ENRE 447/602 Reliability Analysis

Module 1: Course Overview, Reliability Engineering Perspective & Fundamentals

Professor:

Dr. Katrina M. Groth

Mechanical Engineering Department

Associate Director, Center for Risk and Reliability

University of Maryland

kgroth@umd.edu

Co-Instructor:

Dr. Mohammad Modarres

Center for Risk and Reliability

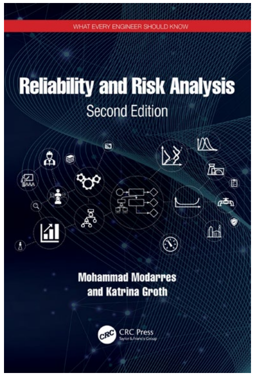
University of Maryland

modarres@umd.edu

Objectives for part 1 of this module

- To introduce ourselves
- To explain how this course is designed
- To set expectations for students and instructors
- To discuss logistics & answer questions about the course

Course Topics (Modules) for ENRE447 & ENRE602



Prof. Katrina M. Groth

Mechanical Engineering,
Center for Risk and Reliability

University of Maryland

By the end of this course, you will understand the fundamental qualitative and quantitative methods for conducting reliability and risk analysis for engineering systems.

Modules

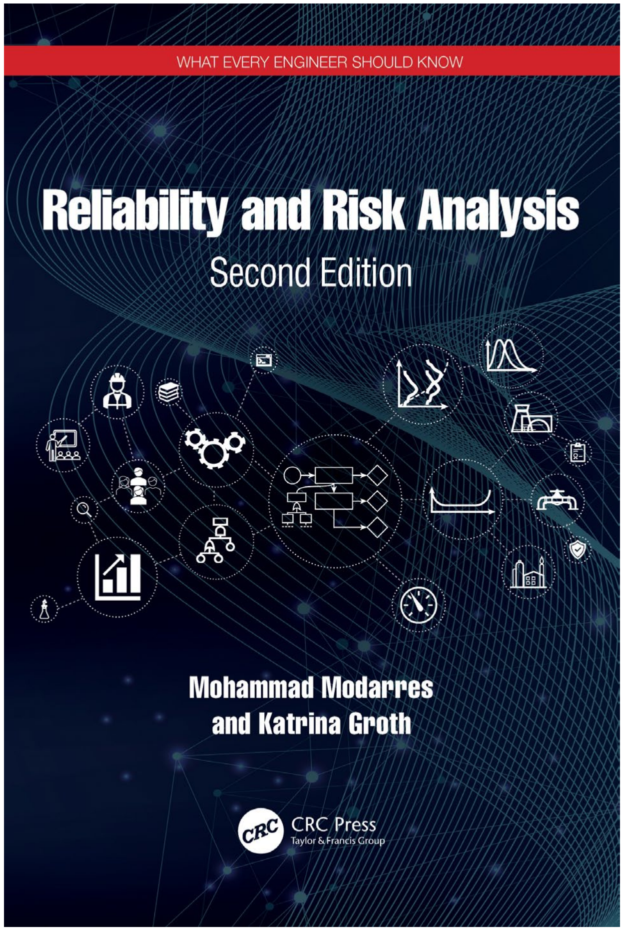
ENRE447: Modules 1-6, 9

1. Reliability Engineering in Perspective
2. Reliability Math: Probability
3. Elements of Component Reliability
4. Reliability Math: Statistics
5. Reliability Data Analysis & Model Selection
6. System Reliability Analysis

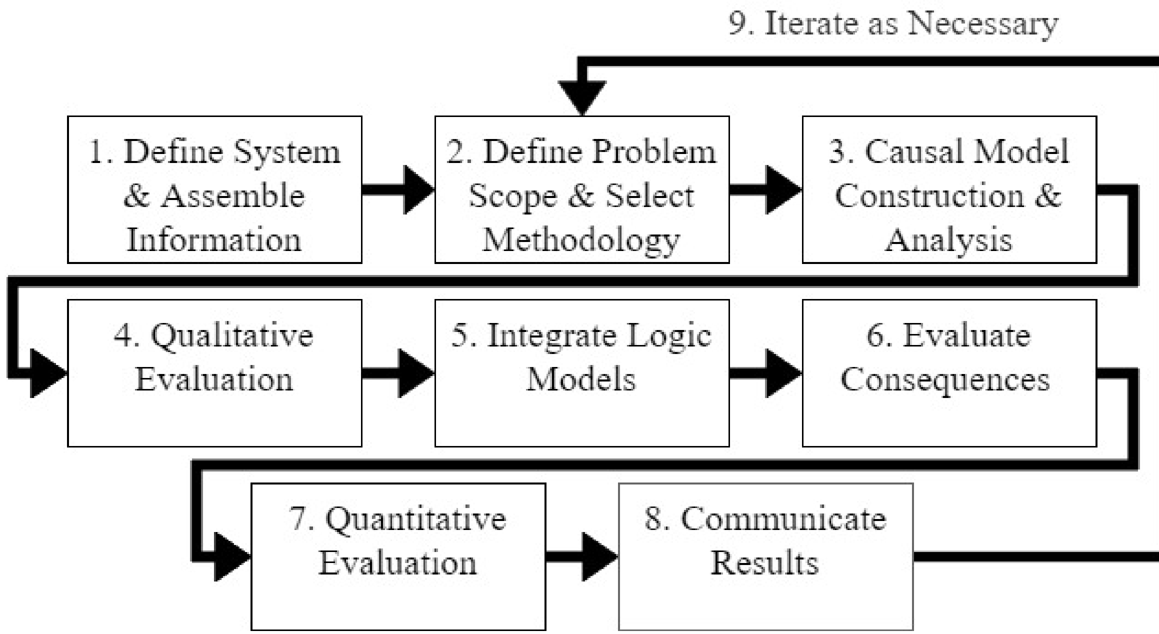
ENRE602: All Modules

7. Reliability and Availability of Repairable Components and Systems
8. Advanced Topics: Uncertainty Analysis, Importance Measures, Human Reliability Analysis, Bayesian Networks, Reliability Research
9. Risk Analysis

Textbook- PRINTED version needed.



Paperback pictured; Hardcover is light blue plain cover



Modarres & Groth, *Risk and Reliability Analysis,* Taylor and Francis, **April 2023**. https://www.taylorfrancis.com/books/mono/10.1201/9781003307495/reliability-risk-analysis-mohammad-modarres-katrina-groth

General Info

- Open the syllabus now. We'll go over it in a few slides.
  - The syllabus is the authoritative source of information about this course. In case of any differences between this presentation and syllabus, the syllabus takes precedence.
- Course format & attendance:
  - Lectured-based with frequent interaction and exercises; On campus & recorded for distance education students (typically asynchronous).
  - On campus students (0101) - attend in person unless you have an excused absence; excused: watch recorded video from this week's lecture. Available on ELMS\Video Lectures.
  - If instructors are unable to attend: class will be asynchronous using previously recorded lecture.
  - Lectures are recorded for future educational purposes. Microphones in this room are always on.
  - Do not distribute course materials or lecture videos to anyone.

Center for Risk and Reliability (CRR)

Home to UMD's Reliability Engineering Program. Location: 0151 Martin Hall

Our Mission

We advance reliability and risk analysis for complex engineering systems through innovative research, education, and collaboration with industry partners.

Our Approach

We *research* why systems fail, how they fail, when they fail, how to prevent failure, and how to mitigate consequences.

We *educate* through coursework, research, and stakeholder engagement. We *engineer* solutions.

Our Impact

We prevent losses and protect life, property, and the environment. Our work improves systems and processes in energy, transportation, defense, space, information systems, and civil infrastructures.

