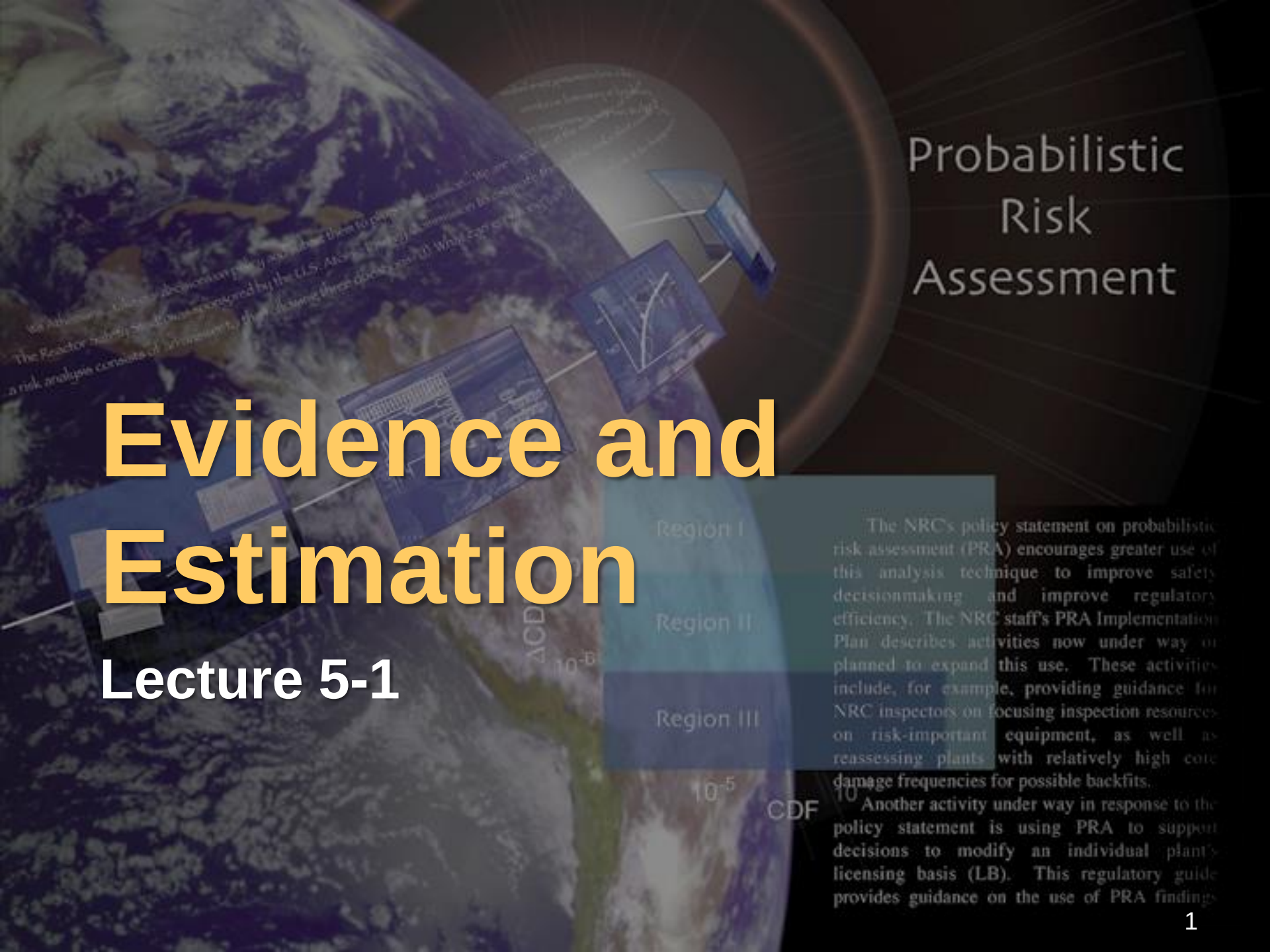

Evidence and Estimation

Lecture 5-1

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Schedule

	Wednesday 1/16	Thursday 1/17	Friday 1/18	Tuesday 1/22	Wednesday 1/23
Module	***1: Introduction***	***3: Characterizing Uncertainty***	***5: Basic Events***	***7: Learning from Operational Events***	***9: The PRA Frontier***
9:00-9:45	L1-1: What is RIDM?	L3-1: Probabilistic modeling for NPP PRA	L5-1: Evidence and estimation	L7-1: Retrospective PRA	L9-1: Challenges for NPP PRA
9:45-10:00	**Break**	**Break**	**Break**	**Break**	**Break**
10:00-11:00	L1-2: RIDM in the nuclear industry	L3-2: Uncertainty and uncertainties	L5-2: Human Reliability Analysis (HRA)	L7-2: Notable events and lessons for PRA	L9-2: Improved PRA using existing technology
11:00-12:00	W1: Risk-informed thinking	W2: Characterizing uncertainties	W4: Bayesian estimation	W6: Retrospective Analysis	L9-3: The frontier: grand challenges and advanced methods
12:00-1:30	**Lunch**	**Lunch**	**Lunch**	**Lunch**	**Lunch**
Module	***2: PRA Overview***	***4: Accident Sequence Modeling***	***6: Special Technical Topics***	***8: Applications and Challenges***	***10: Recap***
1:30-2:15	L2-1: NPP PRA and RIDM: early history	L4-1: Initiating events	L6-1: Dependent failures	L8-1: Risk-informed regulatory applications L8-2: PRA and RIDM infrastructure	L10-1: Summary and closing remarks
2:15-2:30	**Break**	**Break**	**Break**	**Break**	
2:30-3:30	L2-2: NPP PRA models and results	L4-2: Modeling plant and system response	L6-2: Spatial hazards and dependencies	L8-3: Risk-informed fire protection	Discussion: course feedback
3:30-4:30	L2-3: PRA and RIDM: point-counterpoint	W3: Plant systems modeling	L6-3: Other operational modes L6-4: Level 2/3 PRA: beyond core damage	L8-4: Risk communication	Open Discussion
4:30-4:45	**Break**	**Break**	**Break**	**Break**	
4:45-5:30	Open Discussion	W3: Plant systems modeling (cont.)	W5: External Hazards modeling	Open Discussion	
5:30-6:00		Open Discussion	Open Discussion		

Learning Objectives

- Range of evidence used in NPP PRA
- Sources of operational data
- Bayesian estimation
- Treatment of model predictions and expert judgment

Resources

- J. Lane, “U.S. NRC Operational Experience Data Collection Program,” NEA Workshop on the Use of Operational Experience in PSA, Boulogne-Billancourt, France, April 26-27, 2018. (ADAMS ML18123A479)
- U.S. Nuclear Regulatory Commission, “Reliability and Availability Data System (RADS)” https://nrcoe.inl.gov/resultsdb/RADS/
