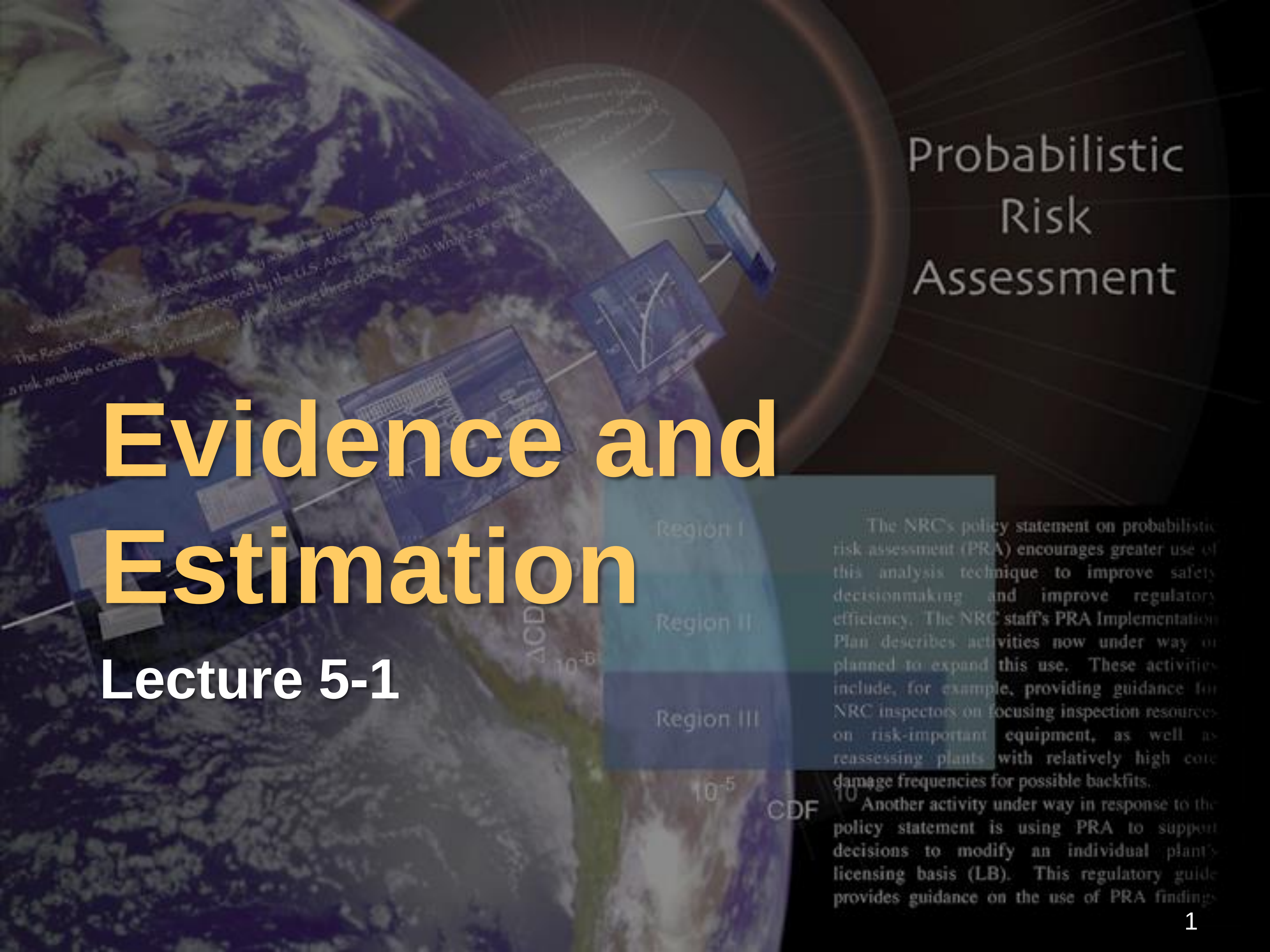
Evidence and Estimation

Lecture 5-1



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

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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.