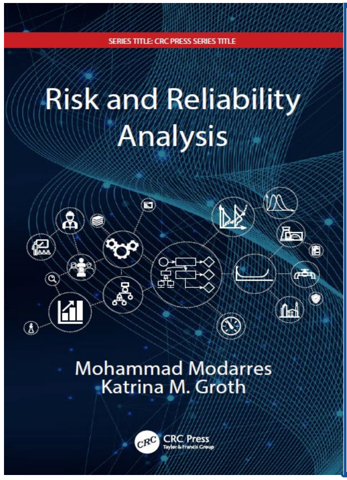
Fast Facts about UMD's Reliability Engineering program & Center for Risk and Reliability

20+
Core, Affiliate, and Adjunct Faculty

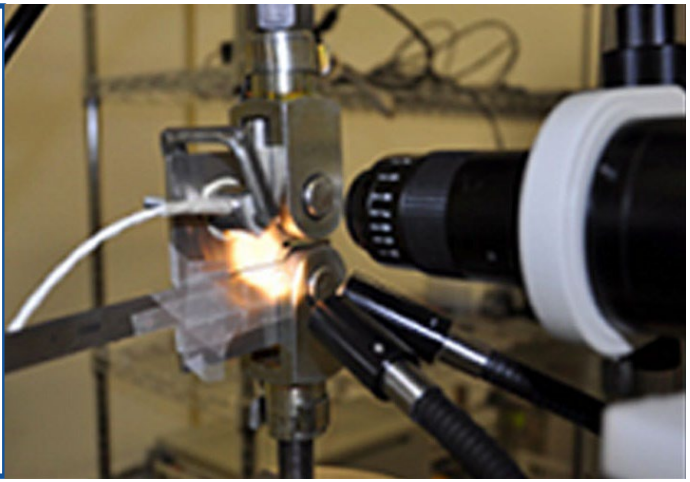
6
Cutting-Edge Research Laboratories

4
Degrees Offered (Ph.D. M.S., M.Eng, Certificate)

500+
Graduates since 1991



- Systems Risk and Reliability Analysis Lab (SyRRA)
- Probabilistic Physics of Failure and Fracture
- Cybersecurity Quantification Lab
- Risk And Decision Analysis Lab (RADA)
- Design Decision Support Lab
- Laboratory for Reliable Nanoelectronics
- Risk-Informed Solutions in Engineering (RISE)



The **#1** Reliability Engineering program in the U.S. (Source: Scopus)

Our alumni are making impact

Government

FDA U.S. FOOD & DRUG ADMINISTRATION
U.S.NRC
Australian Government Defence
Office of Naval Research Science & Technology ONR
Department of Defense United States of America
Naval Air Systems Command
NASA
NIH National Institutes of Health

Academia & Research

Johns Hopkins Applied Physics Laboratory
Colorado State University
Rutgers
University of Maryland
UCLA
China University of Petroleum
University of Illinois Urbana-Champaign

Industry & Tech

AcuTech
Google
Bell
Ford
Capital One
metro
ExxonMobil
amazon
Chevron
FM Global
intel
Northrop Grumman
Marathon
SIEMENS
RIVIAN

Teaching philosophy: why am I a professor?

- To expand the field of reliability engineering via research & students
- Realization that risk & reliability are essential for many disciplines, but that few people have more than one method in their toolbox…e.g. entirely quantitative, entirely qualitative..
- To bring you a spectrum of methods – qualitative & quantitative – to apply to your problems.



Introductions

Instructor & TA

Various administrative contacts:

- M.S. and Ph.D. students: Your advising is through the Mechanical Engineering (and Reliability Engineering) department graduate office (megrad@umd.edu) and proctoring is through DETS.
- M.Eng. and Certificate Students: Your advising (and proctoring) is via the MAGE office mage-advising@umd.edu

- Who are you and why are you here? (Speak loudly! And give me a moment to check my class roster)
  - Ask TA first.

My approach to this class

- The class is an environment, a variety of materials and assignments in multiple formats, which together create a learning experience.
- Math + theory + discussion + engagement + real applications
  - Opportunity to really dig into both the math and the theory and align these
  - Use discussion to provide opportunity for you all to get what you want and need out of this class
- Active learning – Learning is more than listening. You complete problems, some of which will be designed to be hard. You must try (and in some cases fail) now before you are faced with these problems in the field.
- Needs 10-20 hours per week from you.

My approach to this class

- ***You are my product, not my customer.***
  - I have high standards for my product! I want you to become capable engineers and maintain (or increase) the quality and integrity of a UMD engineering degree.
  - I want you all to succeed and have designed the class carefully.
  - You must study & work hard to be a product I can be proud of.
  - As an engineer, I must uphold the fundamentals of the profession; I cannot “release” a faulty product. I don’t give passing grades just for showing up.
- If you are struggling, please reach out and we will figure something out together.

Key elements of syllabus

- Pull up your syllabus and review:
  - Grading
  - Exam dates
  - Schedule
  - Policies and expectations
  - Communication
  - Academic integrity
  - Copyright policy

Grading Rubric – available on ELMS – read it!

- Show me your understanding, not just your answer.
- Most problems will be broken down into multiples of 5 points
- Shows example of good vs. bad solution.

5	**The student clearly understands how to solve the problem and the solution is correct.**
4.75	**The student clearly understands how to solve the problem.** Minor mistakes and careless errors (akin to typos) may have led to an incorrect answer, but they do not indicate a conceptual misunderstanding.
4	**The student understands the main concepts and problem-solving techniques, but has some minor yet non-trivial gaps in their** understanding, reasoning, or explanation.
3	**The student has partially understood the problem.** The student is not completely lost, but requires tutoring in some of the basic concepts. The student may have missed a critical step or aspect of the problem. The student may have started out correctly, but gone on a tangent or may have not finished the problem.
2	**The student has a poor understanding of the problem.** The student may have gone in a not-entirely-wrong but unproductive direction, or attempted to solve the problem using pattern matching or by rote. The student may have shown so little work, or made major errors in notation that the understanding cannot be determined even if the answer is correct. The answer may appear somewhere but cannot be clearly identified.
1	**The student did not understand the problem.** They may have written some appropriate formulas or diagrams, but nothing further. Or, they may have done something entirely wrong.
0	The student wrote nothing or almost nothing.

Other elements of grading: following directions, submitting neat, professional work on time.

Participation / coursework – did your participation enhance the class & the learning experience for the class?

Academic integrity

- Under the Code of Academic Integrity, there are five types of academic dishonesty: **cheating, fabrication, facilitation, plagiarism, and self-plagiarism.**
- **Don't do it.**
  - It hurts all UMD grads and the engineering profession. It devalues your degree and mine.
  - Your academic & professional integrity is more important than any grade or any assignment.
- I will report it. Please report it to me if you find it.
  - Apathy in the presence of academic dishonesty is NOT a neutral act.
  - All of us - students, faculty, and staff - share the responsibility to challenge and make known acts of apparent academic dishonesty.
- *Do you want to get on an airplane designed by someone who cheated to get through engineering school?*

Clarifications on academic dishonesty in this class.

- If you haven't done it: Read the whole Code of Academic Integrity.
- These are NOT a violation:
  - Collaborations on homework is ok! See details on syllabus.
  - Exams – TBD, but they will be either open book/notes OR allow at least 1 page of notes.
  - Asking and answering questions about homework on our course website is ok (within moderation. I.e., not every problem, every week).
  - Using solutions I give you as part of your notes for subsequent open note assignments.
- Examples of violations:
  - Distributing course materials to any person or entity who is not registered in this semester of this course. (Don't upload them to a website, test bank, group chat, etc.)
  - Using any course materials or solutions from a previous semester or any source other than the course website. (Only use solutions that I give you.)
  - Using an outside source without citing it. (Cite any outside sources you use in Chicago or IEEE style.)
  - Changing your answer on a quiz while we are grading it together in class. (Don't!)
  - Copying homework #2 from your friend because you forgot it was due today (Don't! Both of you are cheating now! I drop a homework for a reason!)
  - Using specialized engineering software from work.
  - Using ChatGPT or similar. Using Chegg or similar.

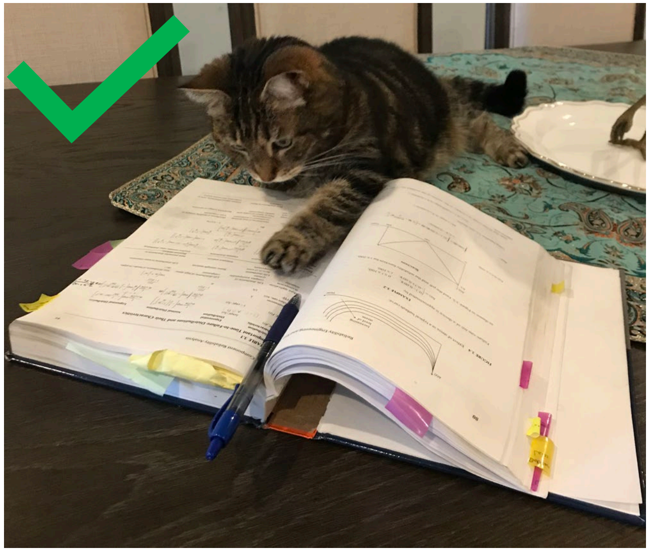
NSPE Code of Ethics: Fundamental Canons

- Engineers, in the fulfillment of their professional duties, shall:

1. Hold paramount the safety, health, and welfare of the public.
2. Perform services only in areas of their competence.
3. Issue public statements only in an objective and truthful manner.
4. Act for each employer or client as faithful agents or trustees.
5. Avoid deceptive acts.
6. Conduct themselves honorably, responsibly, ethically, and lawfully so as to enhance the honor, reputation, and usefulness of the profession.