- U.S. Nuclear Regulatory Commission, “Industry Average Parameter Estimates,” https://nrcoe.inl.gov/resultsdb/AvgPerf/
- N. Siu and D.L. Kelly, "Bayesian parameter estimation in probabilistic risk assessment," *Reliability Engineering and System Safety*, **62**, 89-116, 1998.
- C.L. Atwood, et al., “Handbook of Parameter Estimation for Probabilistic Risk Assessment,” *NUREG/CR-6823*, September 2003.
- R. J. Budnitz, et al., “Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts,” *NUREG/CR-6372*, 1997.

Other References

- "IEEE Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability for Nuclear-Power Generating Stations," *IEEE Std 500-1984*, Institute of Electrical and Electronics Engineers, New York, 1983.
- Center for Chemical Process Safety, *Guidelines for Process Equipment Reliability Data with Data Tables*, American Institute of Chemical Engineers, New York, 1989.
- G.E.P. Box and G.C. Tiao, *Bayesian Inference in Statistical Analysis*, Addison-Wesley, Reading, MA, 1973.
- D. Kahneman, P. Slovic, and A. Tversky (eds.), *Judgment Under Uncertainty: Heuristics and Biases*, Cambridge University Press, Cambridge, MA, 1982.
- M. Granger Morgan, "Use (and abuse) of expert elicitation in support of decision making for public policy," *National Academy of Sciences Proceedings (NASP)*, **111**, No. 20, 7176-7184, May 20, 2014.
- J. Xing and S. Morrow, "White Paper: Practical Insights and Lessons Learned on Implementing Expert Elicitation," U.S. Nuclear Regulatory Commission, October 13, 2016. (ADAMS ML16287A734)

Basic event probabilities reflect state of knowledge

$$P\{X|C,H\}$$

- P = Probability
- X = Proposition of concern (e.g., SI pump failure rate < 10^{-3} per demand)
- C = Conditions of assessment (e.g., key assumptions)
- H = State of knowledge (dependent on assessor)

State of Knowledge (About X)

- Affected by evidence; common forms:
  - Data (operational, tests, simulator exercises, experiments)
  - Generic estimates
  - Model predictions
  - Expert judgment
- Changes in H lead to changes in the probability distributions for model parameters

$$\pi_0(\theta|H_0) \rightarrow \pi_1(\theta|H_1)$$

- Bayes' Theorem is the formal tool for updating

On "Data"

- "Data" (plural of "datum")
  - Facts, information, statistics, or the like, either historical or derived by calculation or experimentation
  - Any facts assumed to be a matter of direct observation
- PRA community uses both views:
  - System analyst: input parameters for PRA model
    - NPP-specific
    - Generic (e.g., IEEE Std-500, CCPS)
  - Data analyst: empirical observations used to estimate input parameters

