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Proving Fuze Safety

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INTRODUCTION

- Fuze safety requirements have a very long evolutionary history. Most safety requirements have been paid for with the lives of soldiers and civilians.
  - WW1 and earlier era fuzes- mostly relied on one safety mechanism and were typically inline systems. Warheads were prone to unintended functioning.
  - WW2 fuzes introduced the requirement of two independent environments for arming.
- Modern safety requirements for fuzing defined in MIL-STD-1316.
  - Base document predates 1967, Revision A circa 1969. Revision F in 2017.
  - New technology creates new safety concerns and the need for continual updating.
- Failure mechanisms become less obvious as technology and design complexity increases.

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INTRODUCTION

Safety and arming are primary roles performed by a fuze:

- Maintains munition safety throughout the Life Cycle Environmental Profile (stockpile-to-target sequence)
- Initiates the munition’s warhead when the target is detected

- The **purpose** of MIL STD 1316 is to establish design safety criteria for fuzes and Safety and Arming (S&A) devices that are subsystems of fuzes.
  - Establishes Design Safety Criteria for Fuzes
  - Mandatory elements of design, engineering, production and procurement of fuzes
  - Design Approval
  - **Verification**

The inadvertent arming and firing of a fuze system can result in Catastrophic material damage & injury or Death to personnel.

- Every effort must be made during the development of the munitions’ fuze safety system to achieve a high degree of safety during the lifecycle:
  - Prior to intentional initiation of the arming sequence (shipping and handling)
  - Prior to tube exit
  - Prior to safe separation

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METHODS FOR ENSURING SAFETY

- Safety cannot be inspected in; It must be designed in!
  - ➢ Analysis
    - – Failure Mode Effects Analysis (FMEA).
    - – Failure Mode Effects Critical Analysis (FMECA). Includes criticality, assurances and controls.
    - – Fault Tree Analysis (FTA).
      - • Probability of unintended function.
    - – Reliability Analysis.
      - • Probability of intended function.
  - ➢ Testing
    - - Developmental testing – Does it meet the design requirement?
    - - Qualification testing – Does it meet the user requirement?
  - ➢ Reviews
    - – Peer reviews.
    - – Review boards.

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METHODS FOR ENSURING SAFETY

➢ REVIEW BOARDS

- Responsible for compliance. Examines safety prior to and including launch.
  - Production, shipping, handling, storage, loading, launch, safe separation.
  - Each service has their own review but meet jointly when fuzes are used on common munitions. All work together to ensure user safety across all services.
    - ✓Army Fuze Safety Review Boards – AFSRB.
    - ✓Navy Fuze & Initiation Systems Technical Review Panel – FISTRP.
    - ✓Air Force Nonnuclear Munitions Safety Board (NNMSB).
    - ✓Joint Service Fuze and Ignition Systems Safety Authorities (JS-FISSA)
  - Each requires intimate knowledge of how the fuze works (no secret sauce).
- In addition, the System Safety Review Board (SSRB) is concerned with overall safety, including:
  - Overhead safety.
  - Reliability.
  - UXO.

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UNDERSTANDING THE SYSTEM SAFETY ISSUES

- What is the safety issue
  - Catastrophic loss of life or property.
- It is critical to understand and communicate how the system is intended to operate
  - State diagrams.
  - Logic diagrams.
  - Schematic diagrams.
  - During safe separation.
- It is critical to understand and communicate how the system can fail
  - This requires imagination
  - Is never 100% inclusive
  - Murphy's law applies, If anything can go wrong just assume it will.

