LA-UR- 11-04092

*Approved for public release;*
*distribution is unlimited.*

*Title:* Integrated System Health Management with Reliability and Risk

*Author(s):* David H. Collins and Aparna V. Huzurbazar

*Intended for:* Presentation at the Joint Statistical Meetings, Miami, FL, July 30-August 4, 2011

Los Alamos NATIONAL LABORATORY EST. 1943

Integrated System Health Management with Reliability and Risk

**Author(s):** Aparna Huzurbazar*+ and David H. Collins **Companies:** Los Alamos National Laboratory and Los Alamos National Laboratory **Address:** MS F600, Los Alamos, NM, 87545,

**Keywords:** prognostics ; flowgraph model ; weapon system ; nuclear reactor

**Abstract:**
Understanding and managing the health of today's complex systems requires a multitude of tools. This talk will give an overview some problems in this area with a focus on Prognostics and Health Management (PHM). The systems that we consider are are typically mission- or safety-critical, expensive to replace, and operate in environments where reliability and cost-effectiveness are a priority. PHM programs are essential for understanding and managing these systems for high reliability at minimum cost. In recent decades, great advances have been made in sensor and monitoring technology, for example, in real-time condition monitoring of aircraft engines, as well as in off-line diagnostic testing. For systems such as military aircraft this results in large, heterogeneous datasets containing information on internal vibration, chemical composition of propellants and lubricants, corrosion, etc., as well as environmental data such as ambient temperature and humidity. The challenge for PHM is to filter and integrate such data to drive predictive models.

# Integrated System Health Management with Reliability and Risk

David H. Collins and Aparna V. Huzurbazar

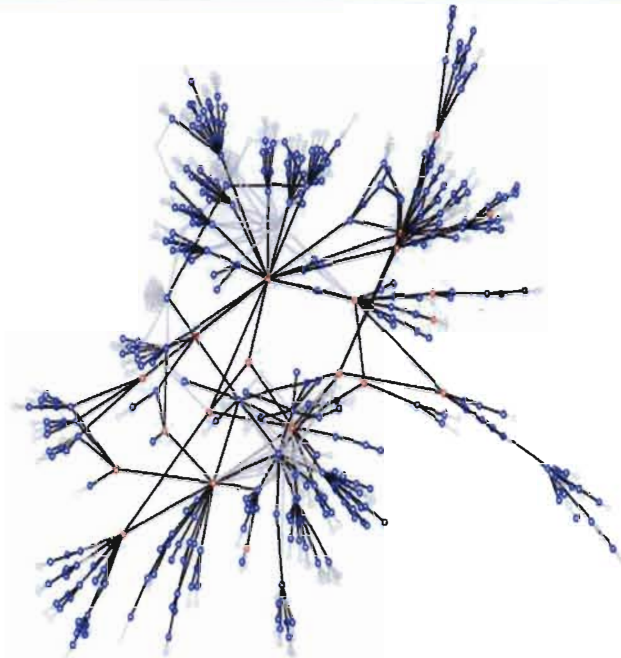
Statistical Sciences Group
Los Alamos National Laboratory

# Integrated Health Management

- Define terms
  - Complex systems
  - System health
  - Prognostics and health management (PHM)
- System models
- The data environment
- Statistical tools
- Issues and challenges

# Characteristics of complex systems

- System: group of components that interact to function as a whole
- Component: part of a larger whole
- Subsystem: component composed of interacting subcomponents
- Unit: a system, subsystem, or component

