  - Arbitration by Claims Commissioner
- Penalty for non-compliance or obstruction
  - Fine
  - Imprisonment (up to 5 yrs)



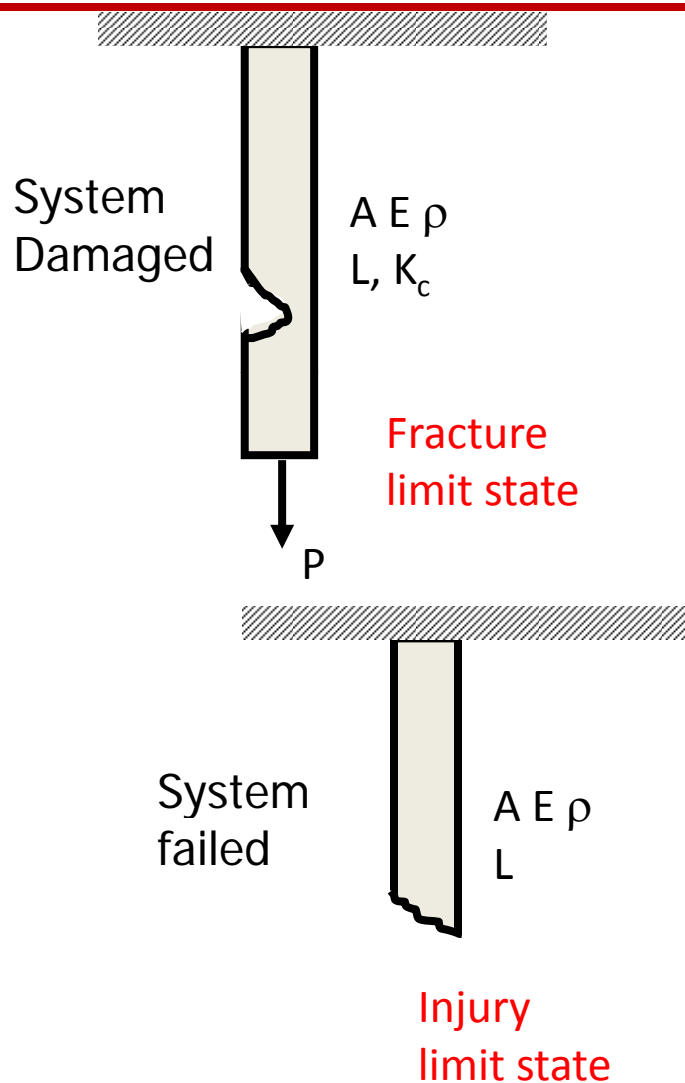
# Evolution of engineering design

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- Modern infrastructure systems
  - Getting bigger and more complex
  - Interaction between structural non-structural and human elements
  - Diffused responsibility – owners vs. operators vs. stakeholders
  - Large failure consequences
  - New challenges



# The engineer's challenges



- Classical approach
  - System will be serviceable
  - System will be fail-safe, damage-tolerant etc.
- New paradigm: thinking beyond failure
  - Damage/failure can happen
    - Revised expectations & priorities?
    - How much loss/ downtime is OK?
  - Post disaster response
    - New system model?
    - Revised uncertainties?
    - Acceptable risk?

# Challenges – system modeling

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- Modeling system in near failure conditions
  - **Efficient simulations**
    - Non-linear models
- Missing important system failure modes
- Over-estimating redundancy
  - Causally related dependence
  - Associative dependence
- Using instrumented/eyewitness data
  - From normal and damaged states
  - For estimating extent of damage
  - For directing disaster response operations