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UNDERSTANDING THE SYSTEM

Caution 1

Oversimplifying a complex system

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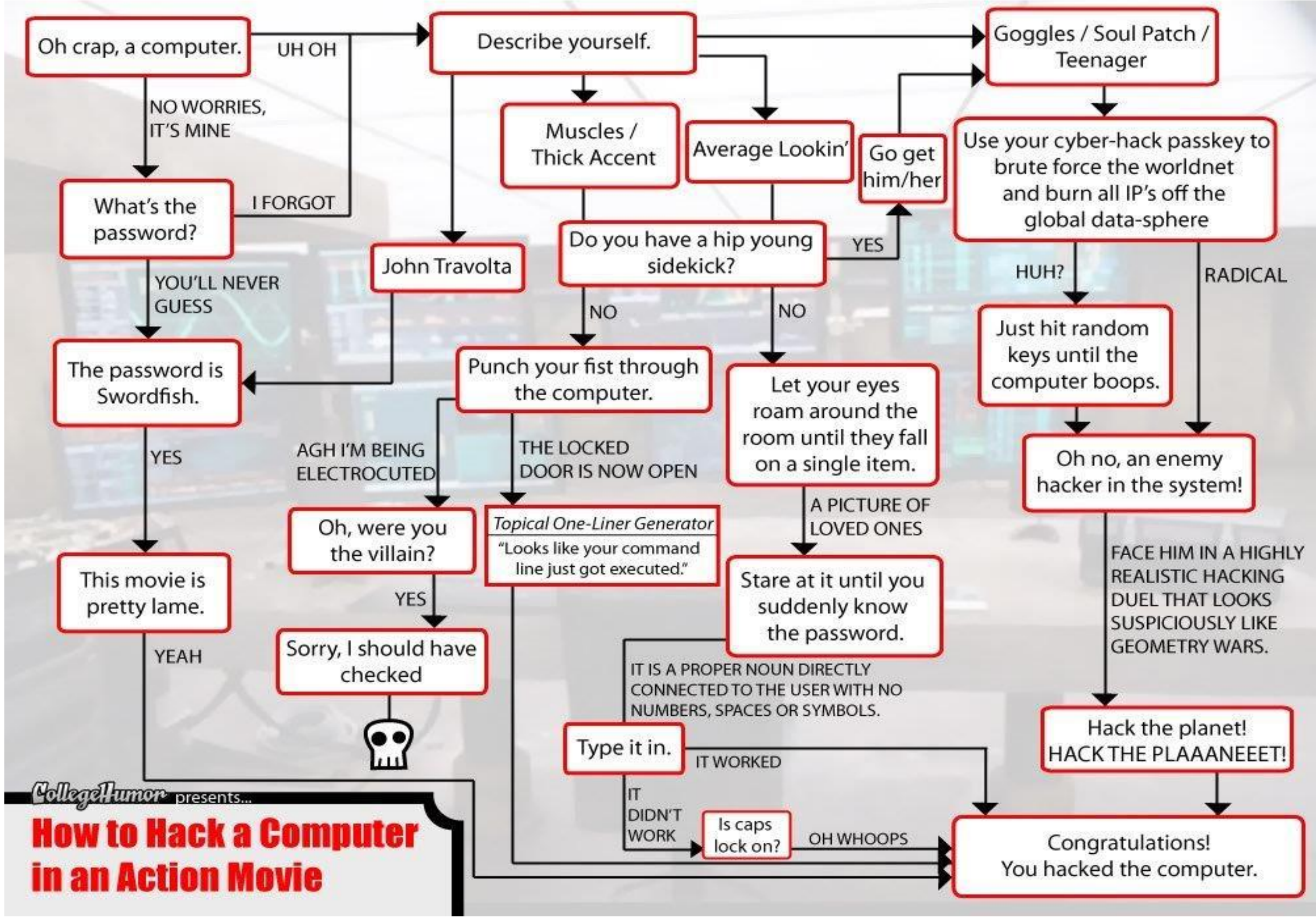
UNDERSTANDING THE SYSTEM

Caution 2

Misrepresenting a Complex system



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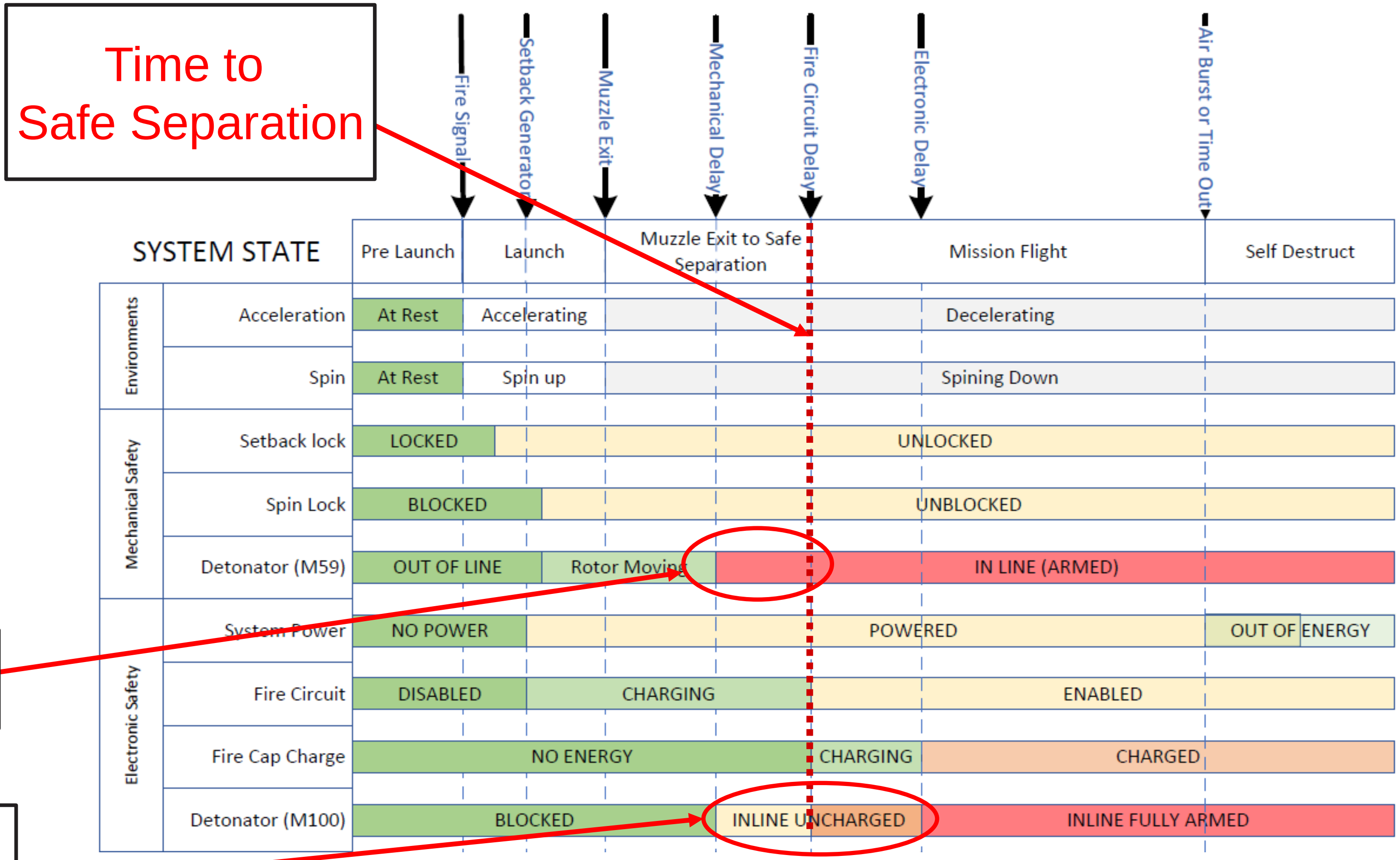
UNDERSTANDING THE SYSTEM