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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)

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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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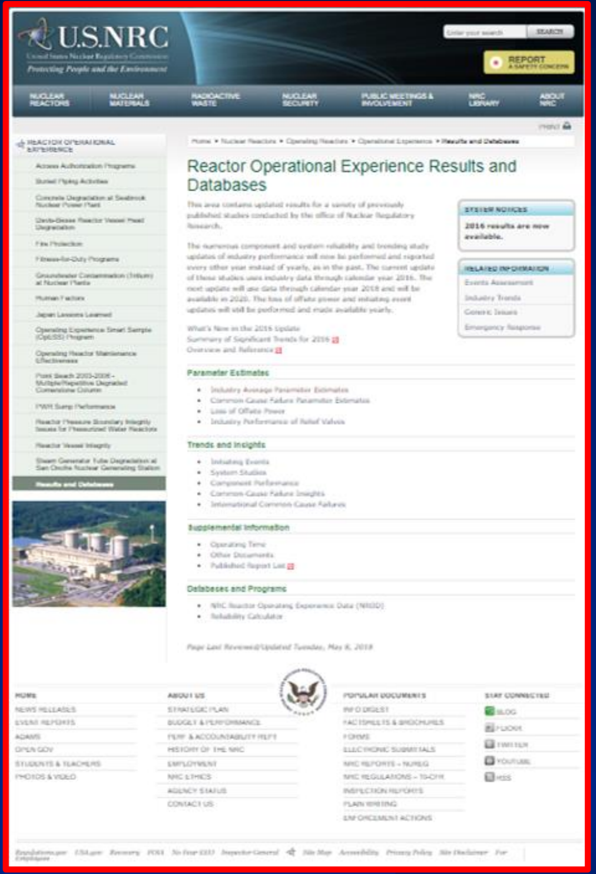
Operational Data

- 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”?

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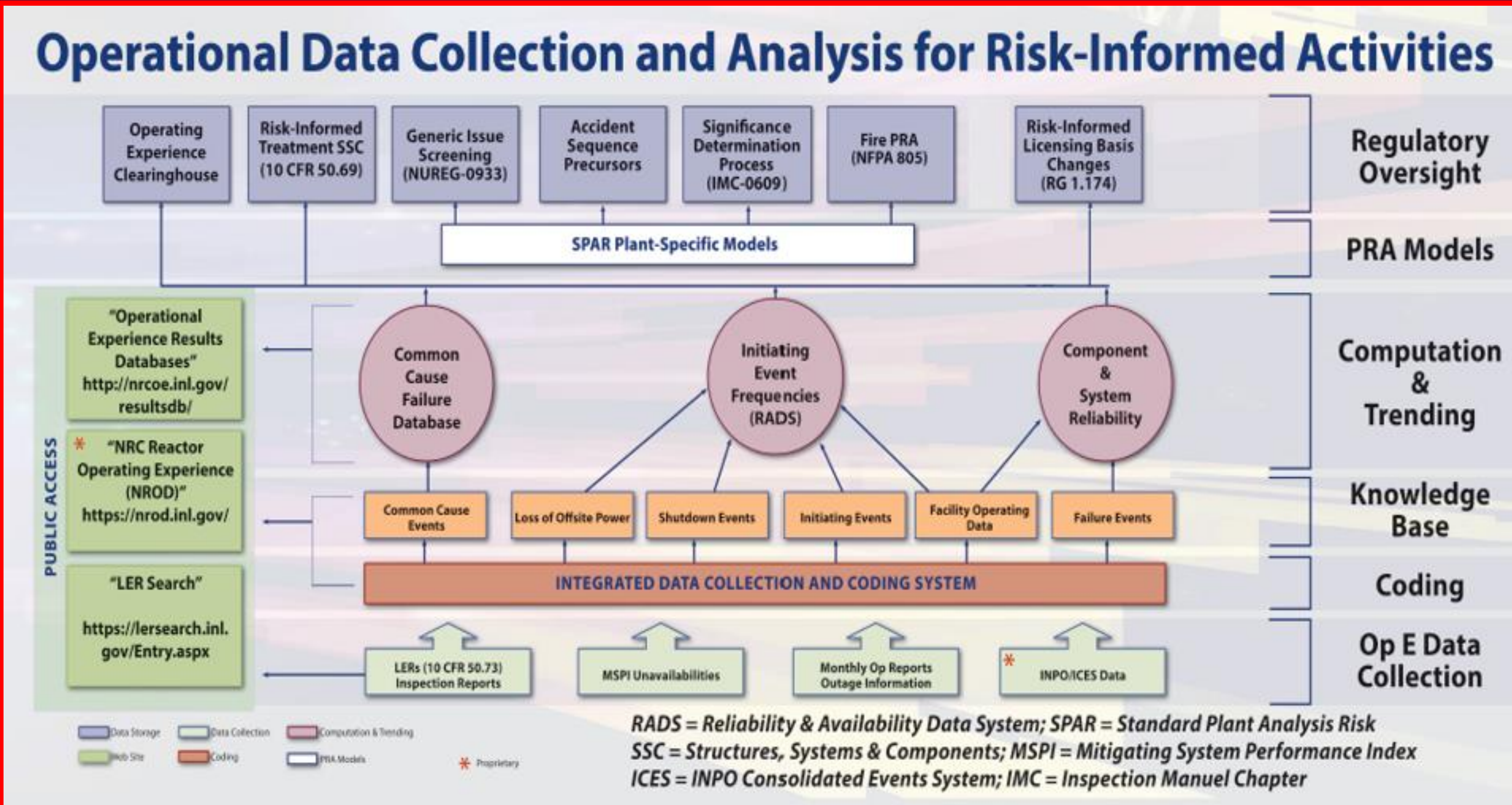
Operating Experience Data