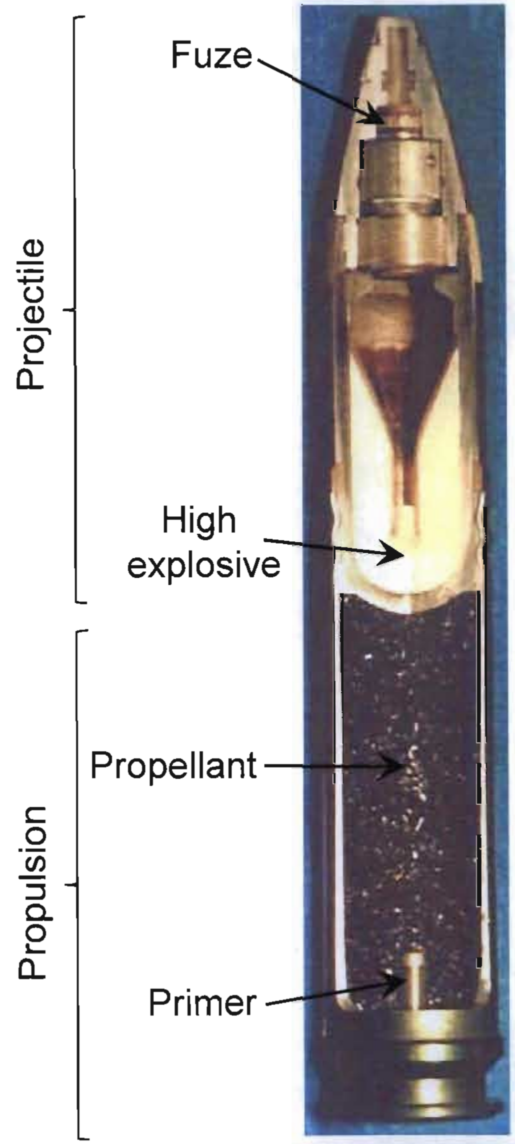


- ***Complex system:*** many components, multilevel hierarchy, difficult to understand and manage
  - Components have varying amounts of interdependence
  - Boundary conditions (interfaces, environment) are significant
  - Available data is heterogeneous, incomplete
  - Challenge: Integrate multiple data sources to produce credible health assessments and aid decision-making

# Complex system example

Campaign 8 Enhanced Surveillance

- M789 30 mm cartridge is a moderately complex system
- Cartridge(s) plus M230 gun comprise a more complex system
- Cartridge(s) plus gun(s) plus helicopter comprise an extremely complex system
- Interactions within/among (sub)systems will affect health/reliability



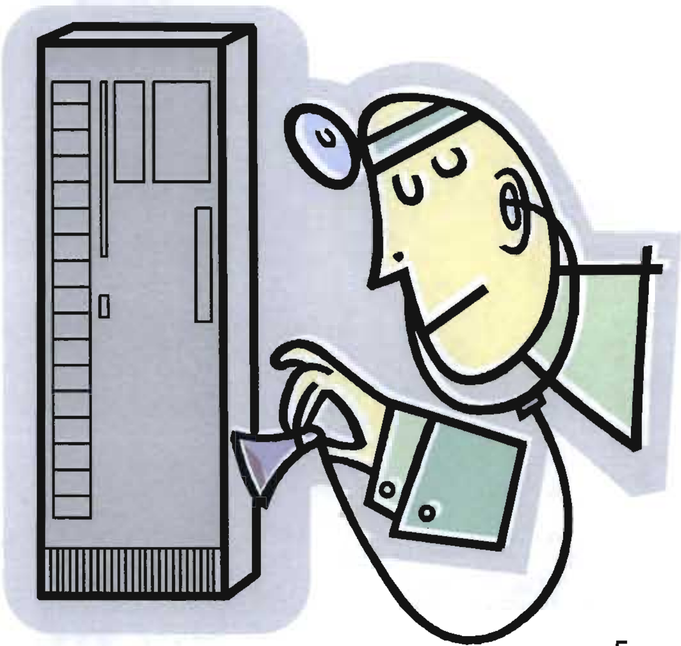
# System health



General definition:

- Adequate safety margins for intended uses, taking into account uncertainties in measurements of system integrity, load levels and environmental conditions
- Absence of observable damage or material changes
- Operating performance within specified ranges
- Predicted reliability within specified range
- No predicted degradation that would compromise system integrity, reliability, or safety within a specified time period

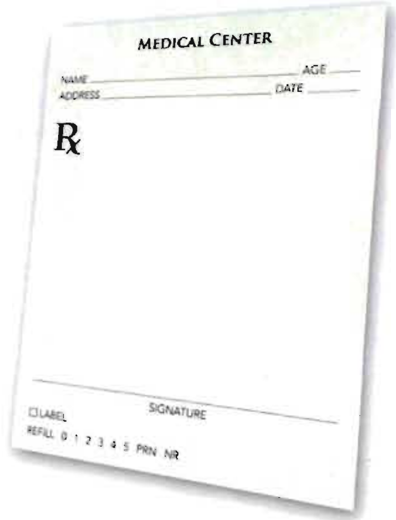
*Application is context-dependent*



# Prognostics and health management

Campaign 8 Enhanced Surveillance

- ***Prognostics***: prediction of future health conditions based on current and historic environmental and condition data, using physical and statistical models.