A real example

FUZE ARMING SEQUENCE



Safety Issue

Mitigation Logic

An Arming Sequence/State Diagram

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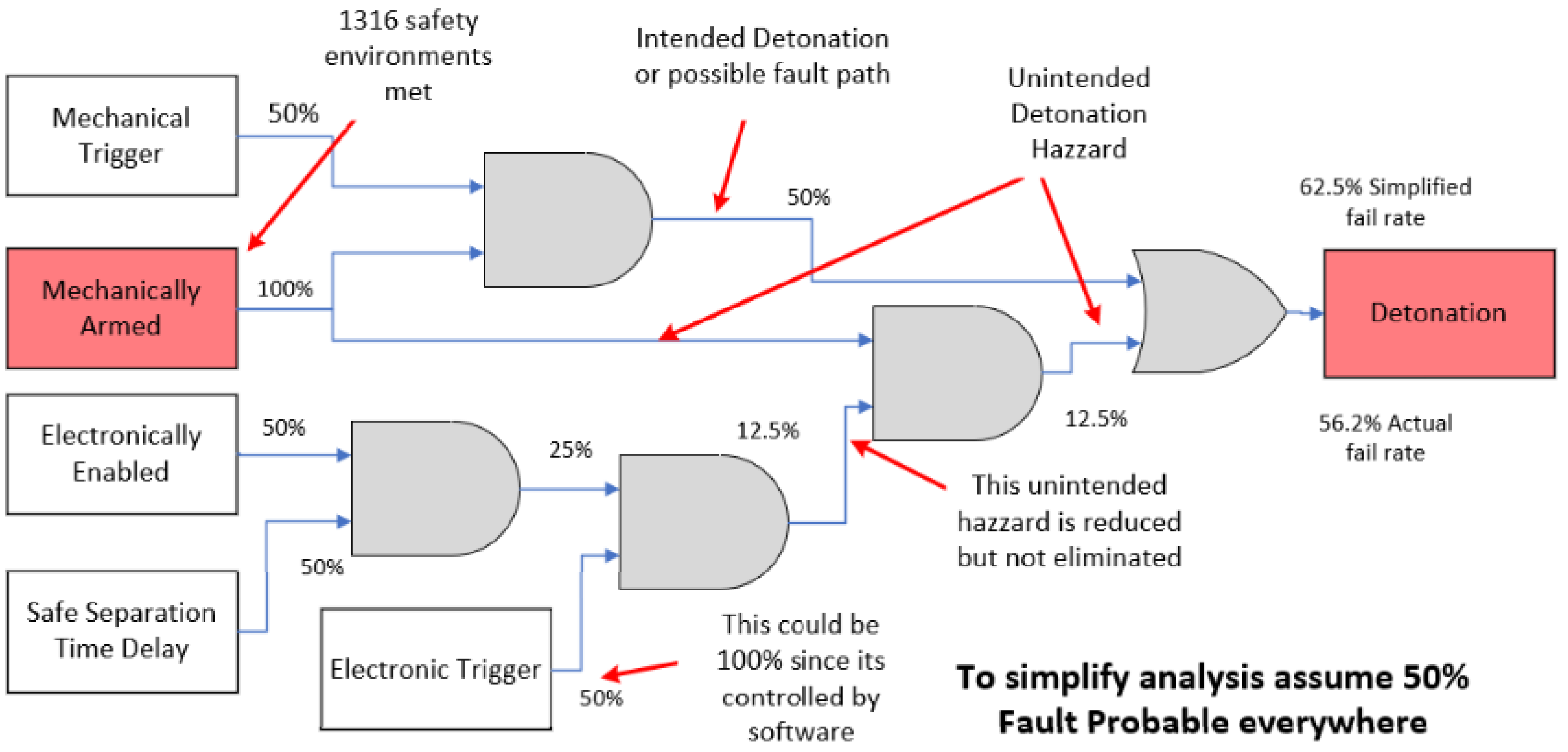
UNDERSTANDING THE SYSTEM