Tips for success

- **Put in the time outside of class.**
- *Work through* the problems in the textbook & slides. (don't passively read)
- Do the assignments. Work through the solutions after they are released.
- Create topic summaries & reference sheets
- Read the textbook. Read the cited references if you have additional questions about specific topics.
- Connect with each other
- Go to the library & read reliable sources:
  - ✓ Reliable: Textbooks, journal articles, government reports, software documentation & some forums
  - ✗ Unreliable: blogs, homework "help" sites (aka cheating websites), twitter, or un-verified information from search engines



Let's have a great semester!

- Any questions?

Breakpoint
Begin Reliability Engineering Perspective & Fundamentals

Objectives for this module

- At the end of this module you will be able to:
  - Identify common motivations for studying reliability engineering
  - Identify multiple approaches used in reliability analysis
  - Define key terms: Reliability, risk, availability, maintainability, failure, performance, system component
  - Define and use failure modes, failure mechanisms, and causes to discuss failure scenarios.

Why study risk & reliability?

- The core of U.S. economy, security and quality of life depends on *complex engineering systems (CES)* that range from power plants, energy systems, and pipelines to aircraft, defense, and transportation.
- Engineers create transformative technologies …but the engineering doesn't end when the product is delivered or the lights come on.
- Systems can be engineered for safety & reliability
- Engineers need insight into how to prevent, mitigate, and recover from system failures, accidents




Things Fail

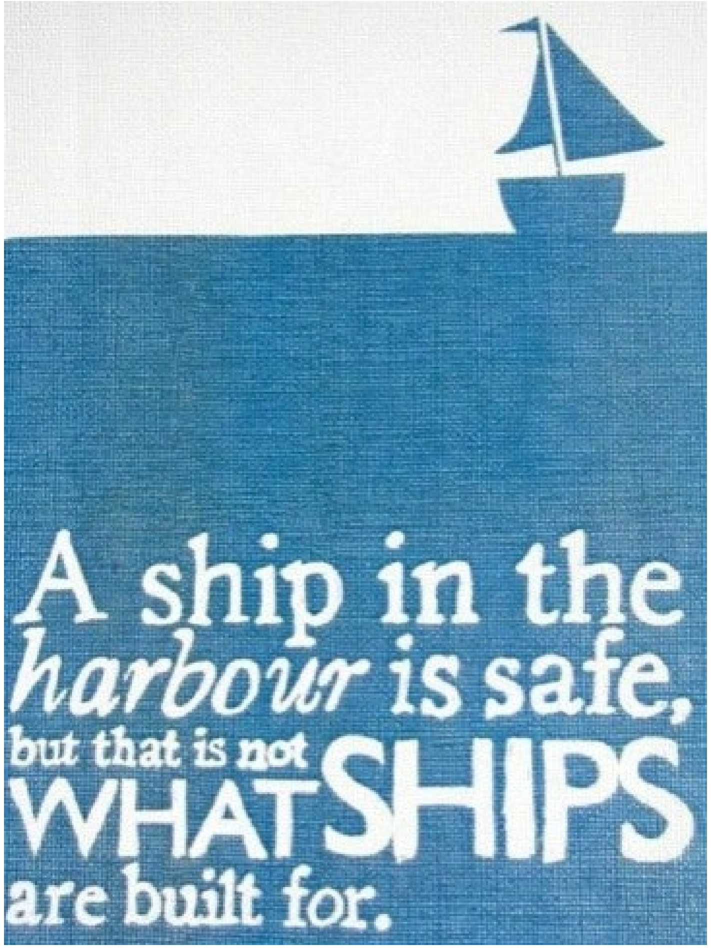
- 2011– Fukushima Daiichi– Earthquake and tsunami induce loss of reactor cooling, resulting in meltdown; radiation release and environmental contamination; evacuation
- 2003 – Space Shuttle Columbia disintegrates on reentry to Earth;
  - Loss of all 7 crew members
  - US space program grounded
  - Small piece of insulation broke off during takeoff –due to aerodynamic forces at takeoff.
- 2009 Air France 447 crashed into Atlantic Ocean en route from Rio de Janeiro to Paris
  - Inaccurate airspeed measurements due to frozen pitot tubes
  - 228 fatalities

…and they keep failing

- Nuclear
  - Three Mile Island
  - Fukushima accident
  - Davis Besse
- Aviation & Aerospace
  - Challenger
  - Columbia
  - Tenerife
- Chemical, oil, and gas
  - Bhopal
  - Piper alpha
  - Deep water horizon
  - Bruno canyon
  - Aliso canyon
  - Texas city
- Buildings & Infrastructure
  - Grenfell fire
  - Triangle shirtwaist factory
  - Rhode Island Station nightclub
- Many less public examples in defense, intelligence

Reliability engineering supports decision-making

- A process **to create knowledge, explore priorities, encourage discourse** and **build a common basis for safety and reliability decisions**
- By creating an understanding of:
  - What the system is supposed to do (performance)
  - Why and how failures occur (e.g., the sources, causes, and likelihood of failures (physics based, human, computational, etc.)
  - How often failures occur (e.g., likelihood)
  - Strategies to reduce failure (e.g., design, operation, maintenance)

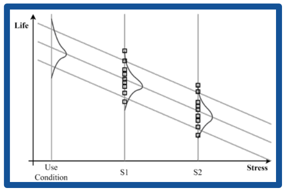


www.curiositiesbydickens.com/wp-content/uploads/ship-in-the-harbor.jpg

History and Evolution of the Field

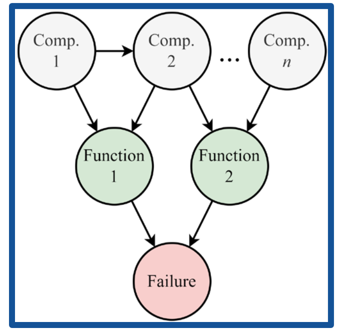
1950s-60s

TTF Distributions
RBDs & FMEA
Physics of Failure



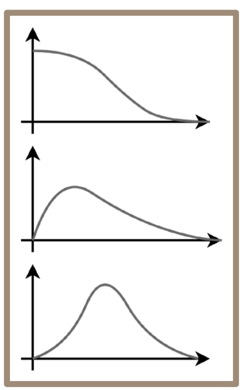
1990s

Probabilistic Physics of Failure
HALT



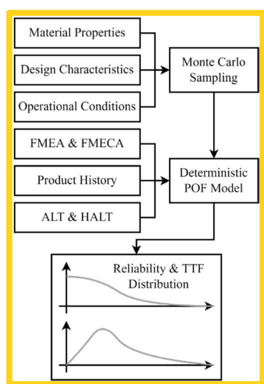
2010s

Bayesian, AI, ML methods
Big Data
PHM & BNs



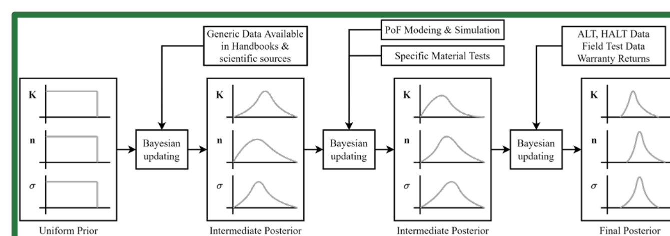
Acc. Life Tests (ALT)
Fault Trees
MLE Methods
Bayesian Estimation

