Tutorial on Probabilistic Risk Assessment (PRA)

What is a PRA?

- **Risk assessments include identification and analysis of…**
  - Initiating events
    - Circumstances that put a nuclear plant in an **off-normal condition**
  - Safety functions
    - Functions designed to **mitigate the initiating event**
  - Accident sequences
    - Combination of **safety function successes and failures** that describe the accident after an initiator
- **Successful response is that the plant transitions to safe, stable end-state for specified period of time**
- **We use a PRA model to look at the frequency and consequences of NOT achieving a safe, stable end-state**

What is the technical basis for the PRA model?

- **The PRA model is constructed to model the as-built, as-operated plant**
- **Multiple sources of information from the traditional engineering disciplines, including:**
  - Plant design information
  - Thermal hydraulic analyses of plant response
  - System drawings and performance criteria
  - Operating experience data
  - Emergency, abnormal, and system operating procedures
  - Maintenance practices and procedures

What is the technical basis for the PRA model?

- **Understanding the plant perturbation – "initiating event"**
  - Transient (loss of feedwater, condenser vacuum, instrument air, etc.)
  - Loss of offsite power
  - Loss of coolant accident
- **Understanding how the plant responds to the perturbation**
  - **Physical responses**
    - Neutronic
    - Thermal-hydraulic (e.g., vessel and containment pressure, temperature, water level)
  - **Automatic responses**
    - Reactor trip/turbine trip
    - Mitigating equipment actuates
  - **Operator responses** (per procedures)
    - Manual reactor trip
    - Manual switchover to sump recirculation

What is the technical basis for the PRA model?

- **This understanding is used to establish success criteria (based on engineering analyses)**
  - Definition of end states:
    - Establish the acceptance criteria for prevention of core damage, e.g., collapsed level greater than 1/3 core height
    - Establish containment capability
  - Determination of system success criteria for a given scenario:
    - Time at which system is required to prevent damage
    - Required system performance, e.g., two out of three pumps

What are the basic components of a PRA?

- **PRA models use**
  - **Event trees** to model the sequence of events from an initiating event to an end state
  - **Fault trees** to model failure of mitigating functions, including equipment dependencies to function as required
  - **Frequency** and **probability** estimates for model elements (e.g., initiating events, component failures)