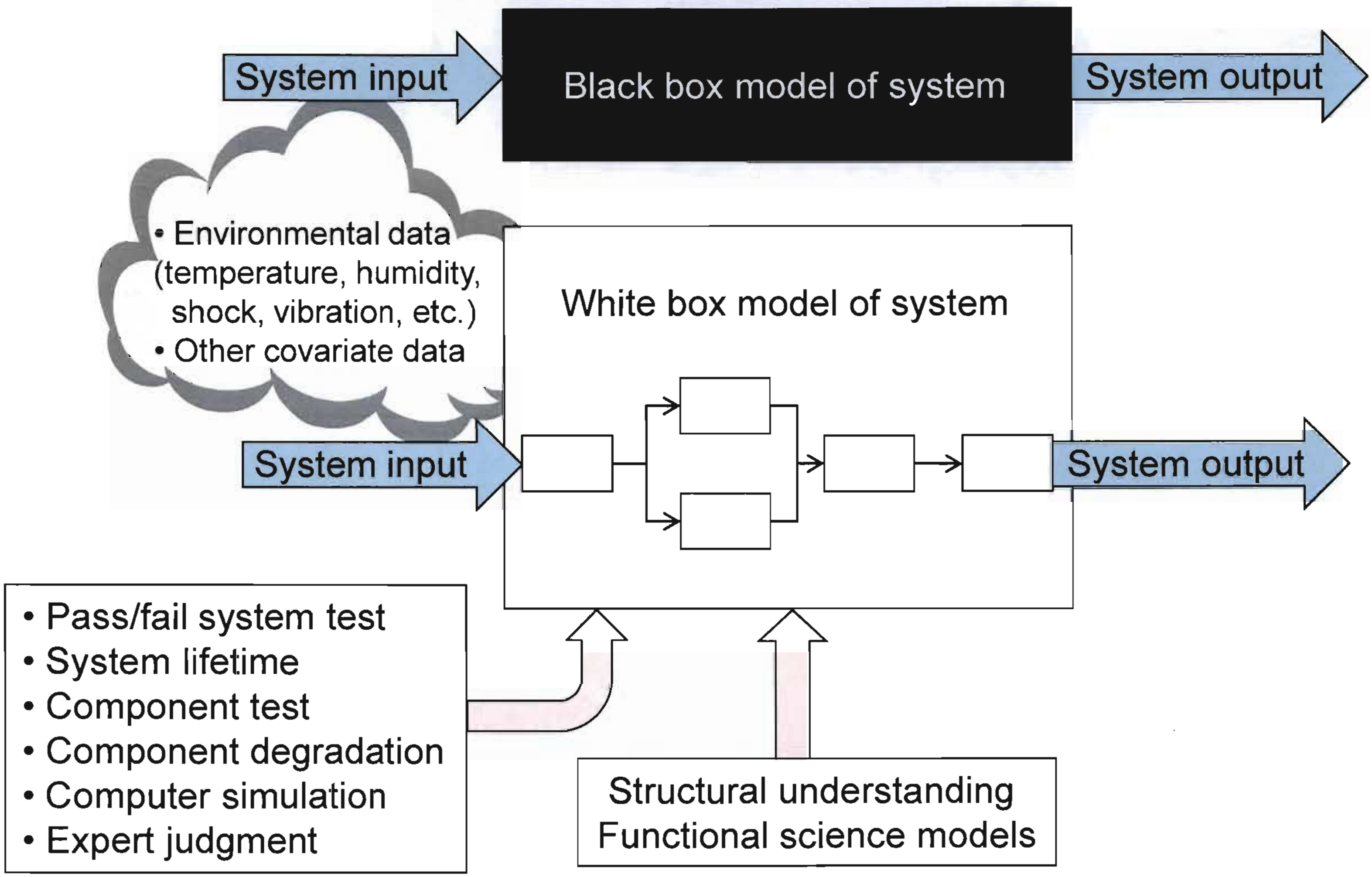



- ***Health management***: use of prognostics to manage maintenance and logistics for increased reliability and reduced cost.