- A real Example

FUZE ARMING SEQUENCE



Arming Sequence as a Logic Diagram for FTA

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FAULT TREE ANALYSIS

- What is the probability of unintended functioning.
  - During assembly.
  - During shipping and handling.
  - During launch.
  - During safe separation.
- Not concerned with functioning as intended.
- A necessary safety document for review boards.
- Guidance for performing the FTA is not well documented in a single standard but it is a necessity for proving safety. Work is ongoing on formalizing guidance in a new JOTP (Joint Ordinance Testing Procedure) through the work of the FESWG (Fuze Engineering Standardization Working Group).
  - A logic diagram of the safety critical system is required. System operation must be clearly understood.
  - Multiple documents/requirements exist.
  - FTA calculations with probabilities greater than 100% indicate a lack of understanding.
  - FTA calculations depending on probabilities smaller than 10^{-12} also misses the point of the analysis

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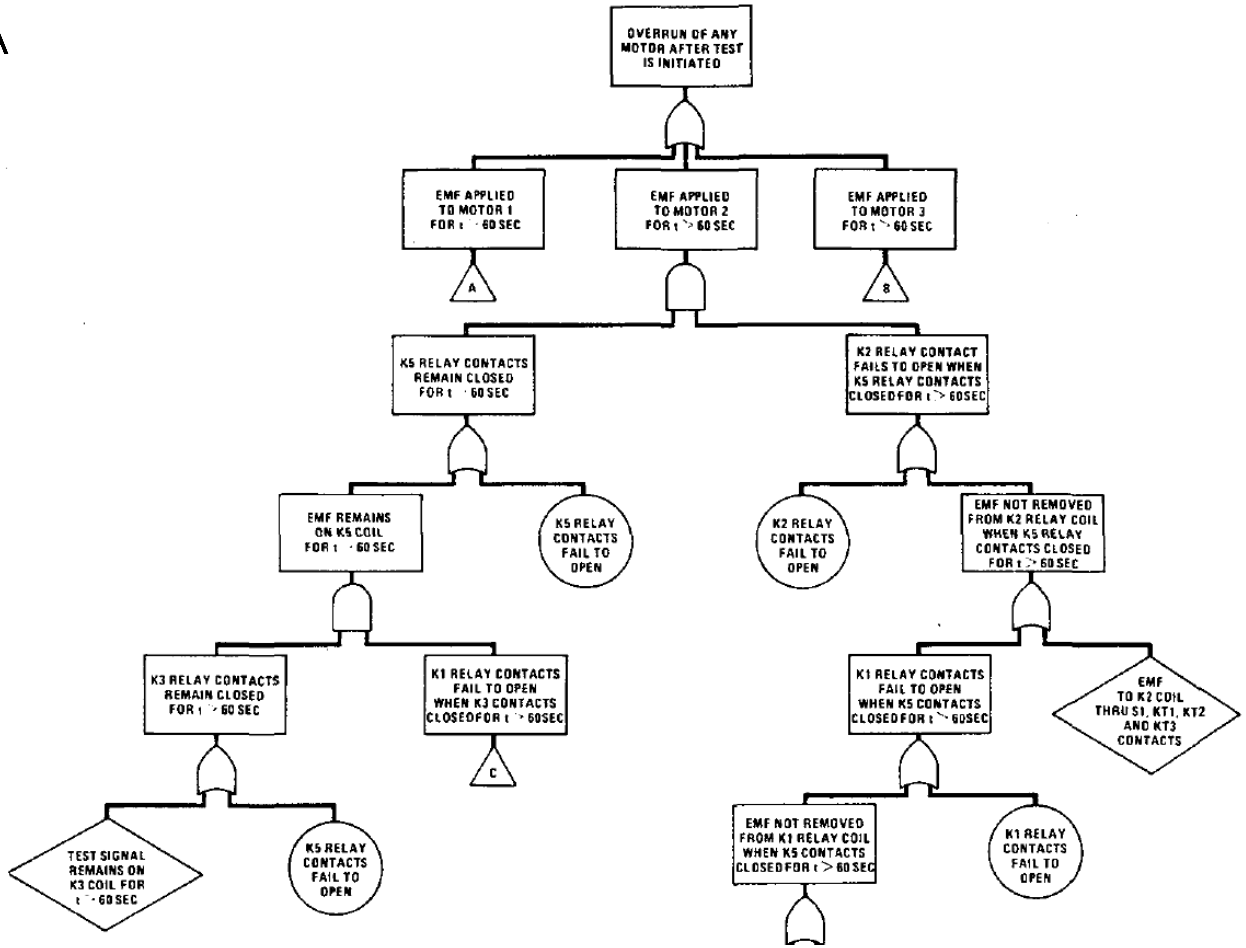
FAULT TREE ANALYSIS