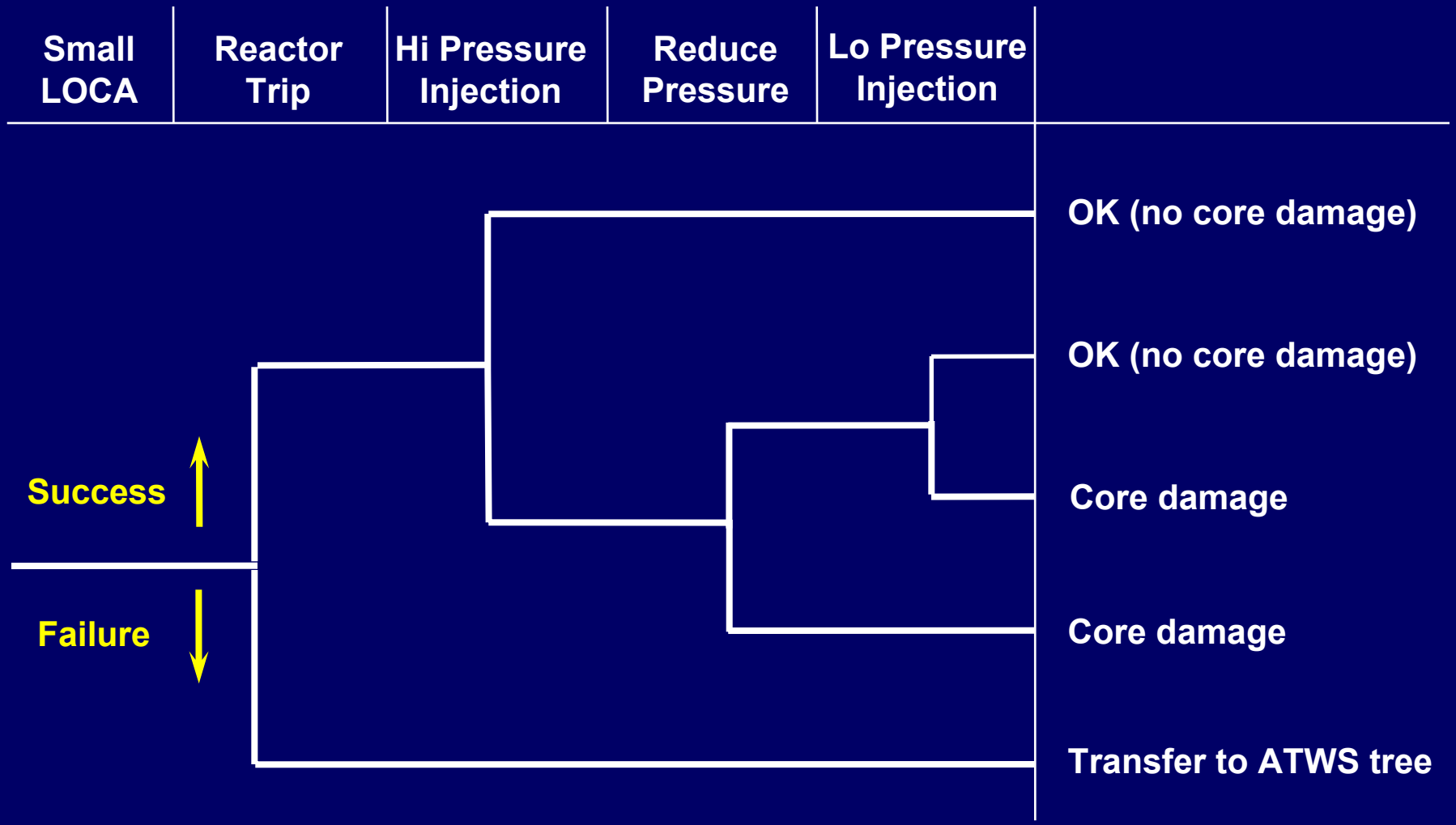
- **Outputs may include**
  - **Core damage** frequency ("Level 1" PRA)
  - **Release** frequencies ("Level 2")
  - **Radiological consequences** to public ("Level 3")

What are the end states of a PRA?