A variety of statistical and other techniques come under the PHM umbrella . . .

# PHM component and system models





# The challenge of heterogeneous data

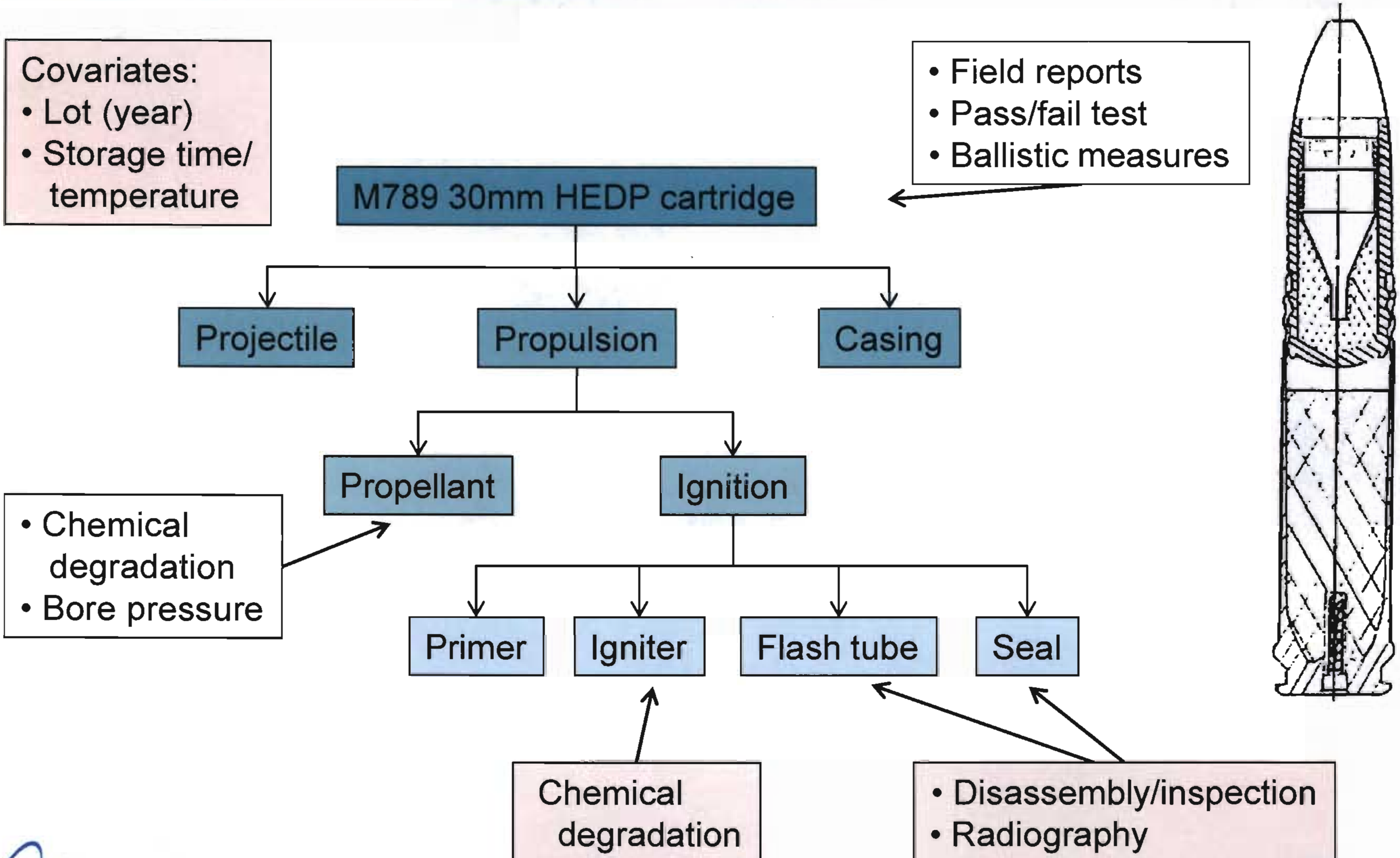
Campaign 8 Enhanced Surveillance

***Typical situation for complex systems:***

- Full system tests expensive and difficult to perform
- Unit test data for some components
- Computer simulations based on scientific models
- Expert judgment may be best available information
- Heterogeneous data types:
  - pass/fail
  - lifetime
  - degradation
- Differing levels of uncertainty, depending on source/quantity of data
- Costs of obtaining data vary widely; issues:
  - cost-effectiveness of data acquisition
  - resource allocation for testing