- Example FTA



Example FTA Logic Diagram from NUREG-492

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FAULT TREE ANALYSIS (FTA)

Requirements from MIL-STD-1316 for Launched Munitions

EVENT	SCENARIO	ACCEPTABLE PROBABLY
ARMING	Prior to Launch	1 E^{-6} (1: 1,000,000)
	Prior to Launch Tube Exit	1 E^{-4} (1: 10,000)
	Prior to Safe Separation	1 E^{-3} (1: 1,000)
FUNCTIONING	Prior to Launch	1 E^{-6} (1: 1,000,000)
	Prior to Launch Tube Exit	1 E^{-6} (1: 1,000,000)
	Prior to Safe Separation	As Low as Practical

- **Primary Intent is to demonstrate there are no single point failure modes in the design**
- **FTA should therefore be evaluated based on the FUZE DESIGN Robustness, and not weighted on production/quality assurance history (in other words, safety performance should be assured by design with less reliance on inspection)**
- **Source for component failure probability numbers: conservative engineering judgment; numerous software FTA programs and historical documents; MIL-HDBK-217F for electronic components**

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FAULT TREE ANALYSIS

- A Logic diagram is essential – Based on fundamental understanding of the system.
  - All functional elements can be reduced to a series of logical operations involving 'AND', 'OR', and NOT gates. (Symbols can include XOR, NAND, NOR).
  - A conservative and realistic probability of failure/fault is assigned to each component of the operation. These can be reduced with rationale on subsequent passes if needed.
  - 'AND' operations will decrease probabilities. Cascaded operation will asymptotically reduce probabilities to zero but never reach zero.

AND Probabilities simply multiply: $P = A * B$ Exact

  - 'OR' operations will increase probabilities. Cascaded operation will asymptotically increase probabilities to 100% but never exceed 100%.

OR probabilities are complicated:

$P = (A + B) - (A * B)$ Exact

$P = A + B$ Simplified

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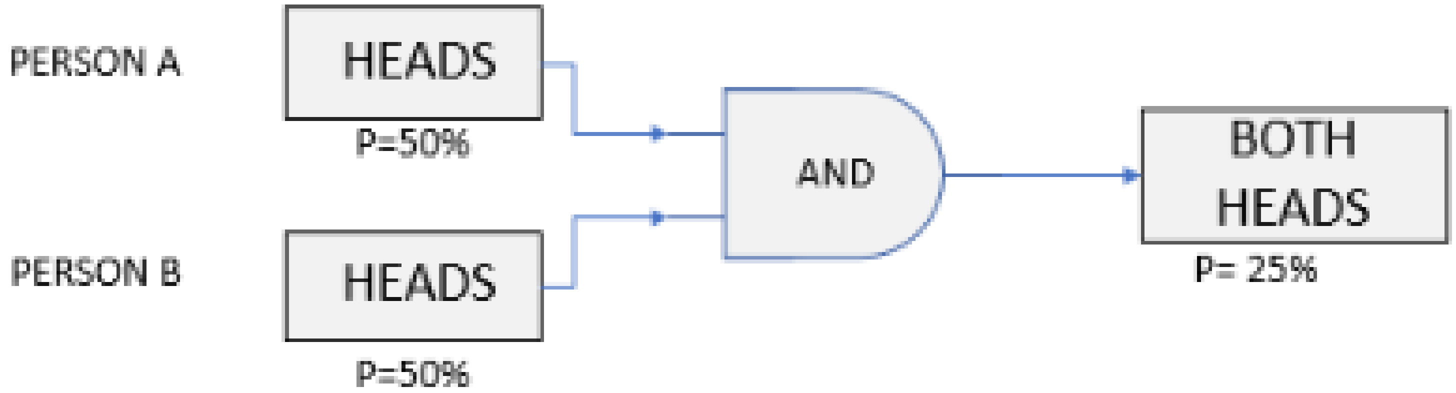
FAULT TREE ANALYSIS

- EXAMPLE1. What is the probability of two individuals getting ‘heads’ when flipping a coin?
  – As common sense would predict: The individual probabilities multiply.



  – This makes sense! If you want to make your system safer, require more things to go wrong in parallel. i.e. Safety depends on two independent environments.