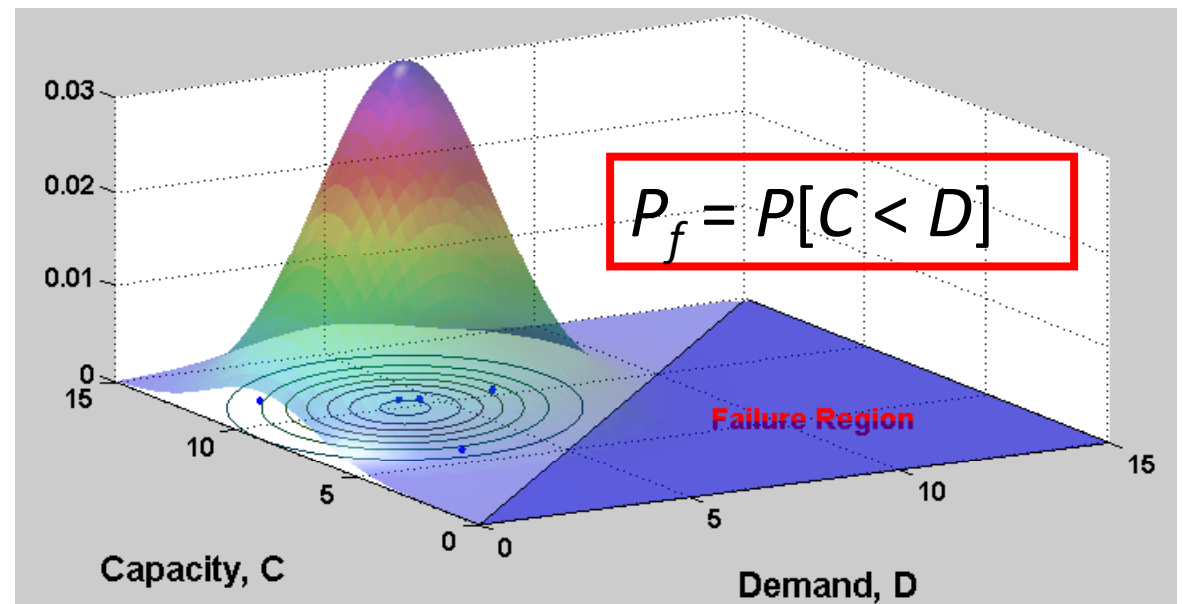
# Efficient simulations

## Basic Monte Carlo Simulations

$$P_f = P(g(\underline{X}) < 0) = \int_{\Omega} \mathbb{I}(g(\underline{X}) < 0) f_{\underline{X}}(\underline{x}) d\underline{x} \approx \frac{1}{N} \sum \mathbb{I}_i$$

$$\text{relative error} \approx \frac{1}{\sqrt{P_f N}}$$

Very low efficiency for low failure probability



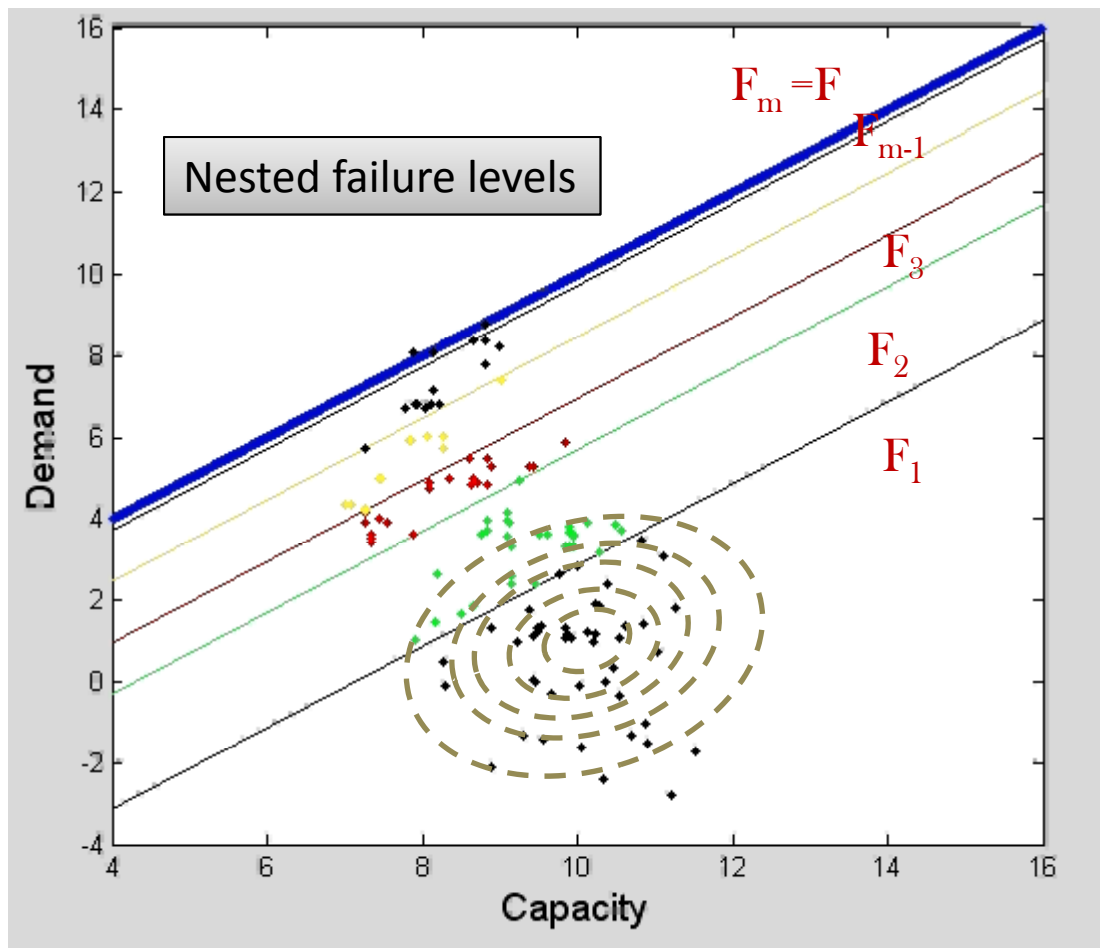
- Large computational demand
- Need efficient simulation schemes