# Heterogeneous data example

Campaign 8 Enhanced Surveillance



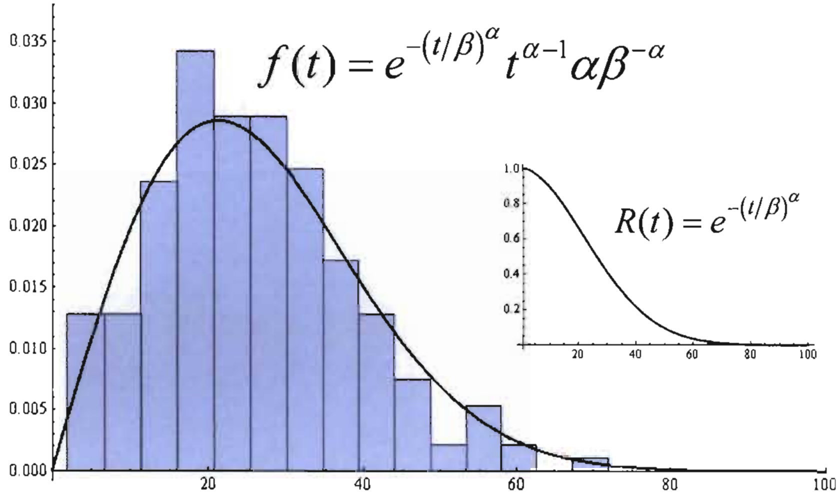
# Statistical tools supporting PHM

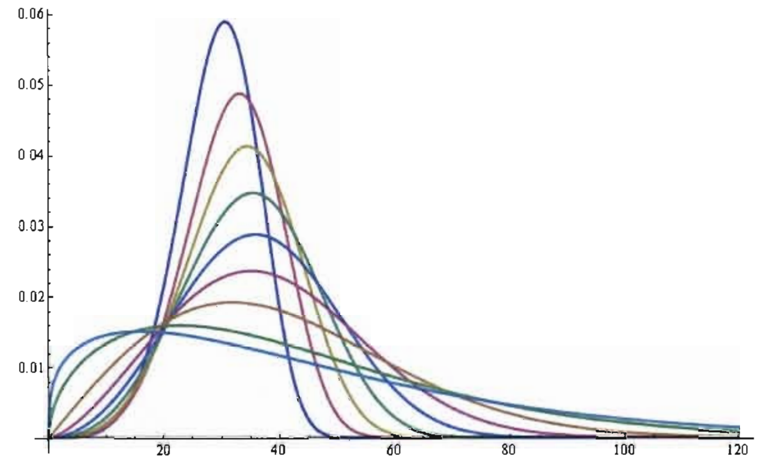


- Black box models for components/systems
  - Lifetime distributions (exponential, Weibull, . . . )
  - Regression models (logistic, probit, Weibull, . . . )
  - Nonparametric regression, empirical distributions
- Structural (white box) models
  - Block diagrams, fault trees, path/cut sets, . . .
  - Multistate models, statistical flowgraphs
  - Bayesian networks
  - Monte Carlo simulation
- Hybrid (meta-analytic)
  - Combine multiple data sets/types for prediction
  - Primarily Bayesian, allows uncertainty quantification
- Plus . . . optimization models, other decision support tools