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)

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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 = $\int_{all\ \theta} L(E|\theta)\pi_0(\theta)d\theta$

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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: $L(n,m|\phi) = \binom{m}{n}\phi^n(1-\phi)^{m-n}$

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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

Knowledge Check

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

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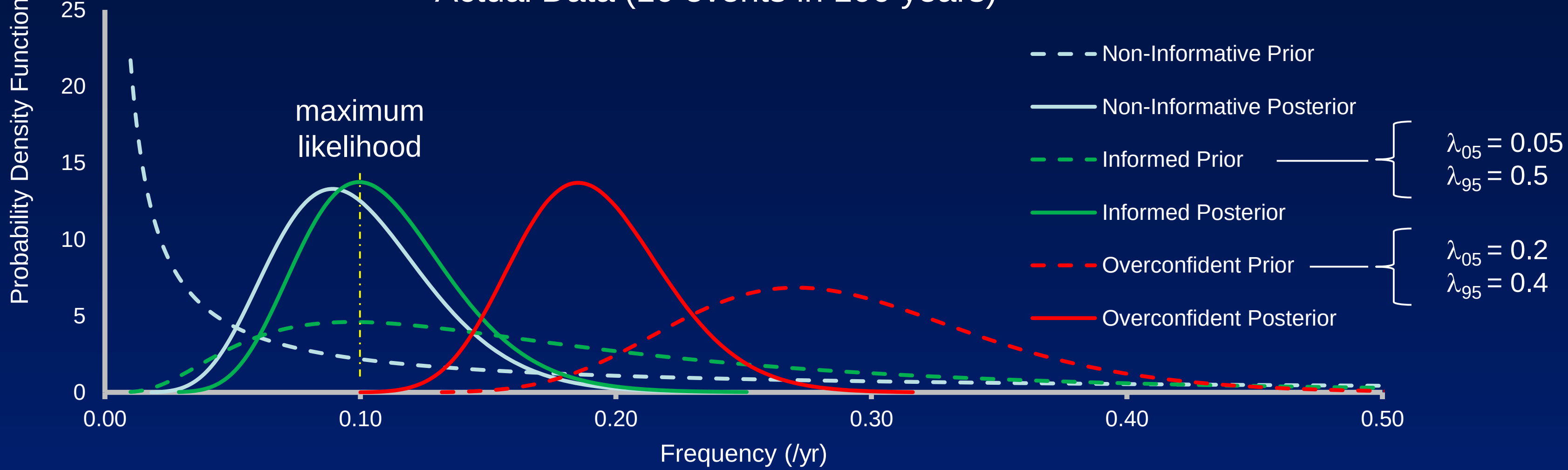
Conjugate Likelihood-Prior Pairs