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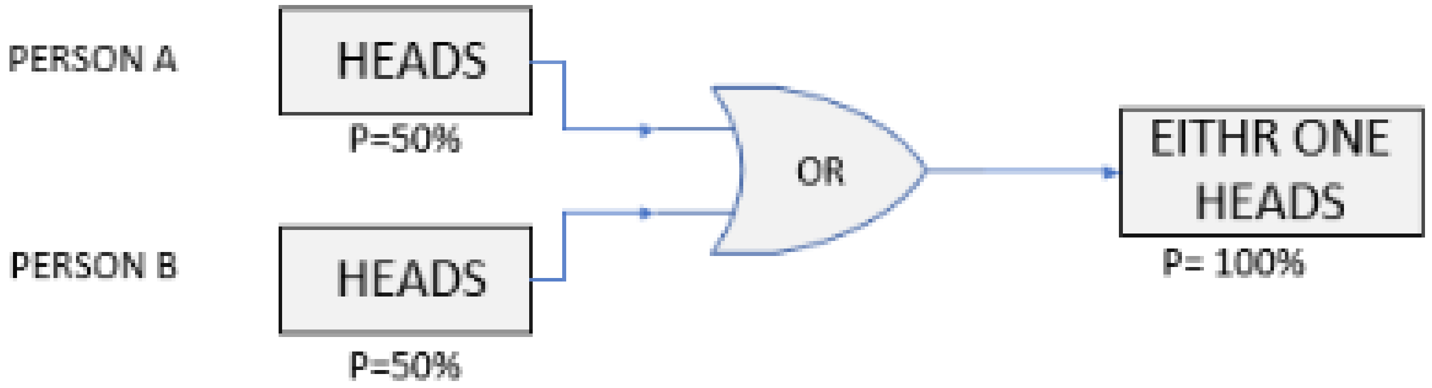
FAULT TREE ANALYSIS

- EXAMPLE2. What is the probability of one individual getting 'heads' when flipping a coin?
  - If we use simplified logic.



  - Hmmm… Something seems wrong here! What happens when we add a third person? 150% chance of getting heads cannot be correct!
  - This result is nonsense and damages the credibility of the analysis.

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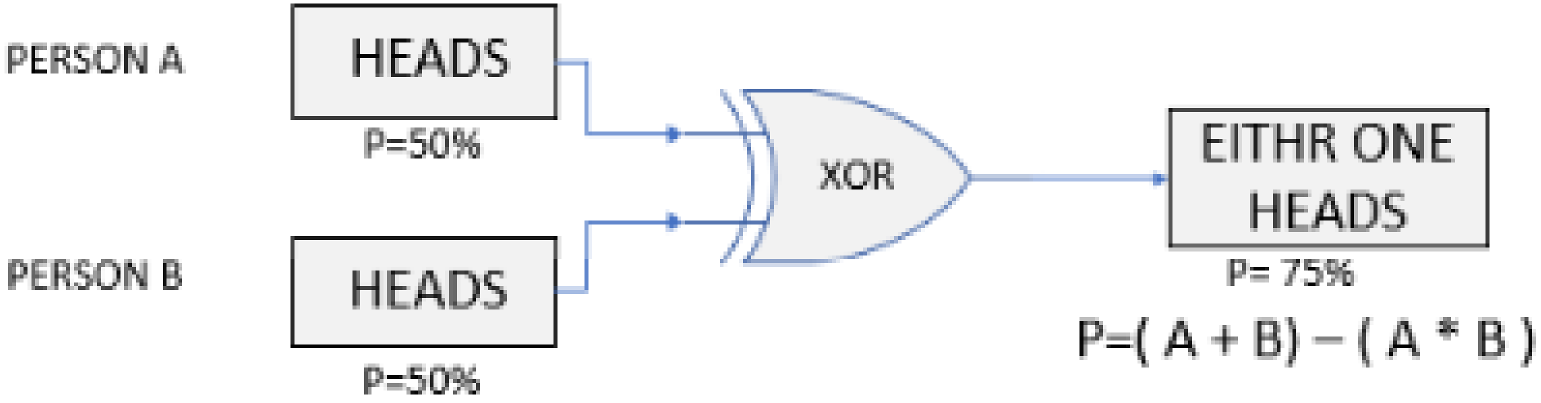
FAULT TREE ANALYSIS

- EXAMPLE3. What is the probability of one individual getting ‘heads’ when flipping a coin?
  - If we use exact logic ‘OR’ becomes ‘EXCLUSIVE OR’.



  - This works, but why?
    - ➢We want an ‘exclusive or’ condition! We need to subtract the possibility that both were heads since any one result constitutes a ‘failure’.

      i.e. The system fails when A or B fails. We do not care if both fail.

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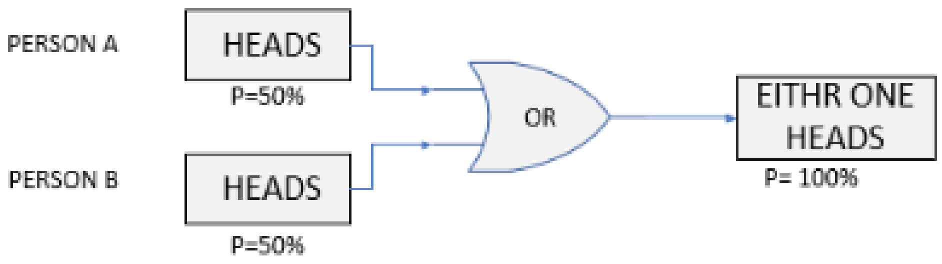
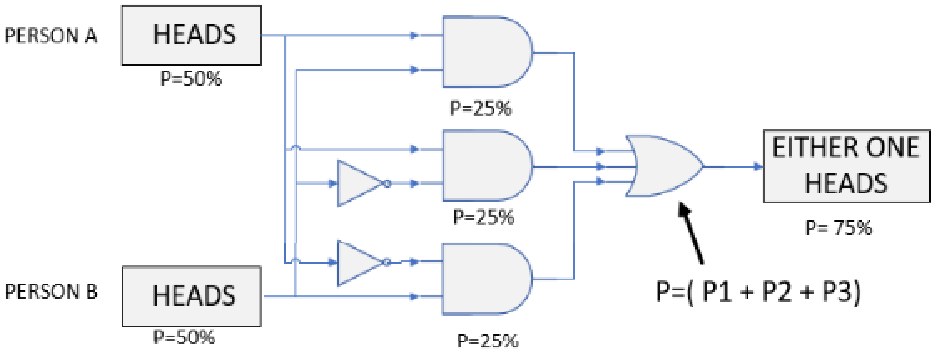
FAULT TREE ANALYSIS