# Example: Weibull lifetime distribution

Campaign 8 Enhanced Surveillance

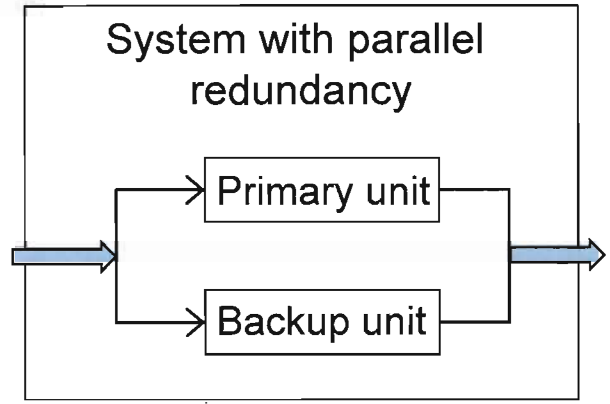


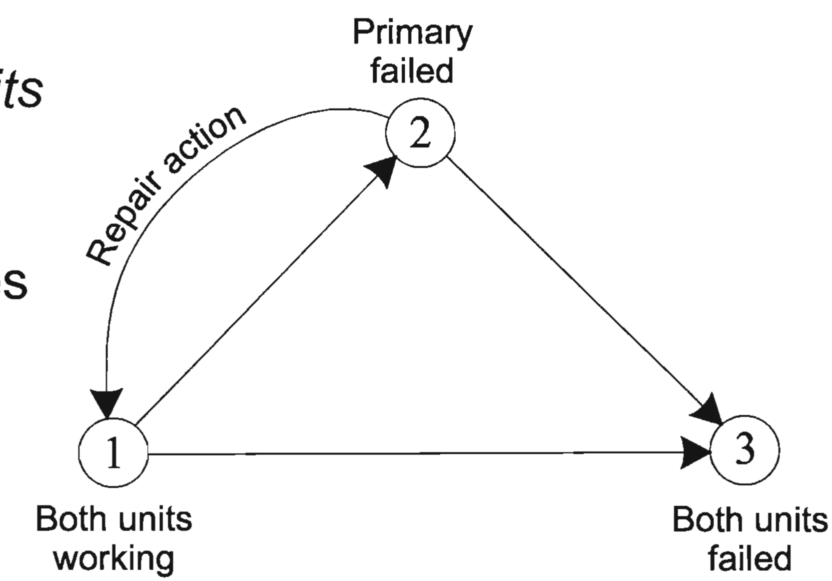

- Parameters $\alpha$, $\beta$, can be related to a physical model (weakest-link model) or fitted to observed data
- Bayesian analysis: place prior distributions on $\alpha$ and $\beta$
- Parameter values may be determined by covariates, e.g., temperature $\tau$: $\alpha = \alpha(\tau) = c_0 + c_1\tau$

# Example: statistical flowgraphs

- Block diagrams, fault trees and similar representations don't capture enough structure