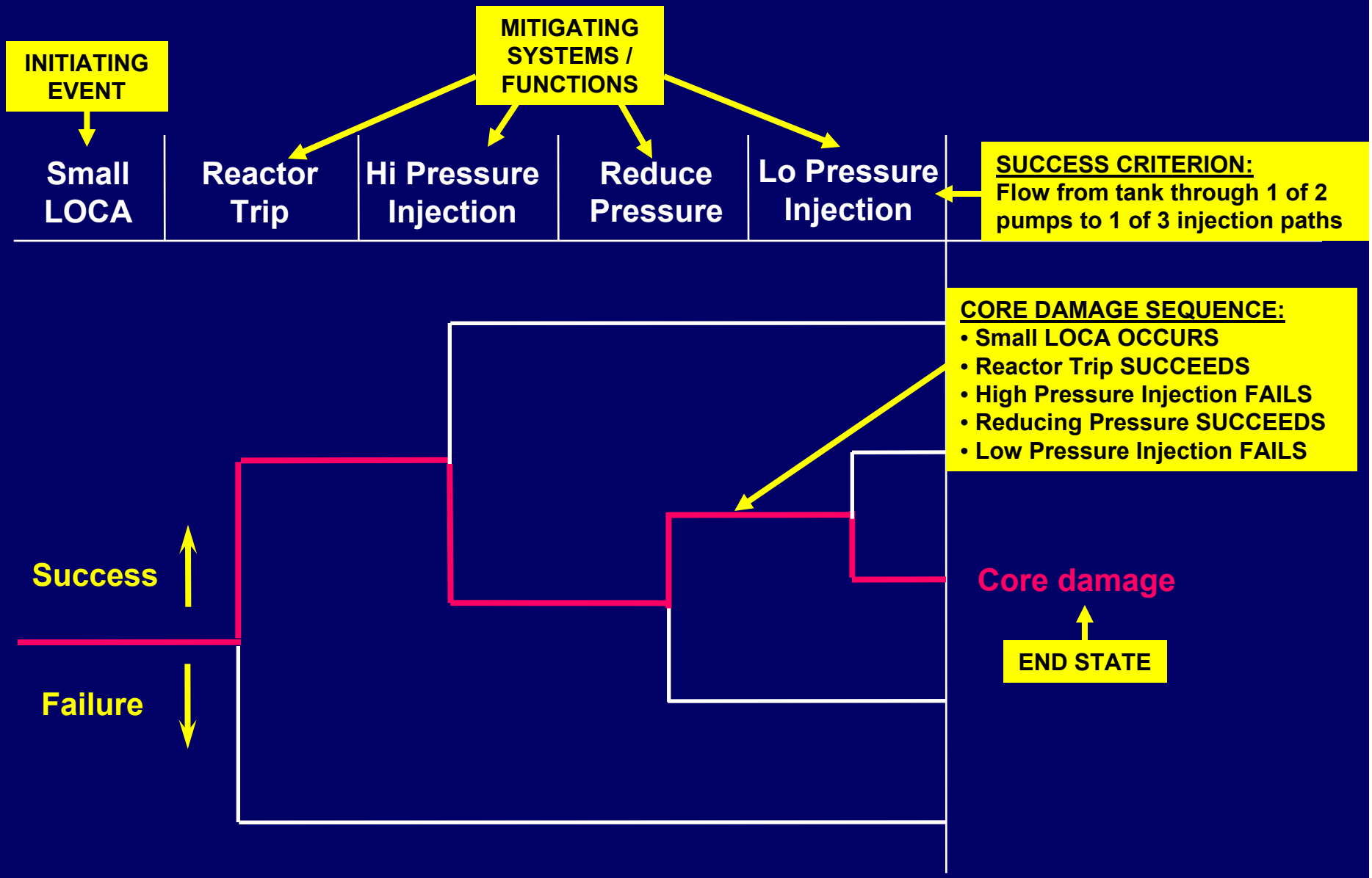
- **Core damage occurs when**
  - **Safety functions** are not met
    - Such as removal of decay heat, control of reactivity, or control of inventory
  - Engineering models show that core parameters exceed certain pre-determined limits
- **Large early release occurs when**
  - Core damage with **containment challenge**, leading to significant, **unmitigated releases prior to effective evacuation** of the close-in population
- **A limited Level 2 PRA provides insights related to core damage and large early release.**

What is an event tree?

A graphical depiction of a sequence of events



What is an event tree?



What is an event tree?

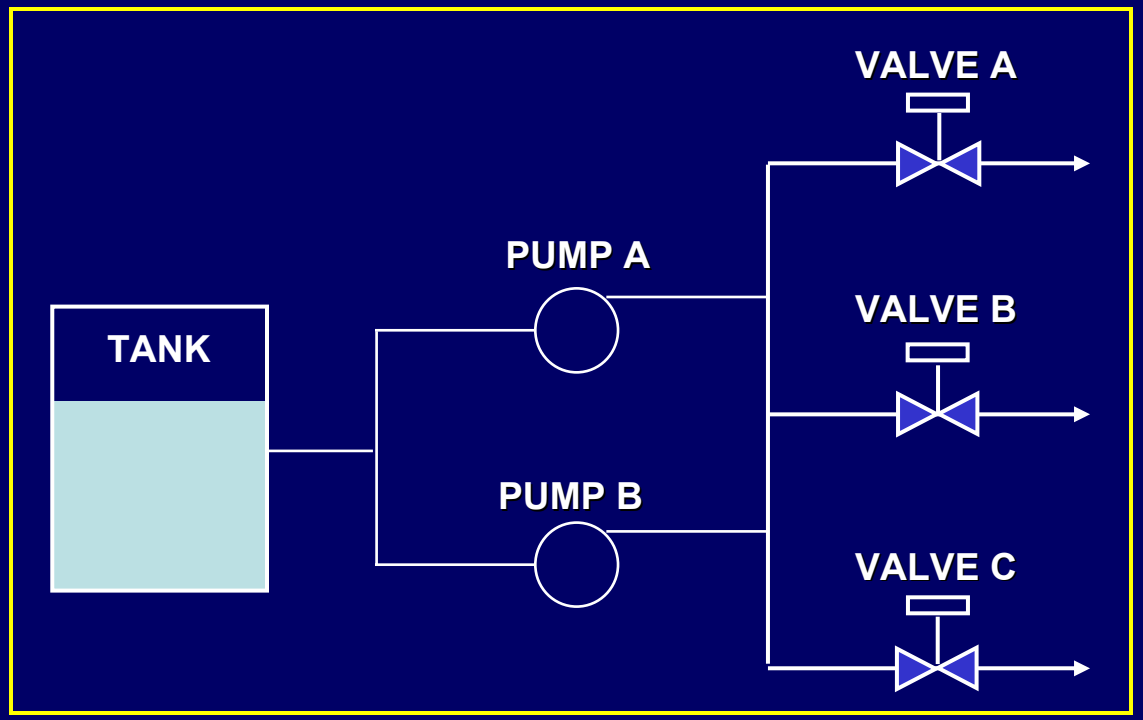
- **Event tree "top events" may represent:**
  - Functions or systems to **mitigate** core damage
  - Key **operator actions**
  - **Containment** support systems
    - Fan coolers, sprays
    - Isolation
- **Event tree also used for Level 2**
  - Use tree to model **core melt and severe accident phenomenology** that challenges containment integrity
  - **LERF is a subset of Level 2** – specific tree end states