# Efficient simulations

Subset simulations involving Markov Chain Monte Carlo moves

Nested sets:

$$P(F) = P(F_1)P(F_2 | F_1)P(F_3 | F_2) \dots P(F_m | F_{m-1})$$



- Each conditional probability is large
- First step involves basic MCS
- Subsequent steps invoke MCMC (with modified Metropolis-Hastings algorithm)

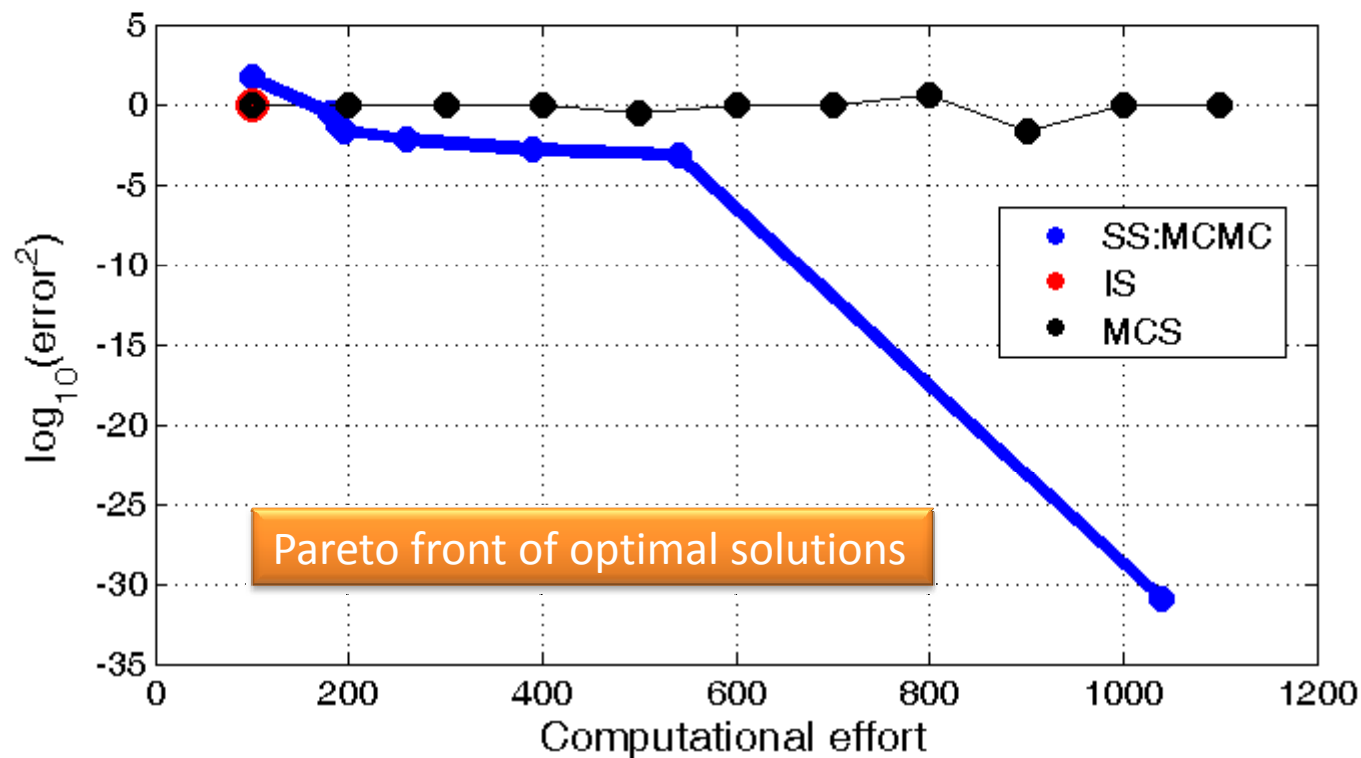
Can be very efficient for low  $P_f$

Can have very large errors