1970s-80s



Hybrid Modeling Approaches (BNs)
MCMC Simulation
CBM & PHM

2000s



Defining Reliability

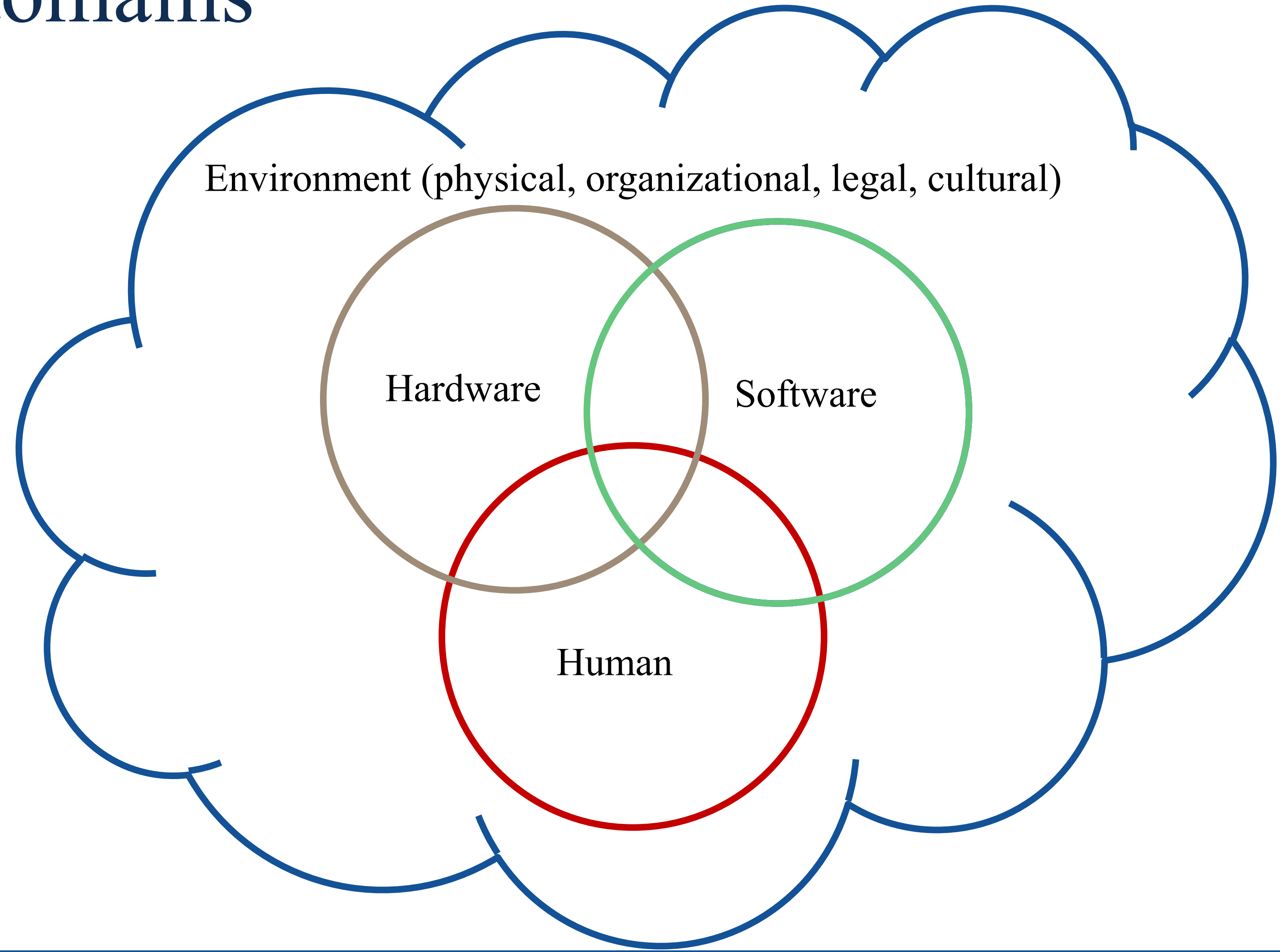
- ***Reliability** is the ability of an item to operate without failure under specified operating conditions to attain a mission having the desired length of time or number of cycles.*
- To assess reliability, we must
    1. Define the item (e.g., part, component, subsystem, system, or structure)
    2. Define the expected mission of the item and what constitutes "success" (or failure)
    3. Define the operating conditions and environments of use
    4. Specify mission variable (e.g., time, # cycles, stress)
    5. Assess ability (e.g., through testing, modeling, data collection, analysis)

Reliability Engineering Approaches

Failure / Damage Data from Field or Test → Failure Model (Distribution) or Physics of Failure Model → Estimate Model Parameters & Uncertainties → Predict Performance / Reliability

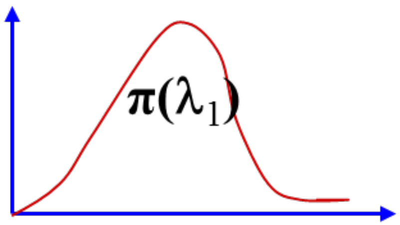
- Deterministic - Understand and model failure mechanisms, physics of failure
  - ENRE600 introduces these in depth.
  - Connects fundamental science and empirical approaches
  - However, it quickly becomes apparent that *predicting failure* inherently involves uncertainty.
- Thus:
- Probabilistic - **Reliability is a *probability***
  - ENRE602 uses the above and adds likelihood (probability) and uncertainty of events.
  - Thus, the probabilistic approach to reliability includes:
    - Understanding failure mechanisms and physics of failure
    - Connecting data and the fundamental sciences (sometimes called a "hybrid" approach.)
    - Using past data to predict future reliability, performance, etc.
    - Using probabilistic and statistical analysis of data
    - Quantifying of uncertainties
      - Random variability (Aleatory)
      - Lack of data, information, knowledge (Epistemic)

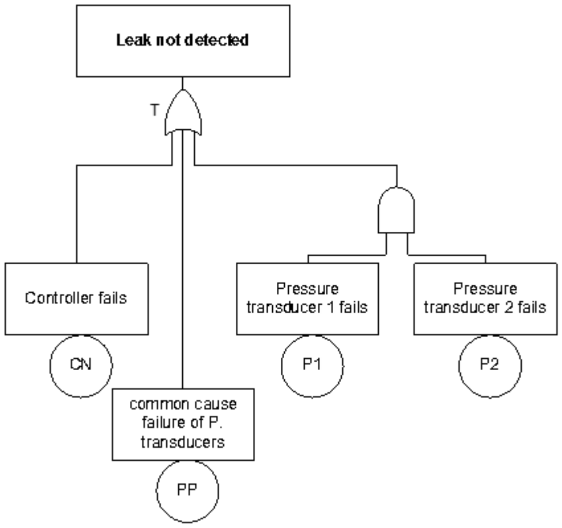
Reliability Engineering covers multiple domains



Another facet of data-driven approaches to reliability modeling

- Approaches to building probabilistic models
  - Statistical models: "How often?"
    - Predictions for static, uncertain conditions
    - Require data
      - Classical statistics: large (infinite) number of exchangeable observations
      - Bayesian statistics: sparse data
  - Causal models: "Why?"
    - Predictions for changing (uncertain) conditions
    - May or may not use "traditional" statistical data





Physics of Failure (PoF) Approaches to Reliability

PoF views failure as a *challenge* exceeding an item's *capacity*.

- Challenges and capacities affected by internal and external conditions (**influencing factors**)
- Challenges are **agents of failure** activated by the influencing factors

- **Performance-Requirement Model**
  - Reliability = performance (e.g., efficiency, output) w/i acceptable limits
- **Stress-Strength Model**
  - Reliability = challenge (stress) within capacity (strength)
  - Stress = aggregate of challenges and external conditions
  - Strength = random variable (r.v.) or uncertainty
- **Damage-Endurance Model**
  - Stress causes accumulating damage over time

Agents of Failure

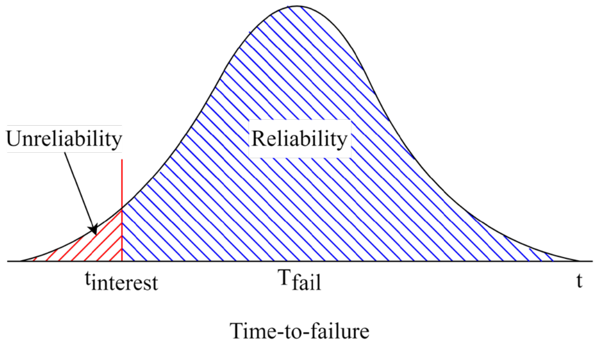
- **Failure Agent**: conditions/occurrences that *cause* items to fail
- PoF approach: challenges are caused by failure agents
- Two most important failure agents are **time** and **stress**
- **Time:** component aging, small cumulative damages over time
- **Stress:** mechanical, thermal, electrical, chemical, radiation
  - Mechanical: loading, cyclic loading
  - Thermal: high heat, thermal cycling
  - Electrical: high voltage
  - Chemical: salt, corrosion
  - Radiation: neutron, ionizing radiation

Measures of performance

- **Reliability:** Item’s ability to operate without failure under specified operating conditions to attain a mission having the desired length of time or number of cycles.
- **Availability:** Probability that an item, when used under stated conditions and support environment will be operational at a given time. (i.e., ability to become & remain operational following a failure)
- **Maintainability:** Item's ability to be quickly restored following a failure.
- **Capability:** Item's ability to attain its functional requirements.
- **Efficiency:** Item's ability to attain its functions economically and quickly with minimum waste.