What is a fault tree?

A graphical depiction of how a system can fail

SUCCESS CRITERION:
Flow from tank through 1 of 2 pumps to 1 of 3 injection paths

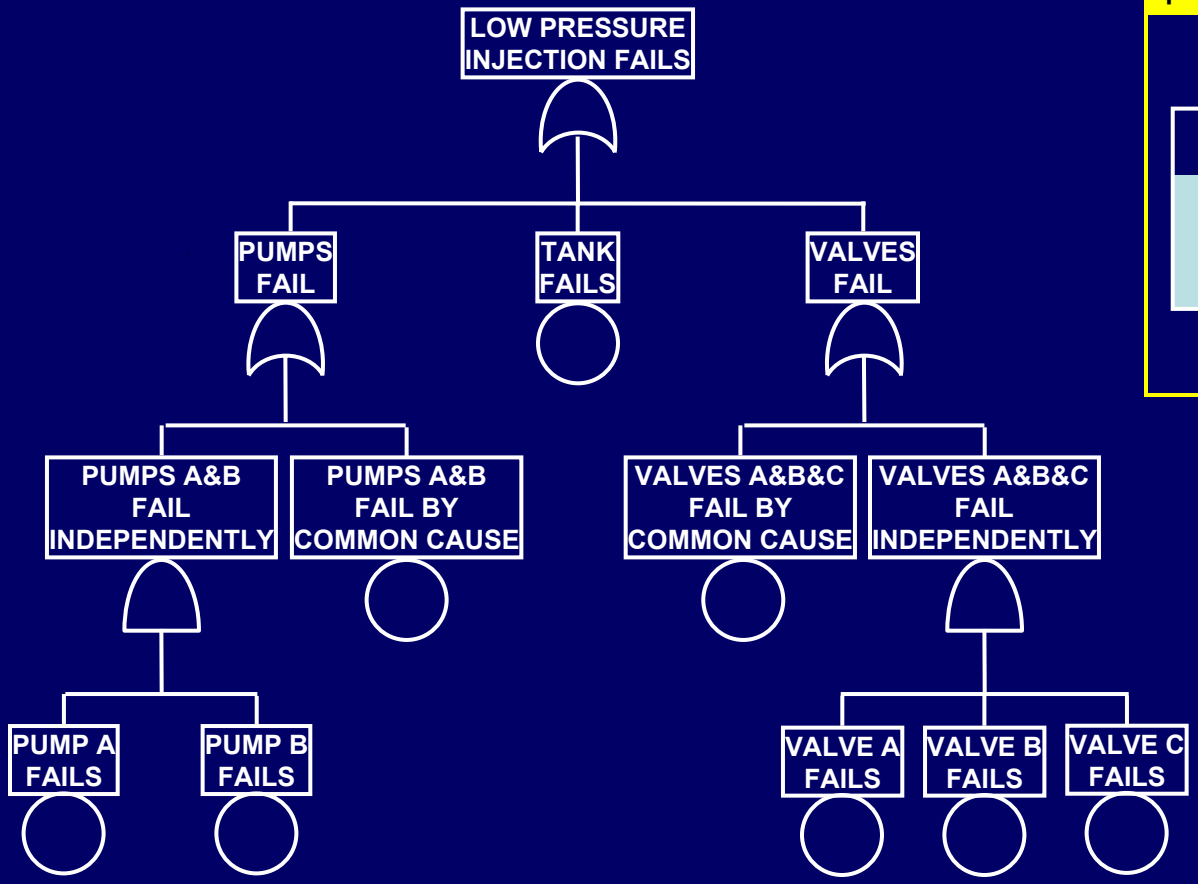
FAILURE OCCURS WHEN:
No flow from tank
OR
No flow from pumps
OR
No flow through injection paths