# Efficient simulations

Optimization: tradeoff between error and accuracy

- What is the minimum possible error?
- What is the best simulation scheme?



# Challenges – uncertainty quantification

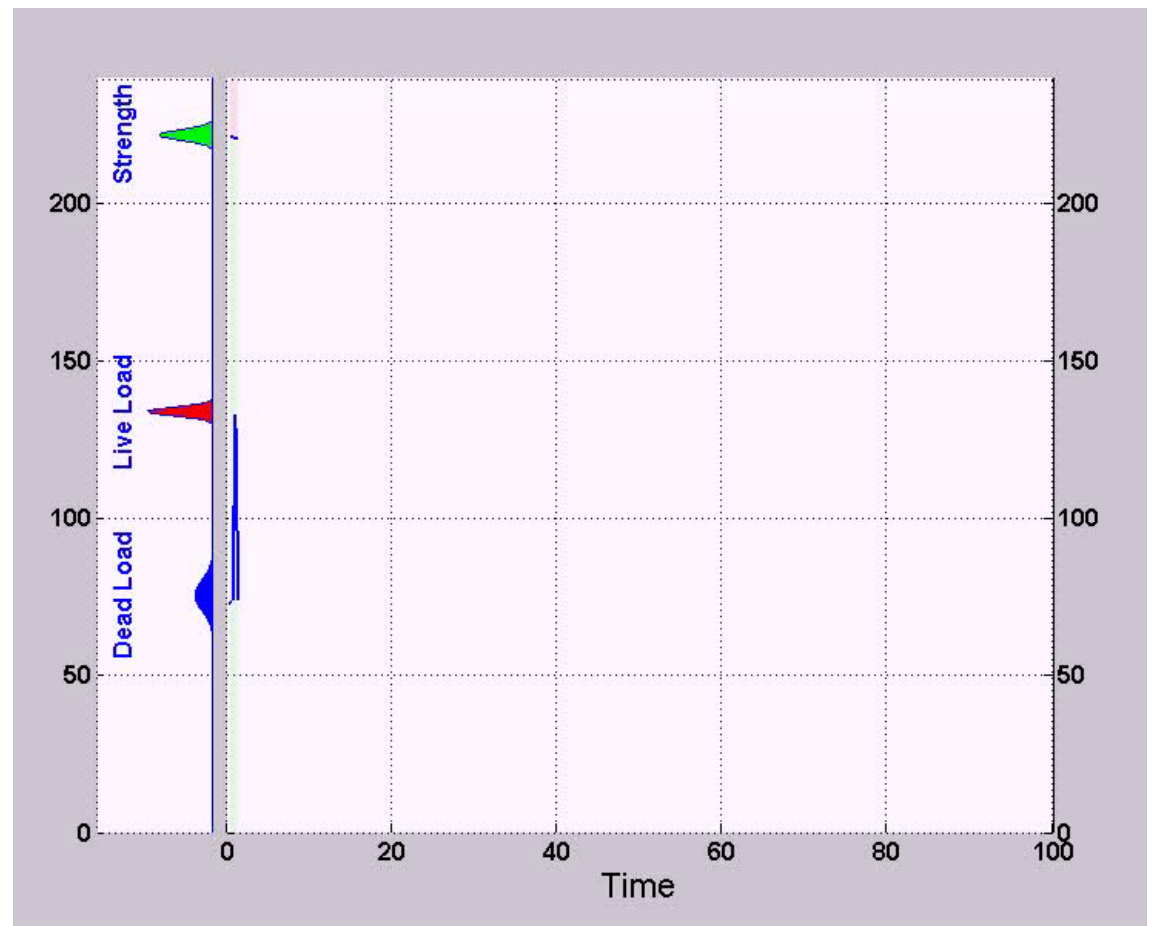
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- **In future loads**
  - Geophysical hazards
  - Intentional harm, etc.
- In damaged system properties
- In uncertainty propagation through a complex system
- In human intervention/error after disaster