Probabilistic definition of reliability

- *Reliability (R) is the ability of an item to operate without failure under specified operating conditions to attain a mission having the desired length of time or number of cycles.*
- $R(t_{interest}) = \Pr(T_{fail} \geq t_{interest} | c_1, c_2, \ldots)$



- Where:
  - $t_{interest}$ = time of interest (e.g., mission time) or aggregate agent of failure
  - T_{fail} = a random variable time-to-failure (cycle-to-failure, stress-to-failure, etc)
  - $c_i, c_2, \ldots$ = Designated operating conditions, environments, etc.

Definitions: Availability & Maintainability

- **Availability & Maintability consider repair:**.
  - Conditions & environment include perfect spare parts, personnel, diagnosis equipment, procedures, etc.
  - Availability is a *probability*, will be discussed further in Module 7
- Notionally, Availability (A) is: $A = \frac{U}{U+D}$, where:

  A = Availability

  U = uptime during time T

  D = downtime during time T

Discussion questions:

- In what types of industries, applications is reliability engineering especially prevalent? Why?

- What are some consequences of unreliability?




Definitions: Risk & Risk Analysis

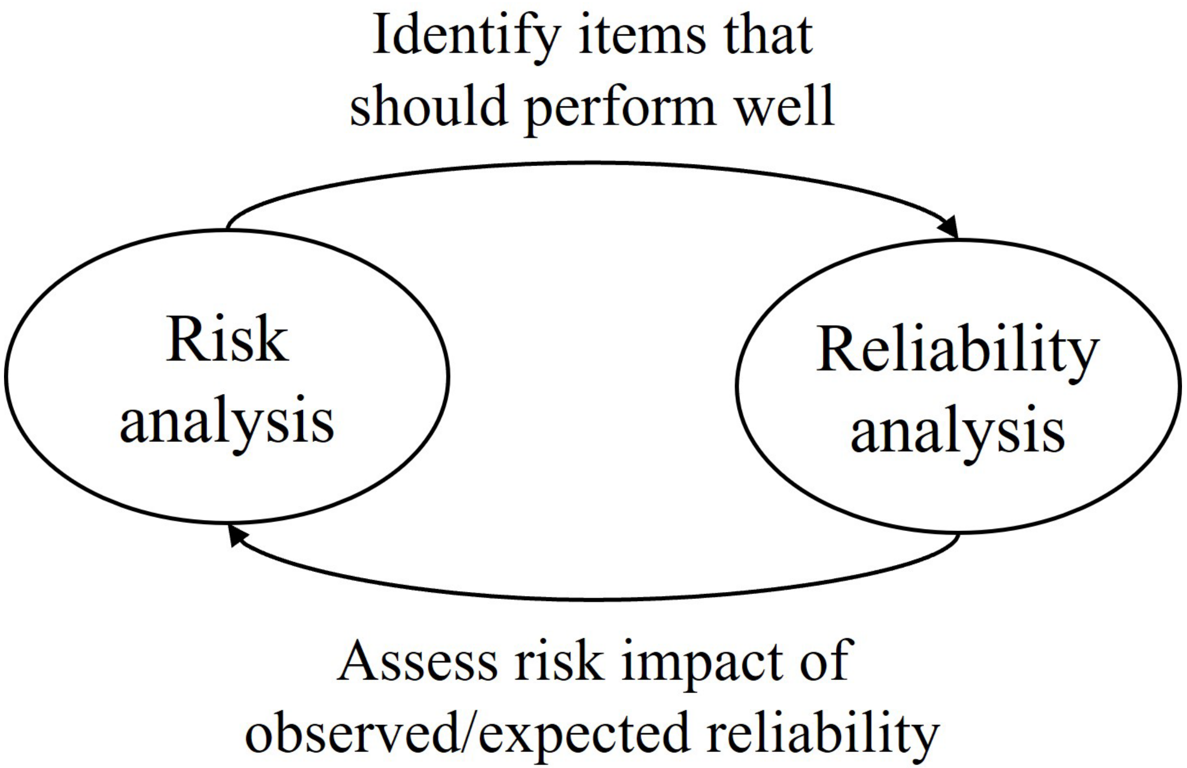
Risk: *"the potential to cause a loss" (more specifically, "the potential of loss resulting from exposure to a hazard"* which is understood to embody "uncertainty about the potential for and severity of loss(es))

Hazard*: a source of damage, harm, or loss*

Risk Assessment		Risk Management
• A process used to identify and characterize risk in a system • What could go wrong? • How likely is it? • What are the consequences?	+	• Provide inputs to decision makers on: • Sources of risk • Strategies to reduce risk • Priorities

$$\boldsymbol{Risk \propto scenarios, probabilities, consequences}$$

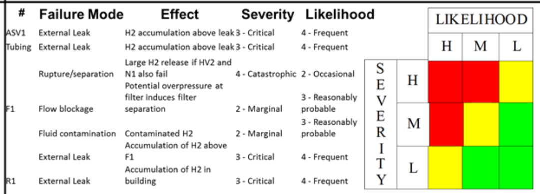
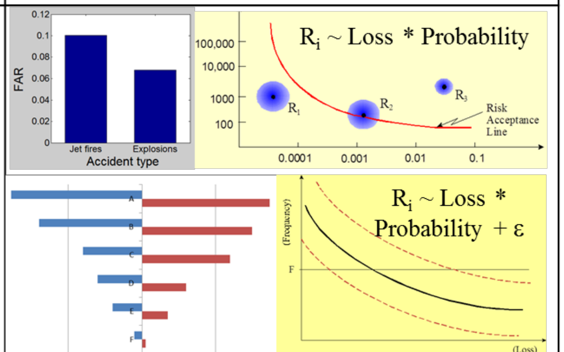
Reliability and risk analysis are closely related



There are many ways to do Reliability & Risk Analysis

- **Caution:** The term "Risk analysis" or "Risk assessment" is associated with over 10,000 methods/models/equations!

Resources, fidelity

Type	Example methods	Example outputs
Qualitative to semi-quantitative	• FMEA • HAZOP • PHA	
Quantitative	**QRA [Quantitative Risk Assessment]** • Fault Trees • Event Trees • Bayesian Networks • Simulations	

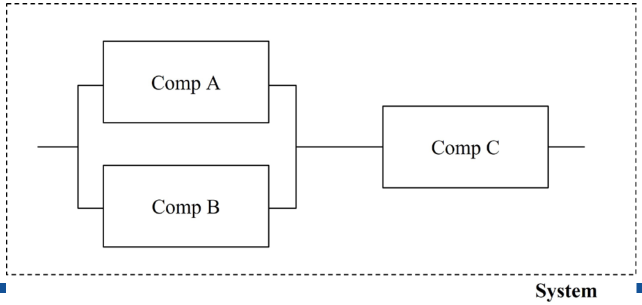
- Rigorous QRA (Quantitative Risk Assessment) methods involve a wide range of inputs, models, & data
- Requirements & practices vary across industry, location, application, & technology – terminology, methods, goals, criteria, & rigor varies widely.