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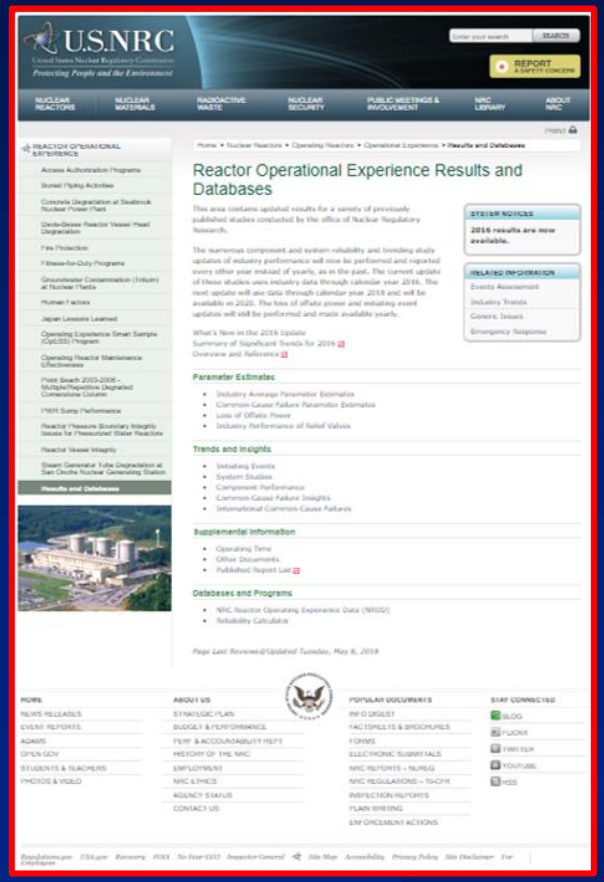
Operational Data

- See Lane (2018): history of NRC operational experience data collection and current programs.
- Key sources
  - Licensee Event Reports
    - See https://lersearch.inl.gov
    - >54,000 records (1980-)
    - Rich source, but level of detail and scope can vary
  - INPO Consolidated Events Database (ICES) – proprietary
    - Required (MSPI program) + voluntary reporting
    - Includes some demand and runtime data



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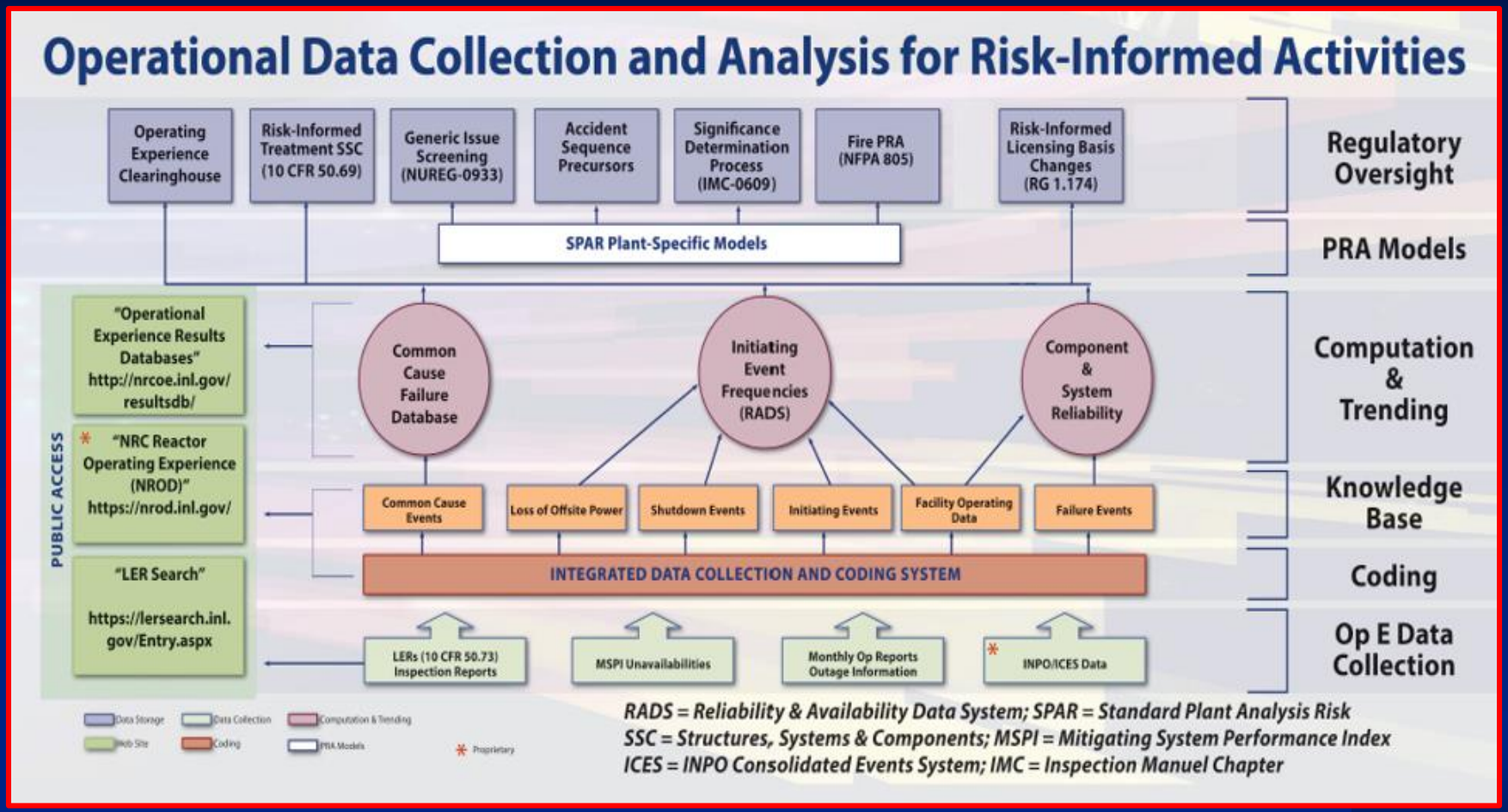
NRC Data Summaries

- Multiple links at http://nrcoe.inl.gov/resultsdb/
- Industry average estimates, trends, and summary data for PRA model parameters: https://nrcoe.inl.gov/resultsdb/AvgPerf/
  - Initiating events
  - Component reliabilities
- Common cause failures: https://nrcoe.inl.gov/resultsdb/ParamEstSpar/

Event reports often require interpretation
- Plant-specific terminology
- Severity – truly a “failure”?