- When adding (OR'ing) failure mechanisms its easy to use the wrong logic!



Simplified



Exact

- Simplified logic only works when input probabilities are small! (i.e. probabilities less than 5% result in a .25% error / 50% probabilities result in 25% error).
  - As per AFSRB guidance: Software and microprocessor logic introduces terms on the order of 100%. This is where the conventional 'simplified' analysis falls apart. Nobody would ever intentionally design in a failure mechanism with a 50% or higher fail probability.

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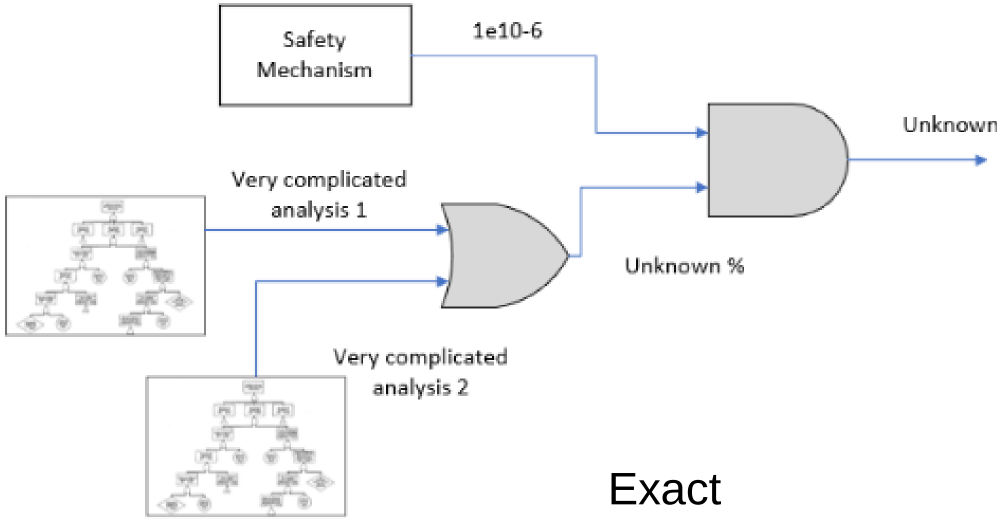
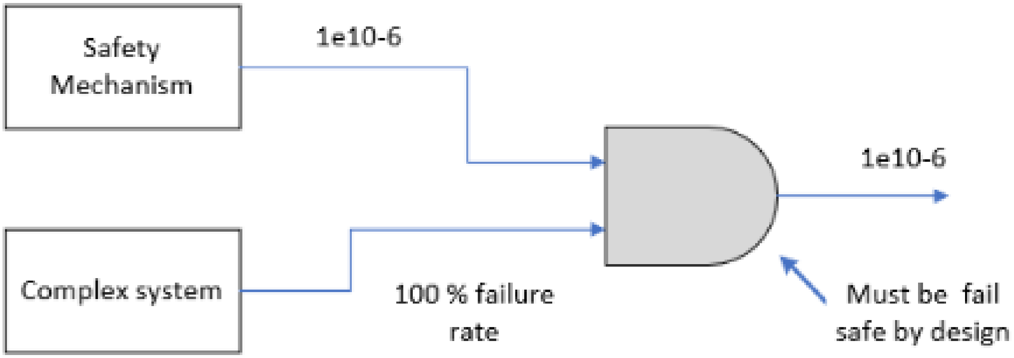
PRUNING THE FAULT TREE

- Why?
  - To avoid analyzing paths that are overcomplex
- How?
  - By assuming a probability of failure of 100% we eliminate all contributing elements in this path
- When can you do this?
  - When the outcome is gated (AND’ed) out by a low probability of failure and the result meets the safety criteria. Software controlled trigger are a perfect example