Exercise (5 min)

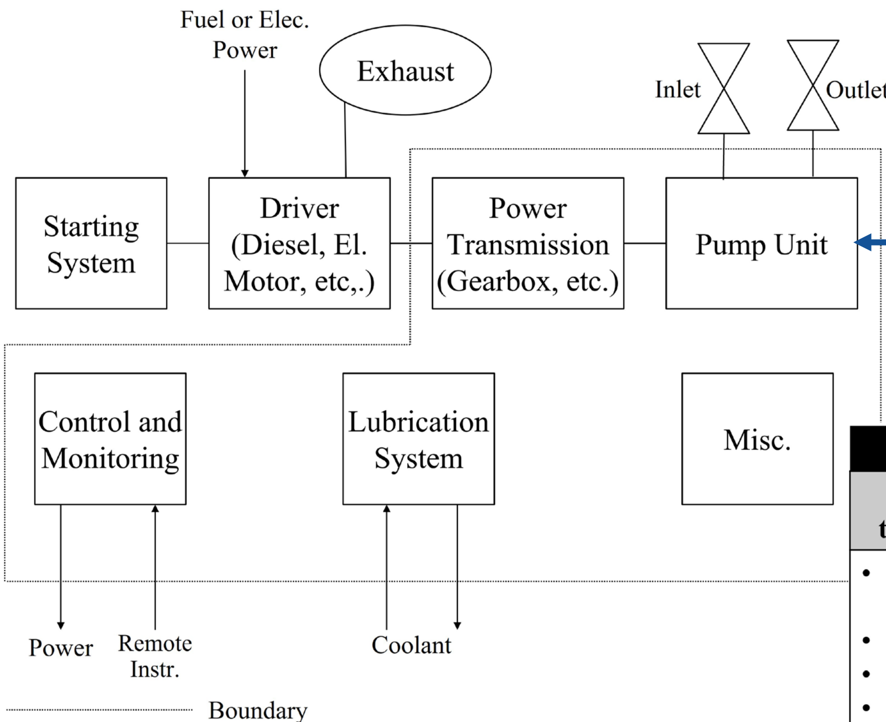
- Break into groups of 2-4 and pick an accident or failure you're familiar with
  - List a hardware failure, a human failure, and an environmental factor which contributed to the accident.
  - Name one consequence of the accident (other than loss of life).
  - (Wait to report out, we will come back to this).

Component vs System vs Function

- **Component:** Basic physical entity of the system analyzed from a reliability perspective (i.e., not further divided into more abstract entities).
- **System:** Collection of items whose coordinated operation achieves a specific function (or functions).
  - Items may be subsystems, structures, components, software, algorithms, human operators, users, maintenance programs, etc.
- The line between component and system is arbitrary and varies depending on objectives, scope, and resources of analysis
- **Function:** The purpose served by an item to meet some system requirement



Example: System & component definition for a pump

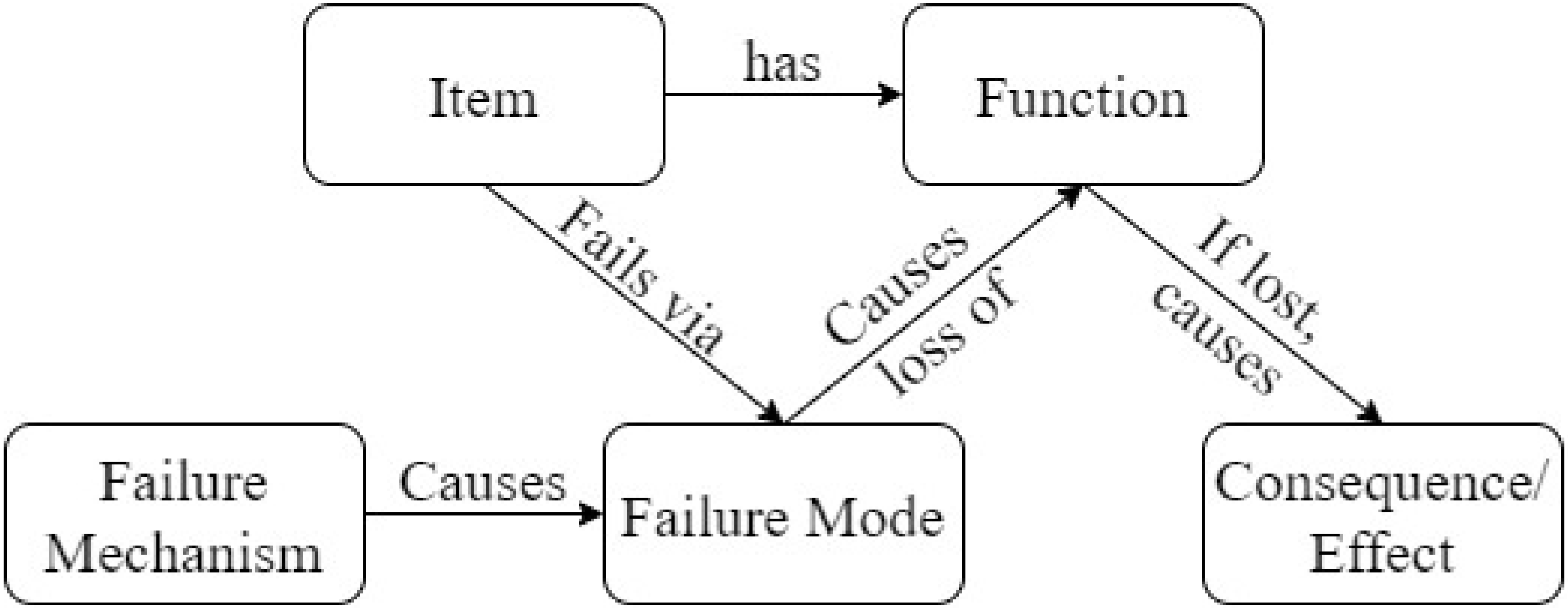


Pump unit can be treated as a *component* in a broader system

Pump System				
Power transmission	**Pump**	**Control and monitoring**	**Lubrication system**	**Miscellaneous**
• Gearbox/var. drive • Bearing • Seals • Lubrication • Coupling to driver • Coupling to driven unit • Instruments	• Support • Casing • Impeller • Shaft • Radial bearing • Thrust bearing • Seals • Valves & piping • Cylinder liner • Piston • Diaphragm • Instruments	• Instruments • Cabling & junction boxes • Control unit • Actuating device • Monitoring • Internal power supply • Valves	• Instruments • Reservoir w/ heating system • Pump w/ motor • Filter • Cooler • Valves & piping • Oil • Seals	• Purge air • Cooling/heating system • Filter, cyclone • Pulsation damper

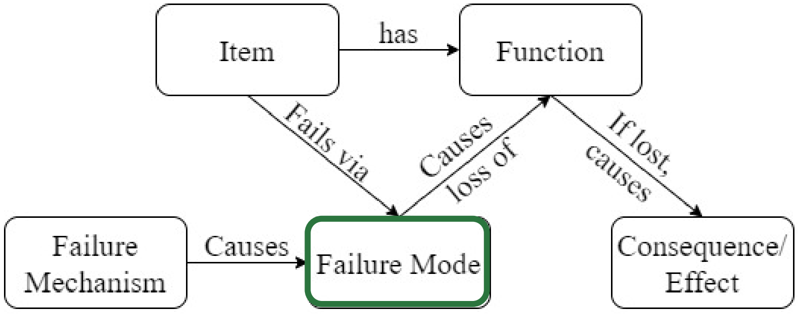
Pump can be treated as a *subsystem* and broken down into smaller *components*

Failure modes, failure mechanisms, and functions are building blocks of risk & reliability scenarios



Failure Modes

- The **Failure Mode** is the manner or way in which an item fails
  - Functional Manner of item (component, system) failure
  - *How* does the item fail?
  - *What* does the item fail to do?
- Some typical failure modes for active hardware components:
  1. Premature operation,
  2. Failure to start operation when needed,
  3. Failure to stop operation at the prescribed time,
  4. Failure to continue operation after start,
  5. Degraded operation.



Example: List of pump failure modes

AIR	Abnormal instruments reading
BRD	Breakdown
ERO	Erratic output
ELP	External leakage - Process medium
ELU	External leakage - Utility medium
FTS	Fail to start on demand
STP	Fail to stop on demand
HIC	High output
INL	Internal leakage
LOO	Low output
SER	Minor in service problems
NOI	Noise
OTH	Other
OHE	Overheating
PDE	Parameter deviation
UST	Spurious stop
STD	Structural deficiency
UNK	Unknown
VIB	Vibration

Source: OREDA – Offshore Reliability Data Handbook, 4^{th} Edition, 2002

Example: Pump failure mode data

Taxonomy no	Item			
1.3	Machinery Pumps			
Population	Installations	Aggregated time in service (10^6 hours)		No of demands
		Calendar time *	Operational time †	
449	61	19.0224	8.6743	11200