Operating Experience Data



J. Lane, "U.S. NRC Operational Experience Data Collection Program," NEA Workshop on the Use of Operational Experience in PSA, Boulogne-Billancourt, France, April 26-27, 2018. (ADAMS ML18123A479)

Bayesian Estimation – Principles

$$\underbrace{\pi_1(\theta|E)}_{\text{posterior distribution}} = \frac{1}{k}\underbrace{L(E|\theta)}_{\text{likelihood function}}\underbrace{\pi_0(\theta)}_{\text{prior distribution}}$$

- Bayes' Theorem: an expression of conditional probability
- Prior distribution quantifies belief before new evidence E
- Likelihood function quantifies probability of seeing E, given θ
- Posterior distribution quantifies belief given E
- k = normalization constant = $\int_{all\ \theta} L(E|\theta)\pi_0(\theta)d\theta$

Likelihood Functions – Examples

- General: $L(E|\theta) = P\{observing\ E|\theta\}$
- Poisson process (frequency = λ)
  - Evidence: n events in time t
  - Likelihood function: $L(n,t|\lambda) = \frac{(\lambda t)^n}{n!}e^{-\lambda t}$
  - Evidence: occurrence times $\{t_1, \ldots, t_n\}$
  - Likelihood function: $L(t_1, \cdots, t_n|\lambda) = \prod_{i=1}^{n} \lambda e^{-\lambda t_i}$
- Bernoulli process (probability = ϕ)
  - Evidence: n events in m trials
  - Likelihood function: $L(n,m|\phi) = \binom{m}{n}\phi^n(1-\phi)^{m-n}$

Likelihood Functions – Another Example

- Expert judgment
  - Evidence = estimate $\hat{\lambda}$ for failure frequency λ
  - A possible likelihood function: lognormal

$$L(\hat{\lambda}|\lambda) = \frac{1}{\sqrt{2\pi}\sigma\lambda} e^{-\frac{1}{2}\left(\frac{ln\lambda - (\hat{\lambda}+B)}{\sigma}\right)^2}$$

  - B = bias
  - σ = measure of confidence in expert

    σ = 0, B = 0 => $L(\hat{\lambda}|\lambda)$ is delta function about $\hat{\lambda}$ => perfect expert

    σ = ∞ => $L(\hat{\lambda}|\lambda)$ is flat => completely non-expert

Likelihood Function = model of the evidence-generating process

Prior Distributions

- General: characterizes state of knowledge regarding uncertain parameter(s)
- Informative
  - Preferred in principle
  - Takes effort to develop
- Non-informative
  - Objective
  - Low effort
  - Conservative but can be “good enough”

Informative Prior Distribution Construction Methods

- Direct quantification
  - Percentiles
  - Parametric form + select characteristics (e.g., moments, percentiles)
- Hierarchical Bayes (notably “two-stage Bayes”)
  - Model plant-to-plant (population) variability
  - Use population variability result as prior for plant of interest
- “Reverse engineering:” make judgments about generated samples (vs. model parameters)
- Be cognizant of biases from common heuristics (Lecture 2-3)
  - Representativeness
  - Availability
  - Anchoring and adjustment

Non-Informative Prior Distributions

- Based upon mathematical definitions of relative ignorance (relative to data) – not generally flat/uniform
- Examples ("Jeffrey's Rule priors")
  - Bernoulli process: $\pi_0(\phi) \propto \frac{1}{\sqrt{\phi(1-\phi)}}$
  - Poisson process: $\pi_0(\lambda) \propto \frac{1}{\sqrt{\lambda}}$
- Other "non-informative" distributions: maximum entropy, constrained non-informative
- See Siu and Kelly (1998) and Atwood et al. (NUREG/CR-6823) for further discussion of forms used in NPP PRAs
- Computational caution: non-informative prior distributions are often unbounded at one or both extremes; need to be careful if using numerical integration

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Knowledge Check

If λ is distributed according to a Jeffrey's prior, what is the mean value for λ?