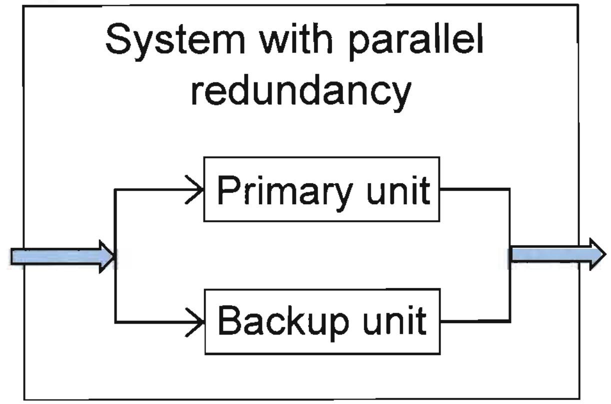


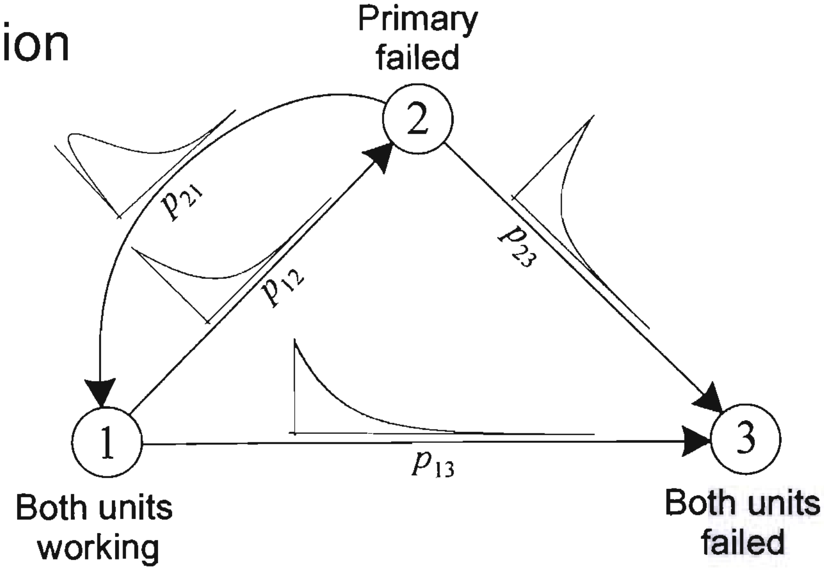

- Representation by *system states* rather than *physical units* can capture
  - repair actions
  - probabilities of state changes
  - holding time distributions in states
  - recurrent events