- 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 $\beta' = t + \beta$

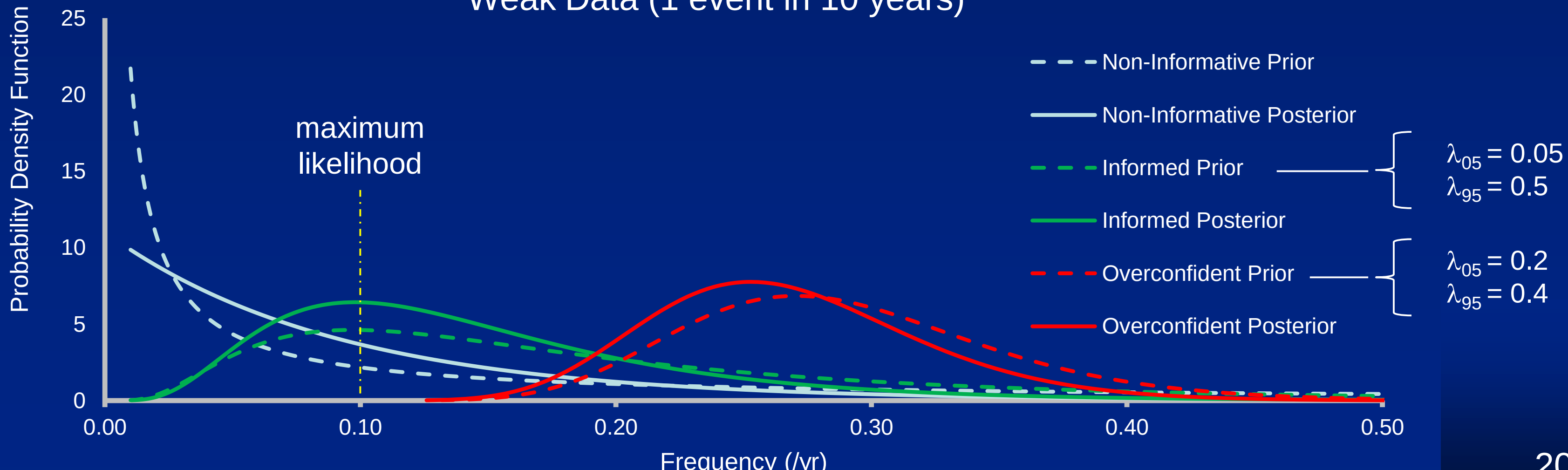
*See Probability Math background slides for more information on the beta and gamma distributions

Sample Results

Actual Data (10 events in 100 years)



Weak Data (1 event in 10 years)



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

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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