Failure mode	No of failures	Failure rate (per 10^6 hours). Lower	Mean	Upper	SD	n/τ	Active rep.hrs	Repair (manhours) Min	Mean	Max
Critical	**524***	**0.00**	**20.52**	**108.44**	**49.34**	**27.55**	**37.3**	**1.0**	**53.1**	**1025.0**
	524†	**1.14**	**65.40**	**204.64**	**72.93**	**60.41**				
Breakdown	45*	0.00	1.27	6.56	5.17	2.37	16.1	3.0	52.5	766.0
	45†	0.01	3.85	15.72	5.95	5.19				
Erratic output	2*	0.00	0.14	0.72	0.58	0.11	19.8	11.0	39.5	68.0
	2†	0.00	0.38	2.00	0.91	0.23				
External leakage - Process medium	86*	0.00	2.38	12.29	9.53	4.52	28.4	2.0	38.3	444.0
	86†	0.00	7.07	33.87	13.94	9.91				
External leakage - Utility medium	46*	0.00	1.20	5.04	5.60	2.42	16.0	2.0	29.8	90.0
	46†	0.00	3.59	16.82	6.84	5.30				
Fail to start on demand	50*	0.01	2.52	9.77	3.62	2.63	52.0	1.0	56.6	551.0
	50†	0.08	13.75	48.28	17.83	5.76				
Fail to stop on demand	2*	0.00	0.10	0.21	0.54	0.11	3.5	3.0	3.5	4.0
	2†	0.00	0.26	1.30	0.56	0.23				
High output	3*	0.00	0.67	3.51	2.44	0.16	-	1.0	3.3	6.0
	3†	0.00	2.31	12.00	5.32	0.35				
Internal leakage	8*	0.00	0.34	1.39	0.52	0.42	95.5	3.0	48.3	188.0
	8†	0.16	0.98	2.37	0.72	0.92				
Low output	46*	0.00	2.50	3.96	15.25	2.42	35.4	3.0	41.2	508.0
	46†	0.00	4.57	13.58	22.90	5.30				
Noise	6*	0.15	0.33	0.56	0.13	0.32	23.3	16.0	60.5	122.0
	6†	0.01	1.03	3.73	1.38	0.69				
Other	8*	0.00	0.57	2.99	2.43	0.42	275.5	2.0	424.5	734.0
	8†	0.00	1.53	7.57	3.21	0.92				
Overheating	5*	0.00	0.27	0.95	0.35	0.26	183.2	3.0	265.0	1025.0
	5†	0.00	6.41	32.56	14.04	0.58				
Parameter deviation	18*	0.00	0.66	3.49	2.31	0.95	11.0	1.0	20.8	88.0
	18†	0.14	1.96	5.66	1.87	2.08				
Spurious stop	133*	0.00	5.69	27.65	11.50	6.99	37.5	1.0	42.1	714.0
	133†	1.57	19.07	53.52	17.47	15.33				
Structural deficiency	33*	0.00	0.41	0.51	4.91	1.73	20.6	5.0	40.5	211.0
	33†	0.00	1.24	3.74	6.18	3.80				
Unknown	1*	0.00	0.05	0.15	0.05	0.05	-	-	-	-
	1†	0.00	0.11	0.33	0.12	0.12				
Vibration	32*	0.00	1.67	7.70	3.10	1.68	81.2	5.0	118.3	896.0
	32†	0.47	5.11	14.03	4.53	3.69				
Degraded	**754***	**0.00**	**44.20**	**210.34**	**86.32**	**39.64**	**20.2**	**0.3**	**26.4**	**798.0**
	754†	**11.39**	**238.41**	**714.72**	**239.40**	**86.92**				
Abnormal instrument reading	9*	0.00	0.80	4.56	2.45	0.47	9.0	2.0	16.0	65.0
	9†	0.00	2.53	11.22	4.42	1.04				
Erratic output	23*	0.00	2.27	12.50	6.03	1.21	14.8	2.0	16.8	65.0
	23†	0.00	7.88	35.25	13.95	2.65				

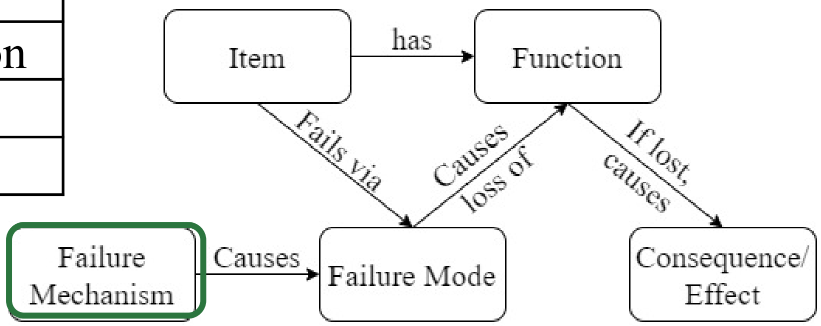
Source: OREDA – Offshore Reliability Data Handbook, 4th Edition, 2002

Failure Mechanisms

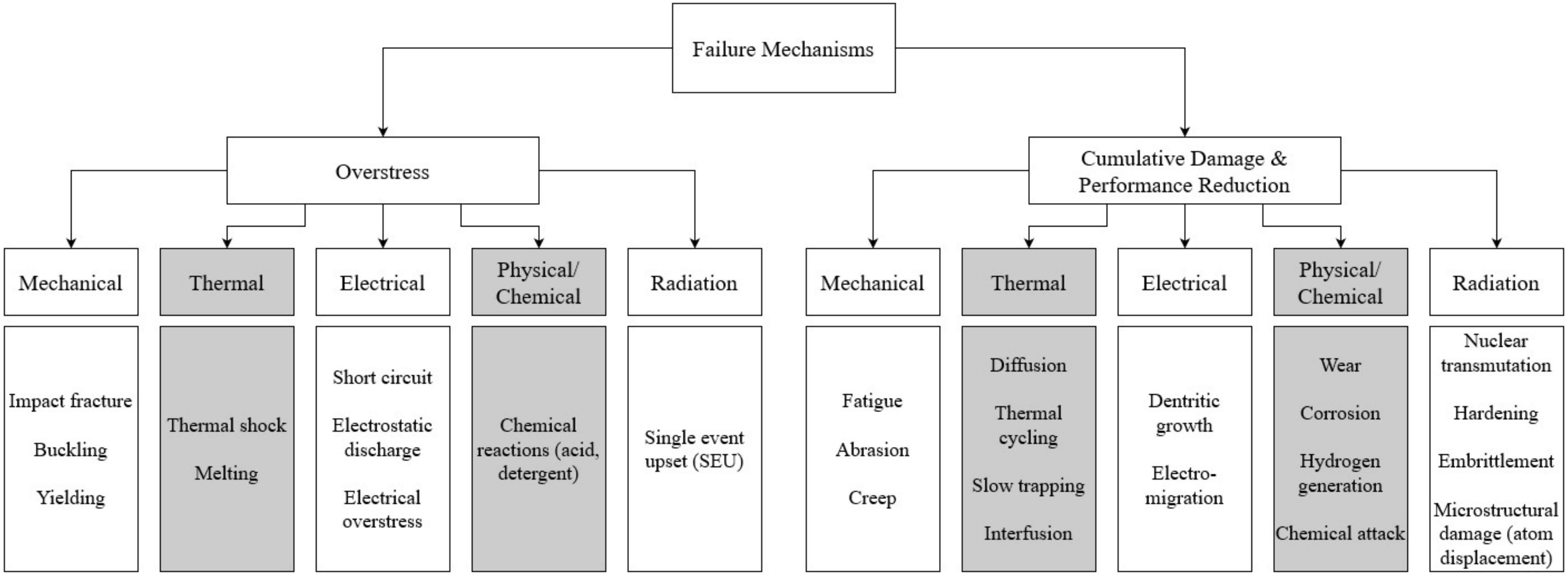
- **Failure Mechanisms** are physical processes through which damage occurs.
- Damage can occur rapidly (abruptly) or slowly (cumulatively).
  - Rapid: brittle fracture, melting, and yielding.
  - Cumulative: fatigue, wear, and corrosion.