Conjugate Likelihood-Prior Pairs

- Result in analytical solution of Bayes' Theorem => often used for computational convenience
- Can be informative or non-informative
- Examples:*
  - Binomial likelihood and beta prior => beta posterior
    - Assume n failures in m trials, and a beta prior with parameters a and b
    - Posterior distribution is beta with parameters a' = a + n and b' = b + m
  - Poisson likelihood and gamma prior => gamma posterior
    - Assume n failures in time t and a gamma prior with parameters α and β
    - Posterior distribution is gamma with parameters $\alpha' = n + \alpha$ and $\beta' = t + \beta$

*See Probability Math background slides for more information on the beta and gamma distributions

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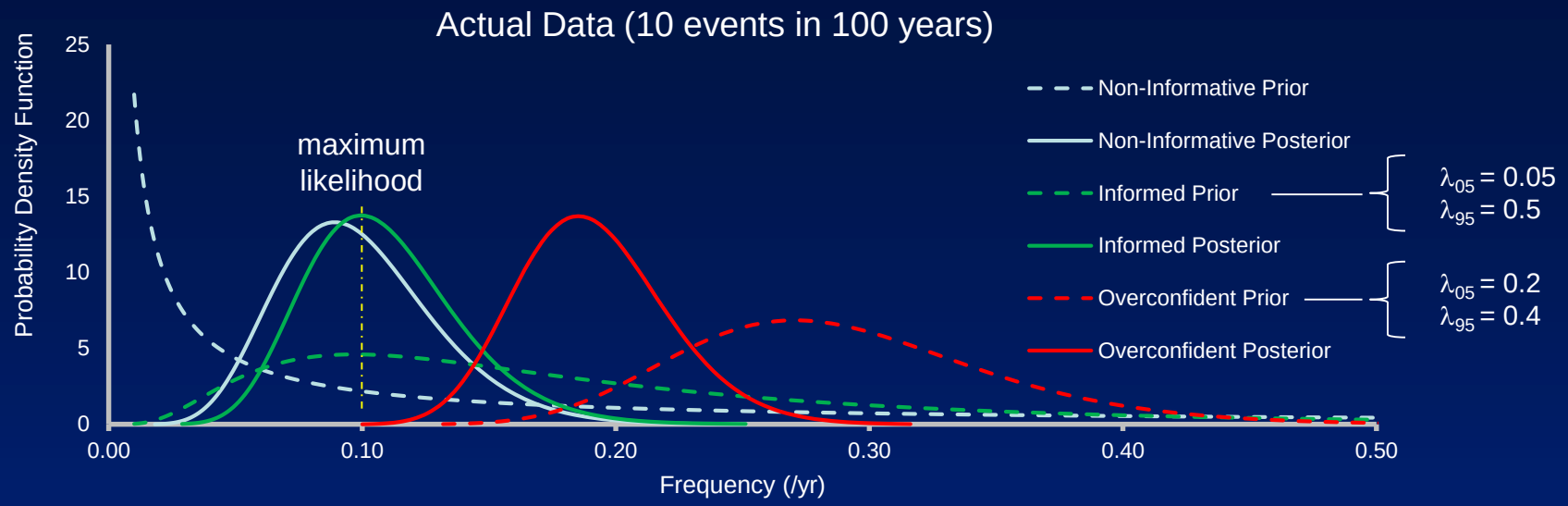
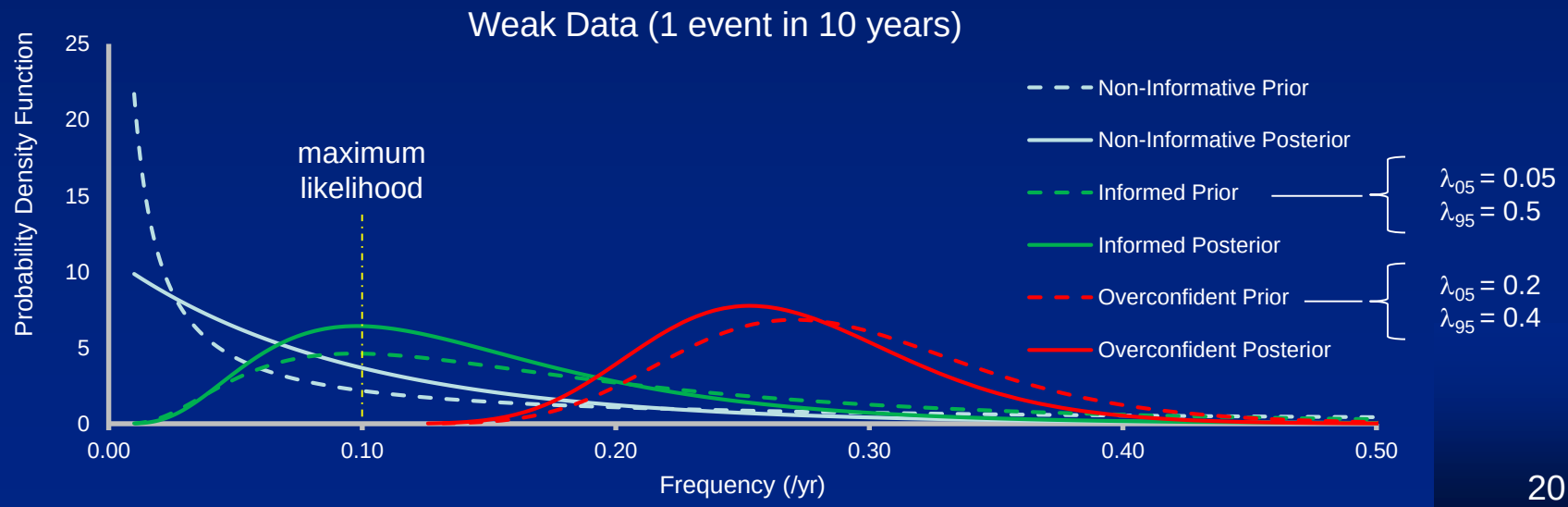
Sample Results