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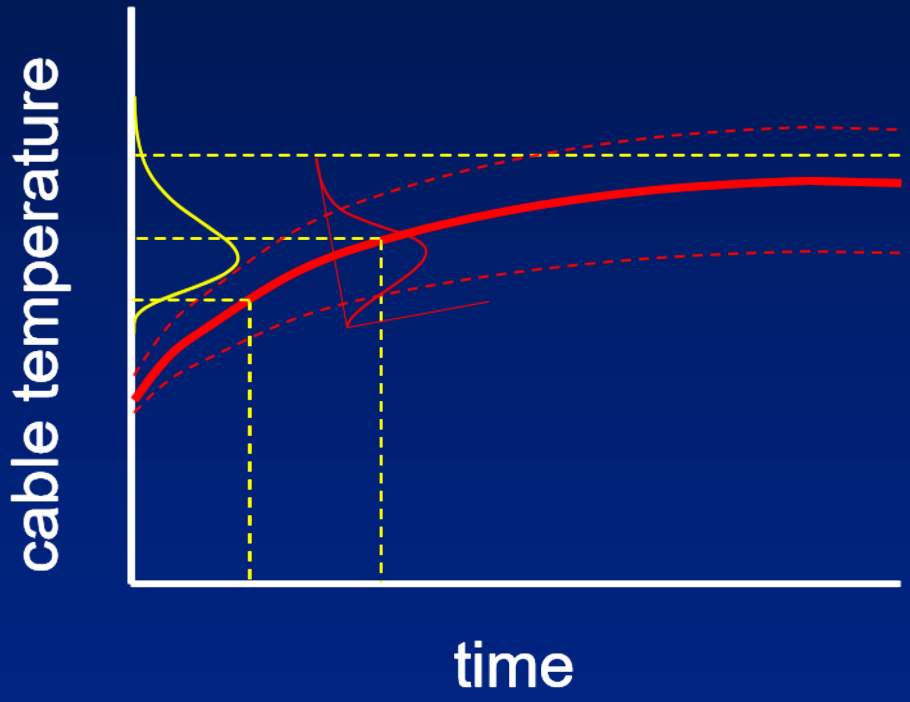
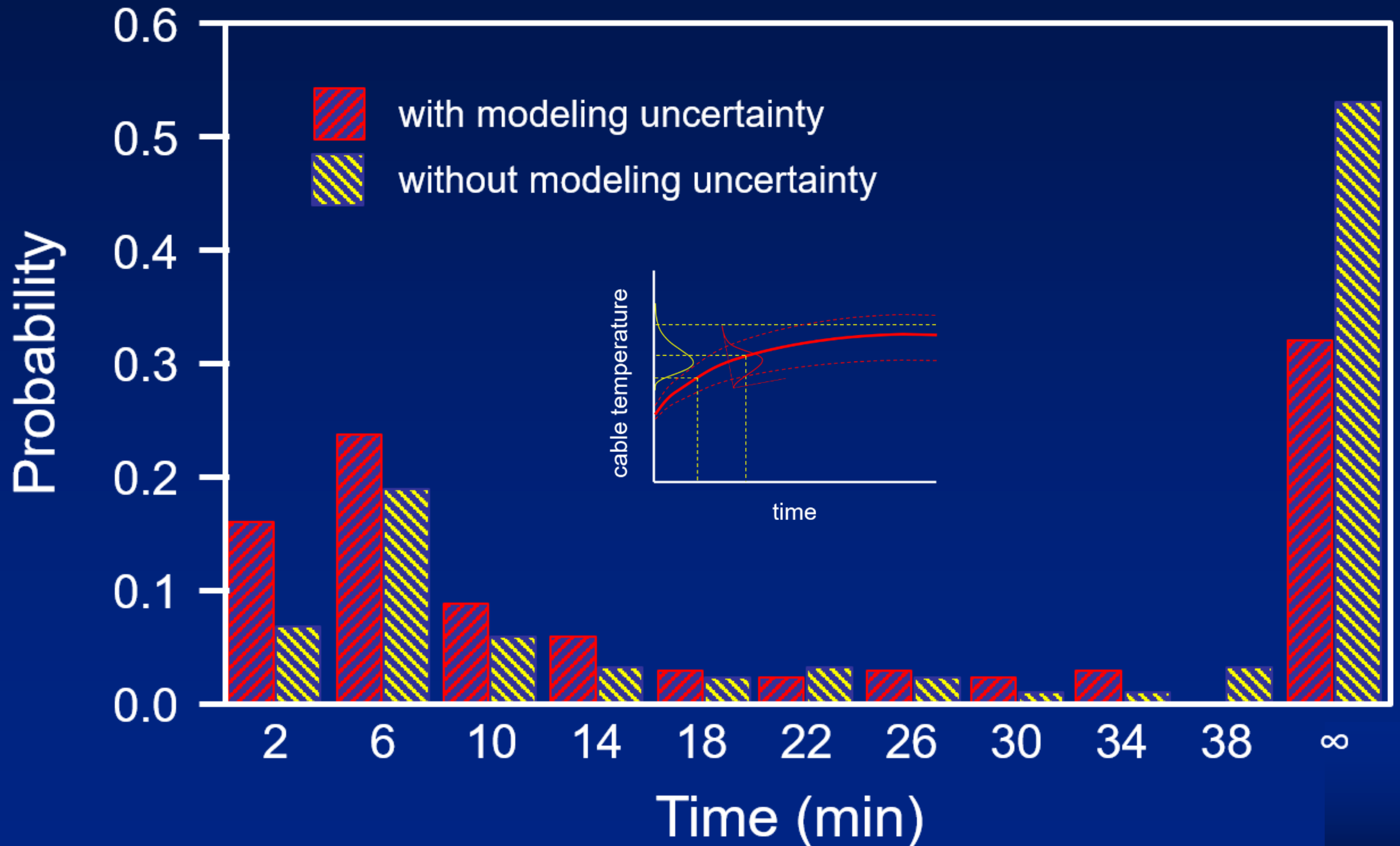
Fire Model Uncertainty Example