Failure occurs when resulting damage exceeds item's capacity

Damage-inducing	**Capacity-reducing**
Wear	Fatigue
Corrosion	Embrittlement
Cracking	Thermal shock
Diffusion	Diffusion
Creep	Grain boundary migration
Fretting	Grain growth
Fatigue	Precipitation hardening



Examples of different types of failure mechanisms



Example: Failure mechanisms & modes

- Failure mechanisms are physical processes, failure modes are the **outcome** of the physical process
- **Example:** neutron irradiation causes embrittlement (cumulative failure mechanism), which results in fracture (failure mode)
- **Example:** short circuit (overstress failure mechanism) in pump results in failure to start on demand (failure mode)
- **Example:** corrosion (cumulative failure mechanism) in pump results in external leakage of process medium (failure mode)

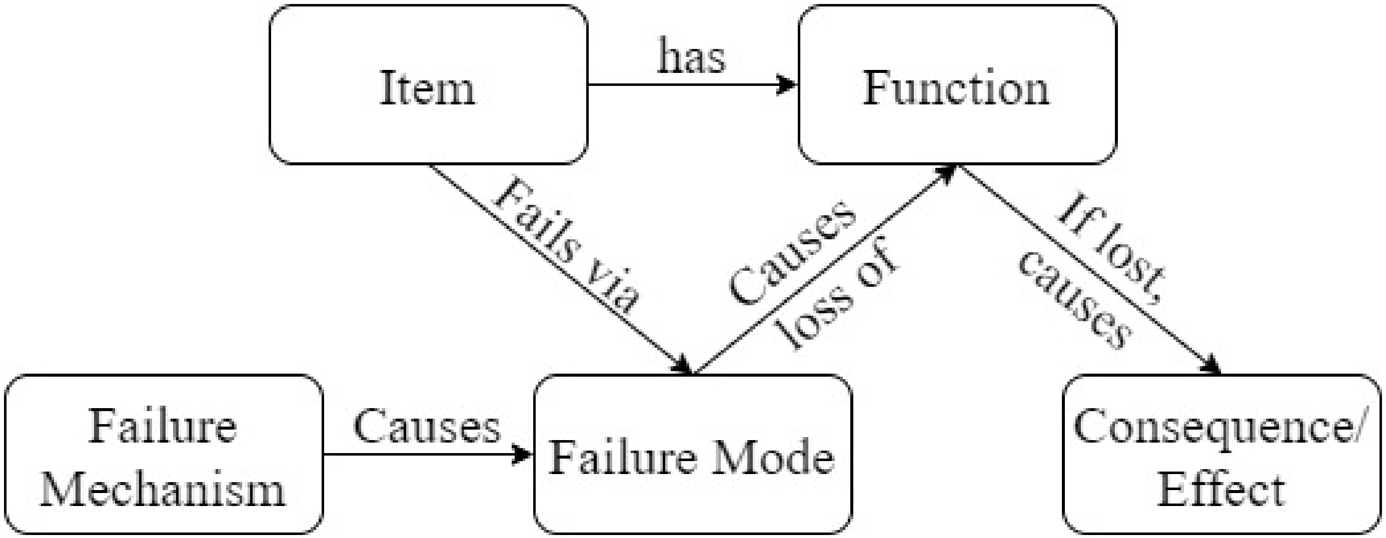
Human functions, failure, and reliability

- Systems are not only hardware and software – **humans** play a critical role in a functioning engineered system.
- Humans are not hardware:
  - **Multiple roles**: design, operation, maintenance, decommissioning
  - Achieve various functions at several levels of abstraction
- **Human reliability analysis** (HRA) provides methodologies to understand and model human failures in a system.
  - **Major human tasks**: Information Gathering, Diagnosis & Decision Making; Action Execution
  - Over 50 methods exist for engineering applications
  - Methods differ in the use of **performance influencing factors** (PIFs)
- Similar importance and modeling for **software reliability**
- We'll dive deeper in Module 8.

Example hardware failure scenario

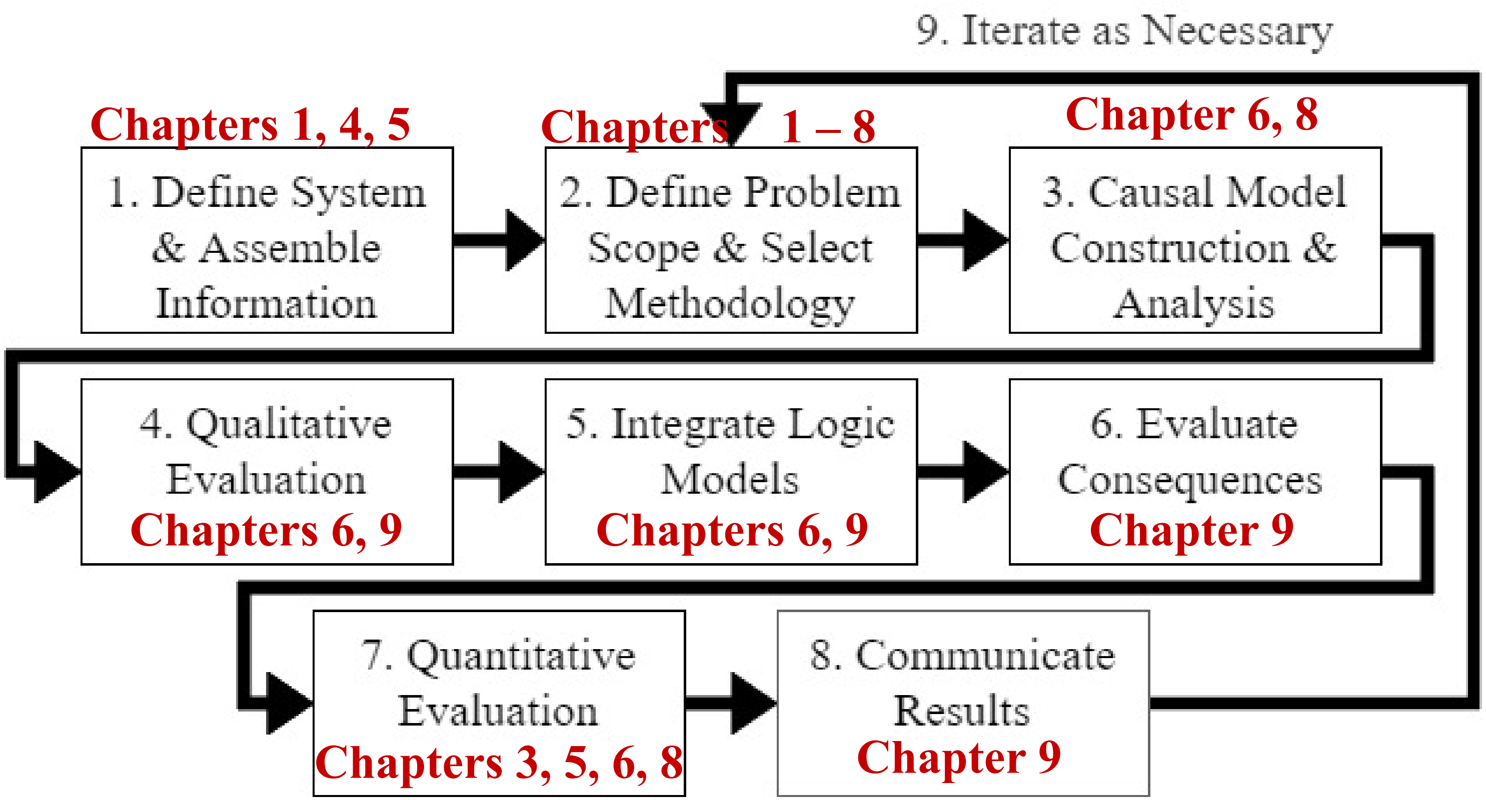
Example for an aircraft's airframe:

Fatigue (failure mechanism) of airframe (component or system), caused by the cyclic stress, cyclic temperature (influencing factors), activated by random flight loads (influencing factor) external to airframe, leading to crack initiation and growth (degradation process), and ultimately causing structural failure during operation (system failure mode). Structural failure causes loss of airworthiness (function), which causes crash (effect).



Risk Assessment Modeling

Putting the pieces together enables us to do risk assessment – and forms the outline of the modules in this course



This just the beginning. ENRE00, ENRE640, ENRE641, ENRE645, ENRE655, ENRE670 and more will delve even deeper into specific facets of the discipline.

Quiz 1: Write a failure scenario for the event you discussed earlier.

- Your scenario **must include**:
  - Event/accident name, date, description (1-2 sentences), and photo
  - System failure mode, operating environment, consequence(s)
  - At least one of: hardware failure mode, failure mechanism, environment, and human failure
- Example: Air France 447 Airbus A330 (July 1, 2009)

Component & failure mode — Component failure mechanism

Flow blockage of **pitot tubes,** caused by **freezing,** led to

Subsystem failure mode — System failure mode

erroneous airspeed indication resulting in **loss of control,**

Consequences

loss of aircraft, fatality of all 228 passengers and crew,

Human failure mode & PIFs

with pilot failure to diagnose the erroneous output due to inadequate information, and time load. Occurred at **high**

Environment

altitude, low temperature, in stormy weather.

Image: Brazilian Navy/ Getty Images