Comments

- When data are plentiful (“strong”), posterior is relatively insensitive to reasonable priors
- When data are weak, prior is important => important to construct carefully
  - Overly broad (undervaluing state of knowledge) => overly conservative results
  - Overly narrow (too confident in state of knowledge) => insensitive to data when obtained
  - Need to be wary of biases from heuristics

Model Predictions

- Common aleatory model: stress vs. strength
  - Time-reliability

$$P\{Failure\} = P\{Time_{available} < Time_{needed} | \theta_{TR}\}$$

  - Fire-induced damage

$$P\{Failure\} = P\{Temperature_{damage} < Temperature_{fire} | \theta_{fire}\}$$

  - Seismically-induced damage

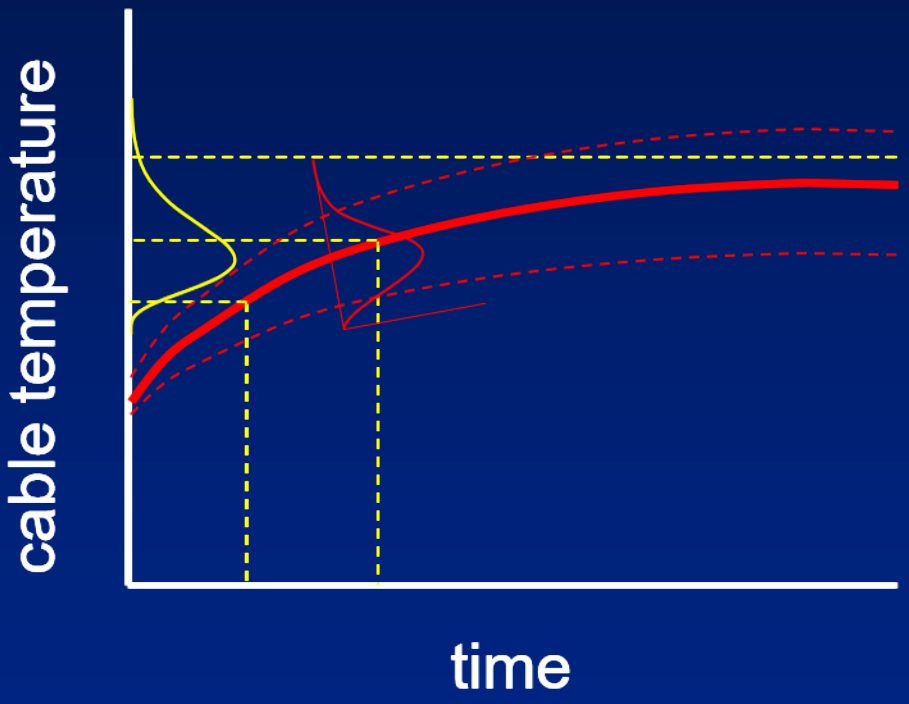
$$P\{Failure\} = P\{Capacity_{seismic} < Acceleration_{EQ} | \theta_{seismic}\}$$

- Uncertainties in parameters can be quantified and propagated through models; uncertainties in model outputs can also be quantified (Lecture 3-2)