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

what "we" know

what "we" believe → $P\{X|C,H\}$

proposition/event of concern

conditions of probability statement

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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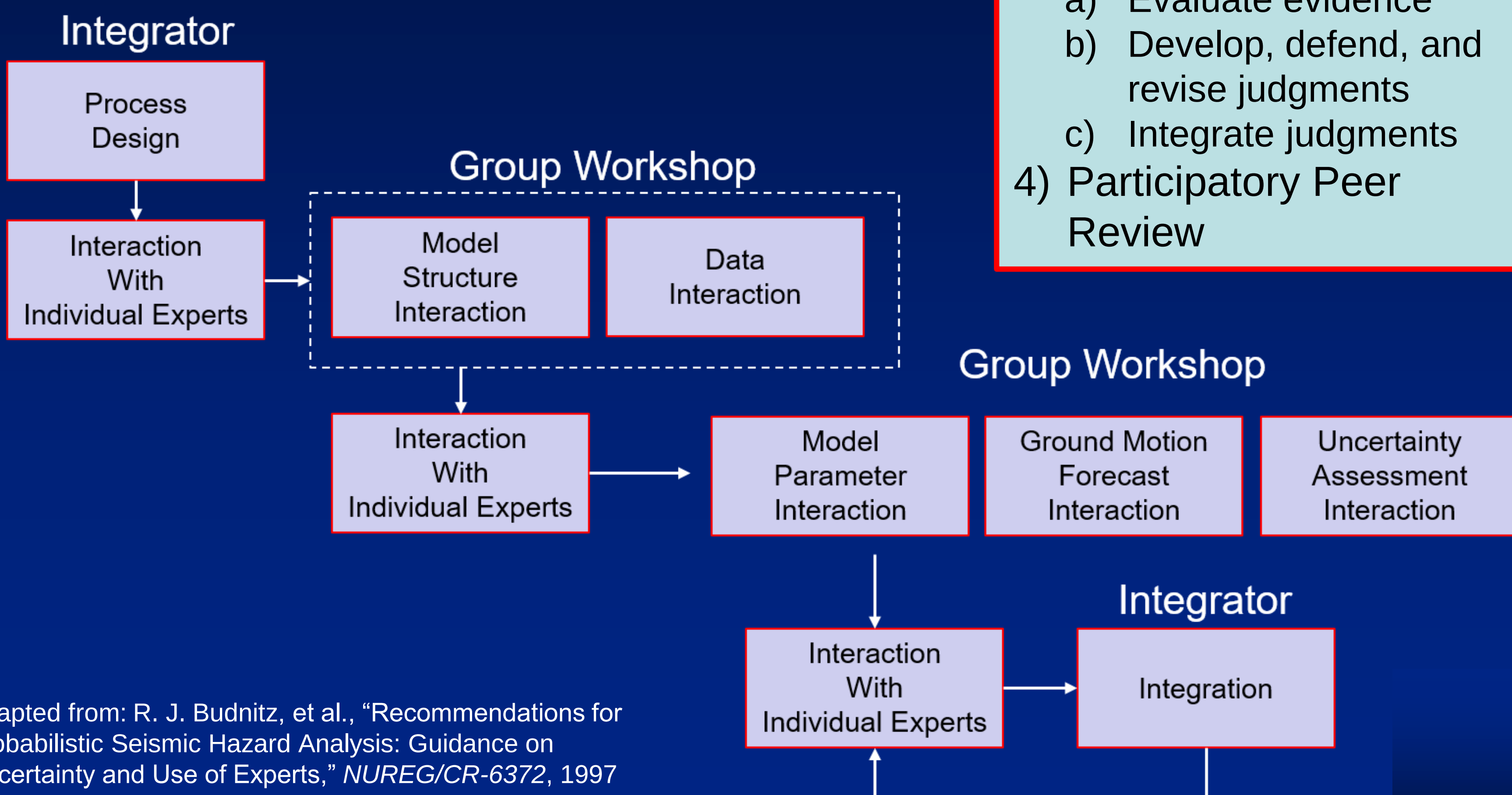
Level 4 SSHAC

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"