Exact



Simplified

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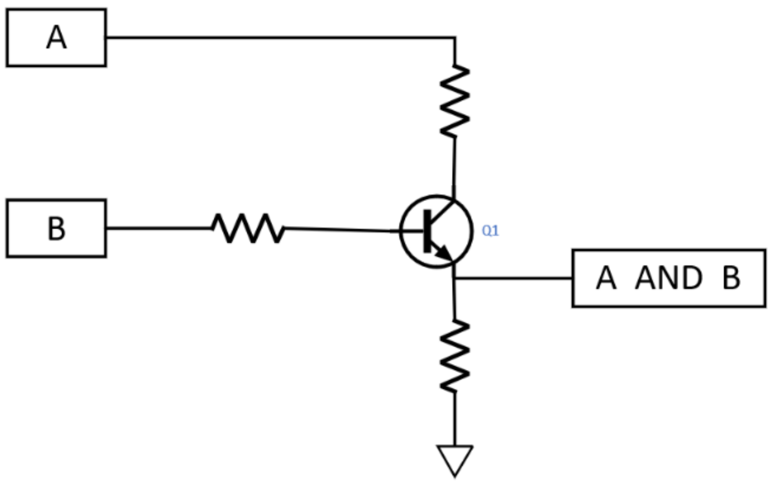
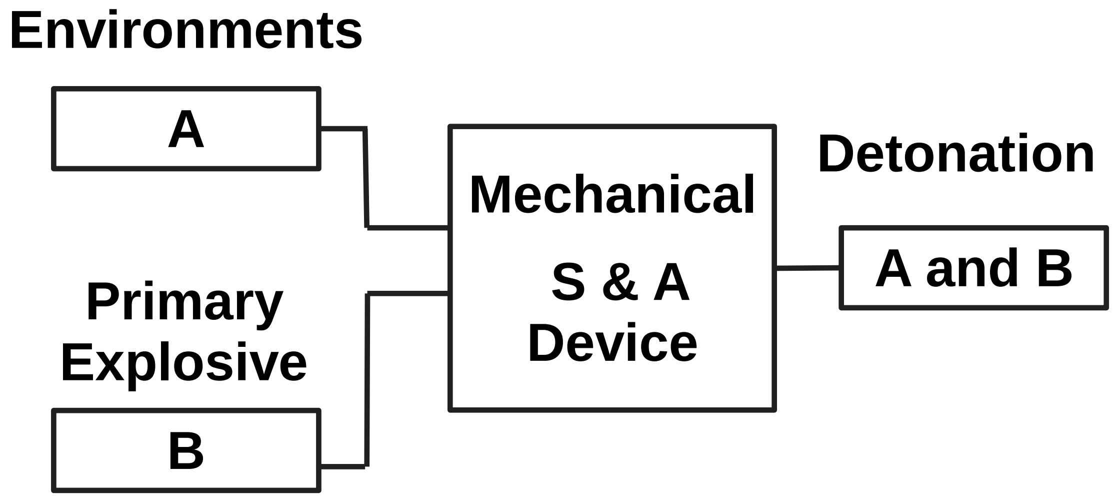
PRUNING THE FAULT TREE



Electrical And Gate



Mechanical And Gate

Fail Safe AND Gates

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IN GENERAL

- Fault trees are built from a logical model of the system. This includes a sequence of events (outcomes) fed by the logic or input to the system from the lowest levels.
  - – A bottom-up analysis.
- Results are dependent on assumed probabilities of fault mechanisms.
  - – Physical factors.
    - – An electronic component fails.
    - – A mechanical component breaks.
    - – Environments cause freezing / melting.
  - – Human factors.
    - – An operator installs the wrong component.
    - – An operator skips a step in assembly.
    - – Something is mislabeled.
  - – MIL-STD-882, System Safety provides guidance for root cause probabilities.

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YOU CAN ALWAYS EXPECT THE UNEXPECTED

- Despite rigorous analysis, testing and review, safety critical systems can manage to find new ways to fail.
  - ➢Most will involve human factors.
  - ➢All will involve mechanisms and interactions never conceived of. Examples from my 40 years of experience.
    - Example1: Early termination of STS-83 in 1997. Root cause: Technician not cutting strings with scissors as per documented instructions.
      - Fuel cell failure leads to shut down of non-critical systems.
      - Excessive moisture build up and condensation in cabin.
      - One IMU (Inertial Measurement Unit) fails causing early mission termination IAW flight safety rules (i.e. three guidance IMU's required at all times).
    - Example2: Aperiodic network outages for over 2 years. Root cause: Landscape service not reading English.
    - Example3: Certified component failures. Root cause: Marking component with 'pass'.

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IN CONCLUSION

- You can claim a system is 100% safe but not 100% of the time.
- In the end, safety will depend on the quality of the assumptions made in the analysis.

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REFERENCES

- DOD, MIL-HDBK-338B, Electronic Reliability Design Handbook, Oct 1998
- Texas A & M University, Fault Tree Analysis, Construction/Evaluation/ Application. Preston l. Parker, 1977
- DOD, MIL-STD 1316F, Fuze Design Safety Criteria, 2017
- DOD, MIL-STD-331D, Fuze and Fuze Components Environmental and Performance Tests for
- DOD, MIL-STD-882D, System Safety
- Fault Tree Handbook, NUREG-0492, 1981

QUESTIONS?

THANK YOU.

For more information feel free to contact:

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