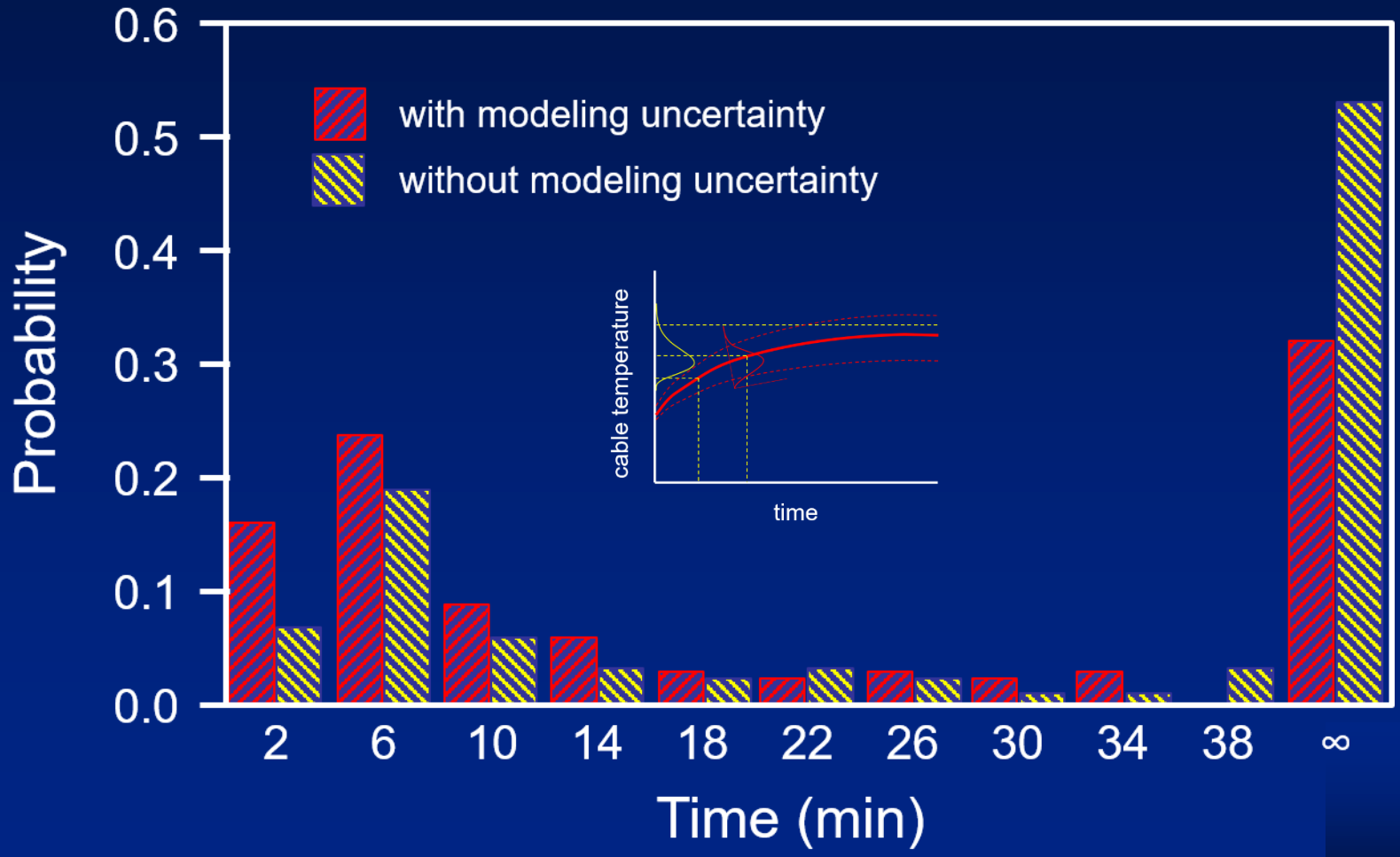
Mechanistic Modeling - Comments

- Results and even models used in NPP PRAs
  - Component behavior (e.g., reactor coolant pump seals)
  - Success criteria
  - Internal and external hazards
- "Physics of Failure" models proposed for various issues (e.g., aging, CCF)
- Appealing approach to better account for current, relevant state of knowledge ("what we know")
- Need to account for parameter and model uncertainties
- Increases vulnerability to completeness uncertainty

Fire Model Uncertainty Example



Fire Model Uncertainty – Results

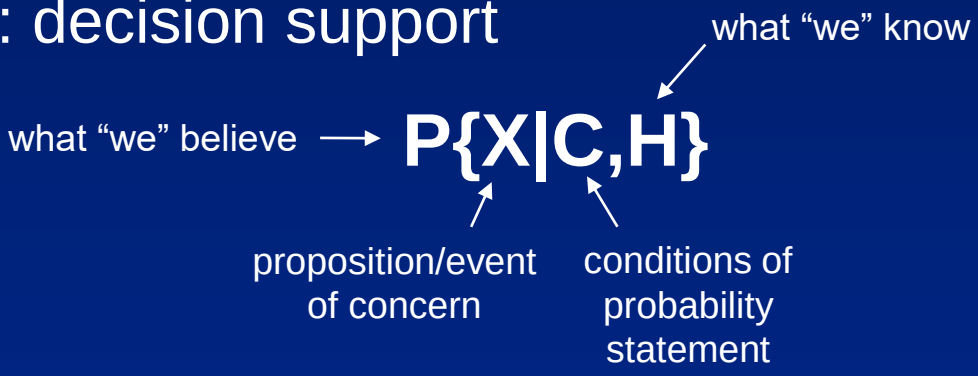


Cautionary Examples

- Multi-unit trip due to loss of communication
- Capacitor failure from operation at below-design voltage (non-nuclear)
- Increased accident consequences of a stronger pressure vessel (non-nuclear)
- Reactivity accident from rocking

Expert Judgment

- Fundamental component of PRA
  - Modeling
  - Data selection and analysis
  - Direct elicitation (qualitative and quantitative)
- Justification: decision support



For RIDM, "we" = informed technical community (not just analyst/analysis team)

Direct Elicitation

- Aim
  - Take advantage of human ability to consider/integrate complex information
  - Engage a wide variety of expert viewpoints
- Key PRA applications
  - Problem formulation, planning of experiments and analyses (Phenomena Identification Ranking Tables)
  - Scenario development (logic trees)
  - Estimation of model parameters
- Key guidance documents
  - Processes designed to address known sources of biases
  - NUREG/CR-6825 and subsequent documents (Senior Seismic Hazard Analysis Committee: “SSHAC”)