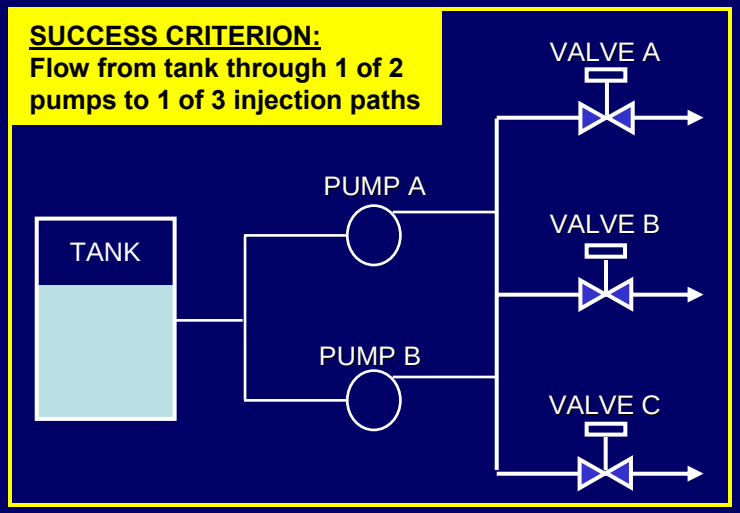


What is a fault tree?