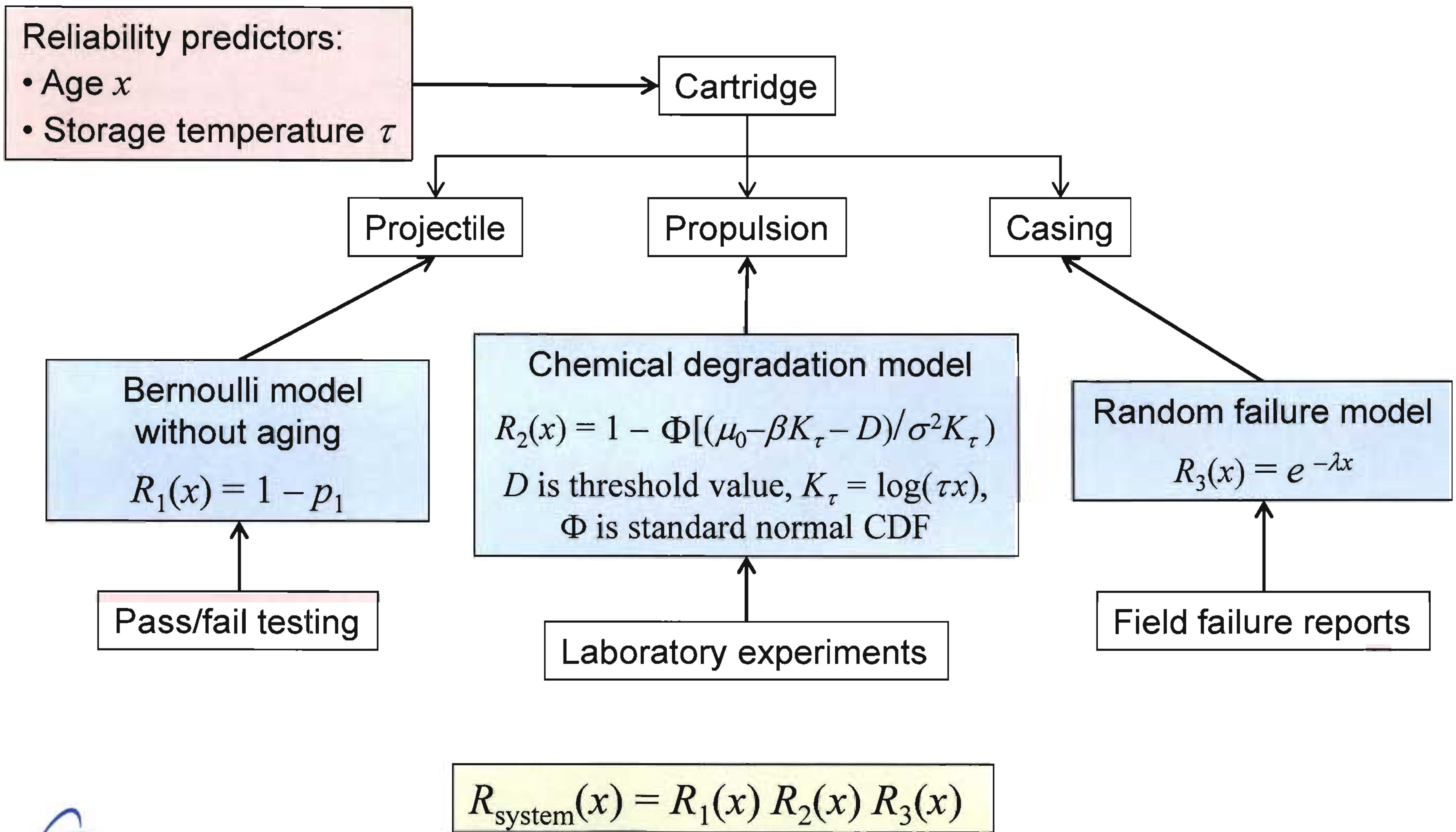
# Example: statistical flowgraphs

- Flowgraph representation includes
  - system states
  - probabilities of transitions between given states
  - holding time distribution in a state, given the destination state
- Statistical flowgraph framework computes distribution for first passage between arbitrary states



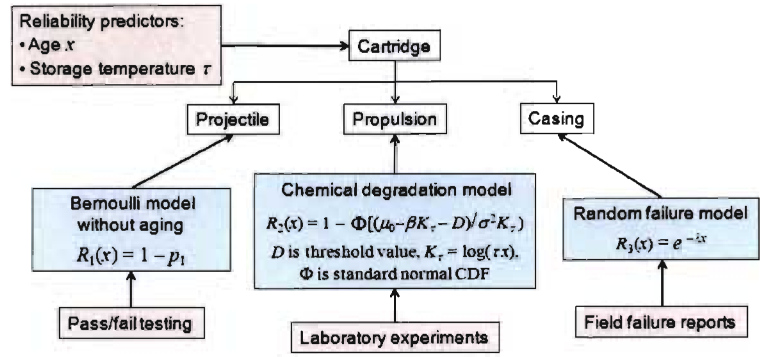



# Example: combining reliability data



# Example: combining reliability data

***Note:*** this model is highly simplified for illustrative purposes.




$$R_{\text{system}}(x) = R_1(x)\, R_2(x)\, R_3(x)$$

A more complete analysis, using Bayesian methods, enables

- Combining system-level test results with component-level results
- Accounting for component dependencies
- Accounting for differences in test quality and model uncertainty
- Incorporating expert judgment and experience
- Producing quantitative estimates of uncertainty in system reliability predictions

# Supporting sound decision-making

Campaign 8 Enhanced Surveillance

- Examples of quantitative statistical outputs:
  - Distribution of the number of system/component failures over a time period
  - Distribution of the time to system/component failure
  - System MTTF, MTTR
  - Probability of mission success
  - Expected number of launches to achieve a given number of successes
  - Confidence/tolerance intervals
  - Etc.
- Examples of decisions to be made:
  - Optimal spares stocking, preventive maintenance policy
  - Risk assessment, need for backup systems
  - Number of missions to launch to meet objective
  - Etc.

# Issues and challenges

Campaign 8 Enhanced Surveillance

- Presentation of predictive information and associated uncertainties to decision-makers
- Use of large heterogeneous datasets
- Integration of rich structural models (e.g., flowgraphs)
- Allocation of resources for acquiring data
- Integration of PHM with existing tools (FMECA)
- Cost justification of PHM

# Summary

- PHM is increasingly important for understanding and managing complex systems.
- Diagnostic/prognostic data is heterogeneous, incomplete
- Integrating data for decision-making requires new statistical tools
  - for prediction
  - for uncertainty quantification
- We have presented a menu of tools, with examples
- Ongoing work aims at improved integration and usability, better uncertainty quantification