SSHAC Overview

- Designed with recognition of potential individual and social biases, e.g.,
  - Underestimation of uncertainties from heuristics (availability, anchoring and adjustment, representativeness, etc.)
  - Social influences on individual judgment (e.g., group dynamics, organizational influences)
- Emphasizes characterizing full community point of view (center, body, and range); documentation (and ownership) of bases for judgments
- Different “levels” for different needs

Level	Characteristics
1	TI only (literature review, personal experience)
2	TI interacts with proponents and resource experts
3	TI brings together proponents and resource experts
4	TFI organizes expert panel to develop estimates

TI = Technical Integrator
TFI = Technical Facilitator/Integrator

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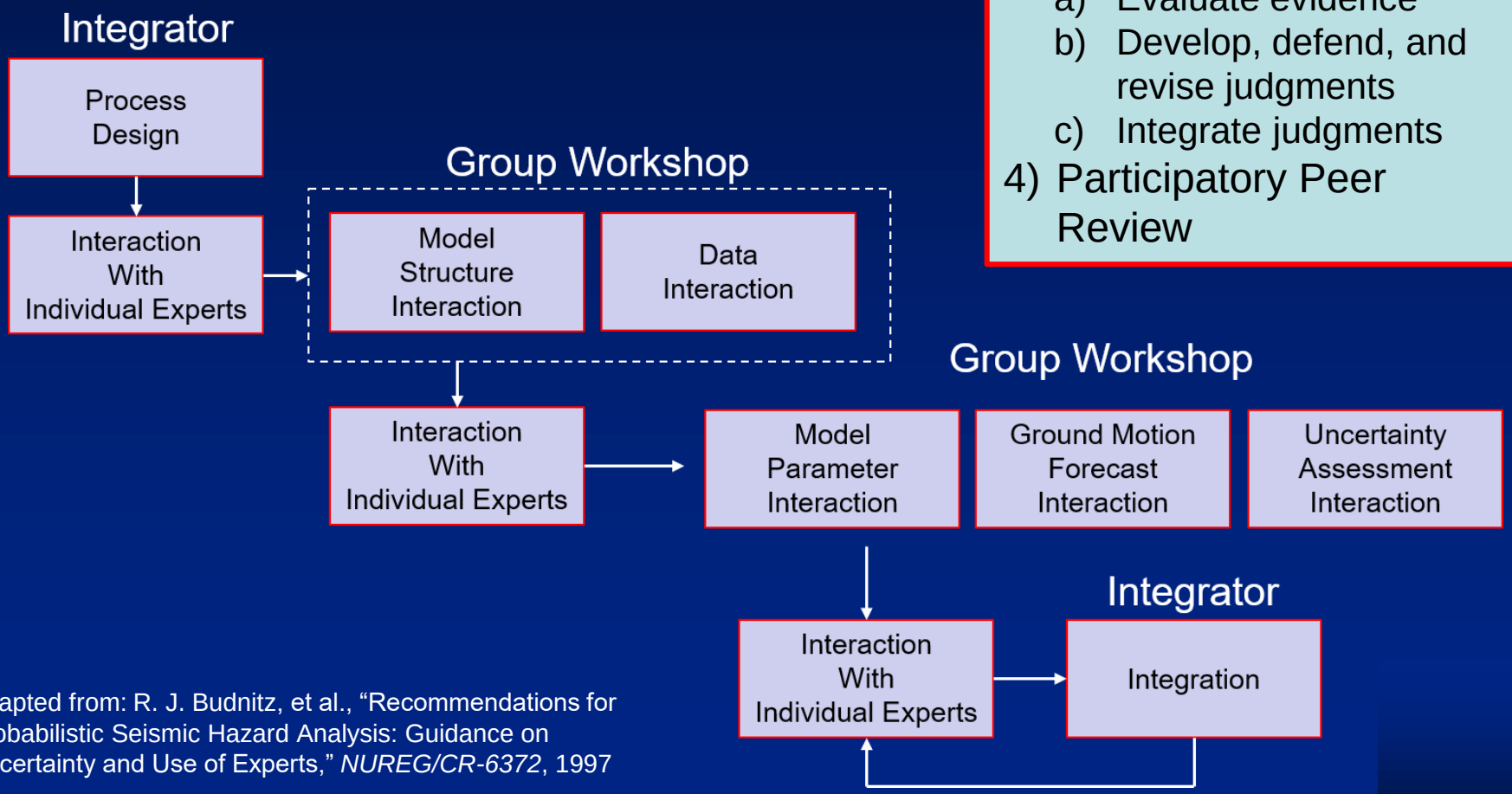
Level 4 SSHAC

General Process

1) Preparation
2) Piloting/Training
3) Interactions (Workshops)
   a) Evaluate evidence
   b) Develop, defend, and revise judgments
   c) Integrate judgments
4) Participatory Peer Review



Adapted from: R. J. Budnitz, et al., "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts," *NUREG/CR-6372*, 1997

Direct Elicitation – Cautions

- Experts
  - Key experts might not be available during project
  - Difficult to get undivided attention for extended periods of time
  - Different perspectives/frameworks => considerable effort to develop common understanding of problem
  - Inclination to provide the “right answer” based on individual point of view
  - Subject to usual human biases
- Results can be viewed as “the final solution”

A serious, important activity, but not the “Easy Button”