# Load modeling

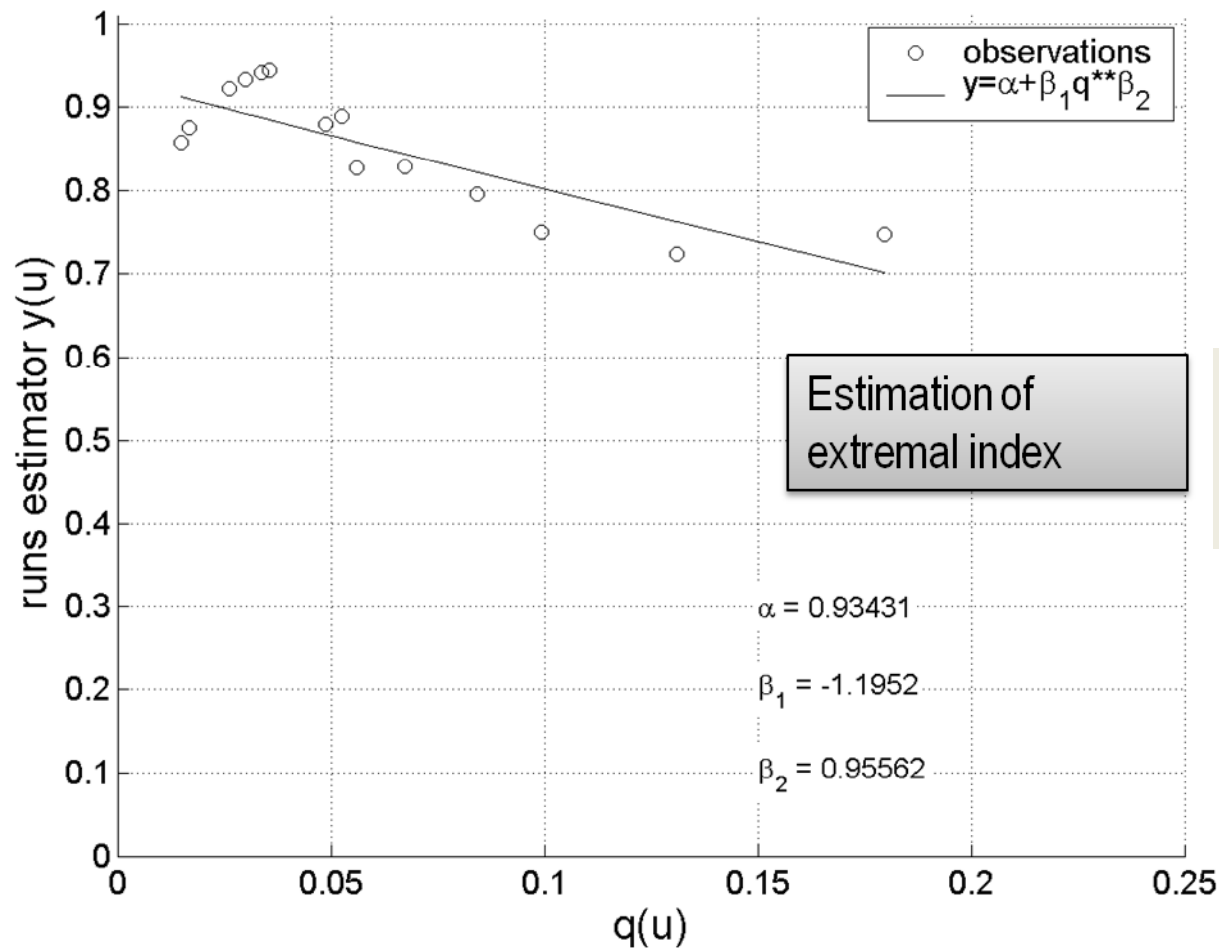
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- Estimation of:
  - Maximum load during design life
  - First passage time from safety to failure
- Issues:
  - Non stationarity
  - Short-term or long-term dependence
  - Clustering effects
  - Periodicity



# Load modeling

Lifetime maximum distribution



- Limiting distribution of maxima  
 $Z_n = \max(X_1, X_2, \dots, X_n) \sim H_n \rightarrow H?$
- Measure of average cluster size:

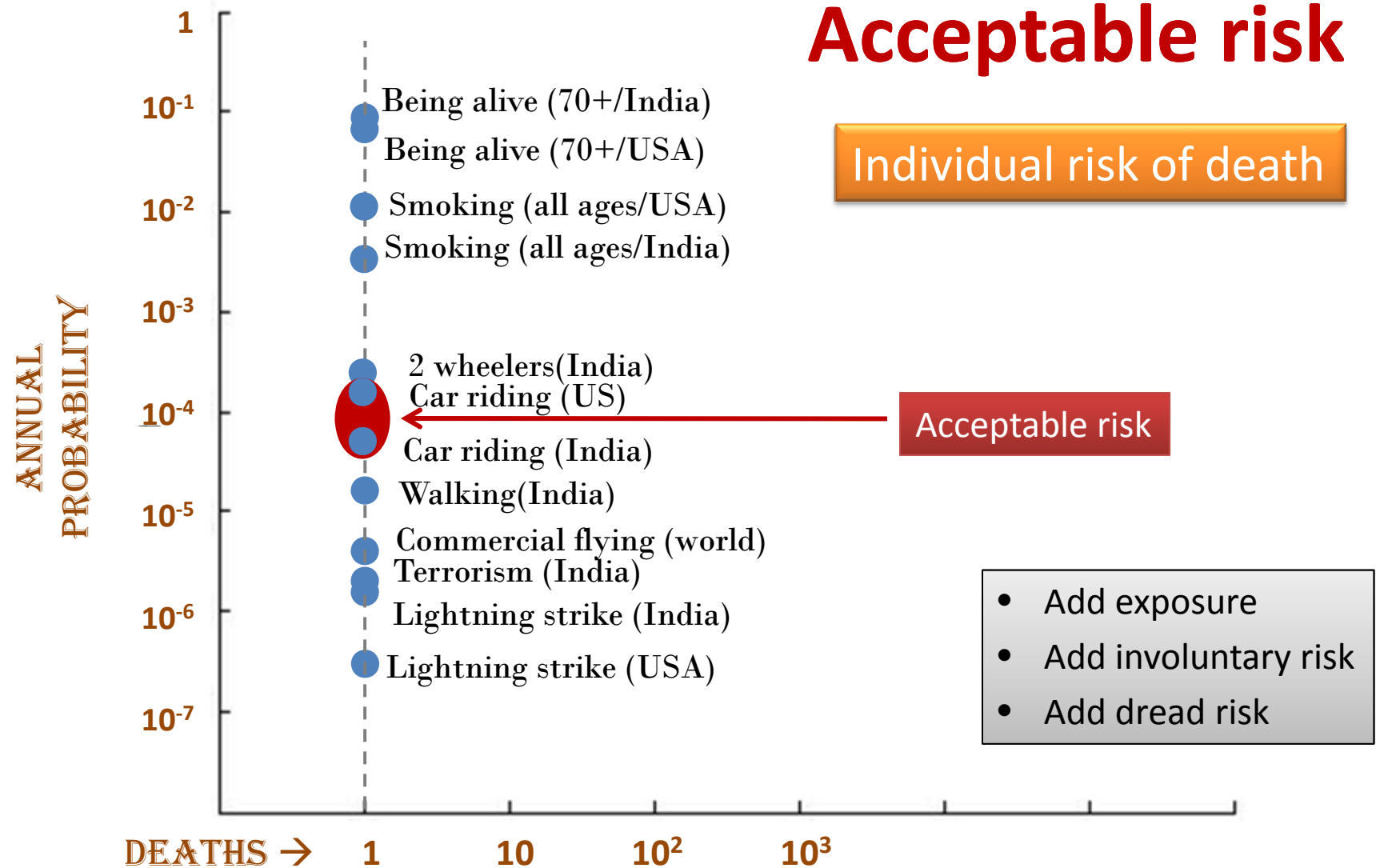
$$\hat{\theta}_R(x, r, n) = \frac{\sum_{i=1}^n \mathbb{I}_{B,i}(I_i > x \geq M_{i+1, i+r-1})}{\sum_{i=1}^n \mathbb{I}_{A,i}(I_i > x)}, \quad r \geq 2$$

# Challenges: risk quantification

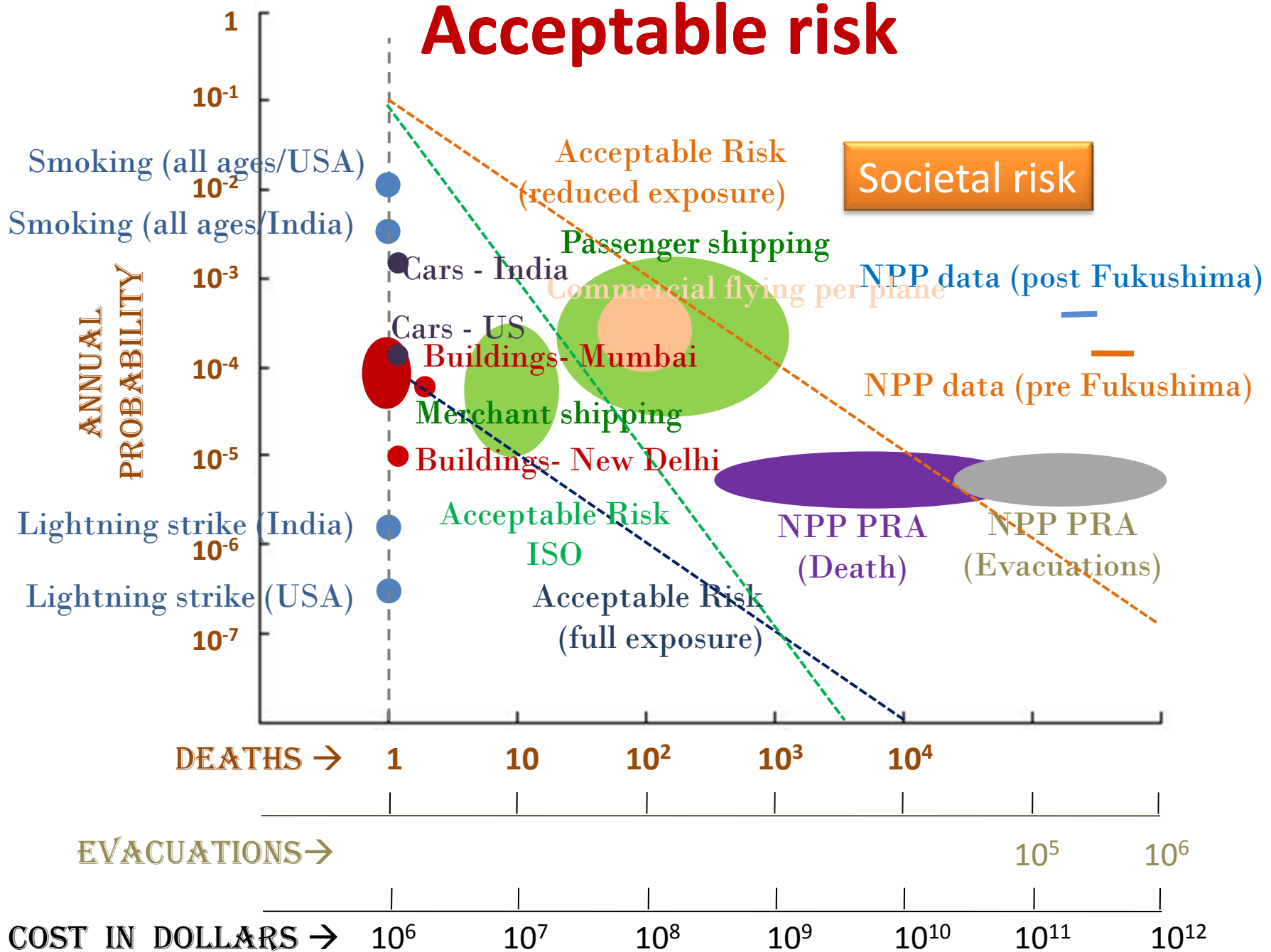
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- **How safe is safe enough?**
  - How much risk to life, property and environment is OK vis a vis the benefits?
  - How much money to buy additional safety?
- What failure costs are to be taken into account?
- How to communicate the proper risk?
  - Difference between actual risk and perceived risk
  - Tolerable risk may change with time

# Acceptable risk



# Acceptable risk



# Conclusions

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- Modern infrastructure systems
  - Large failure consequences
  - Damage/ failure can occur
- Thinking beyond failure
- Challenges
  - System modeling
  - Uncertainty quantification
  - Risk assessment

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