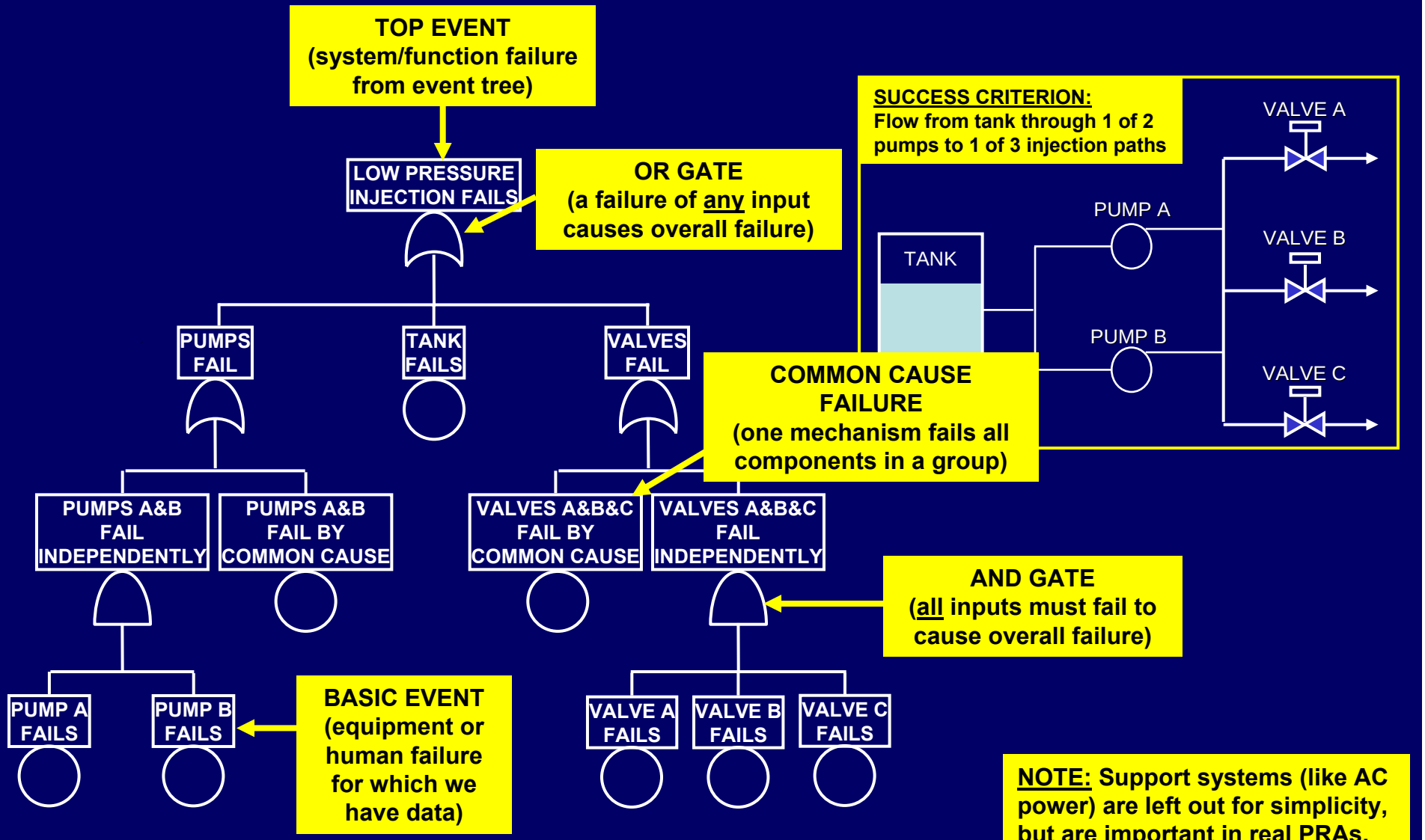
- **Developing fault trees**
  - Need for fault tree usually arises from the event tree
    - What equipment can provide the function?
    - What operator actions must take place?
  - Define **success criteria**, e.g.
    - How much flow is needed to remove decay heat?
    - How much flow is necessary to restore inventory?
    - How many valves must close to isolate containment?
  - Determine the **failure modes** to include in the tree
  - Determine supporting systems; e.g., electric power, room cooling, seal and cooling water, control power, etc.
  - Continue modeling to **basic event level**

What is a fault tree?





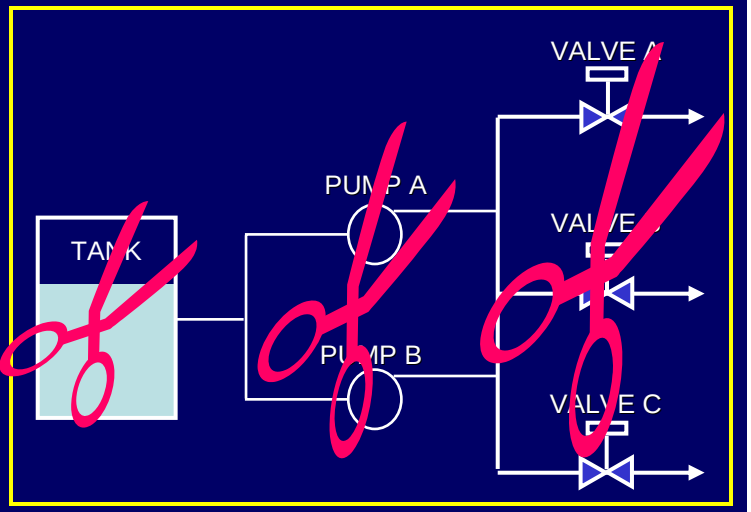
What is a fault tree?



NOTE: Support systems (like AC power) are left out for simplicity, but are important in real PRAs.

How do we solve fault trees?

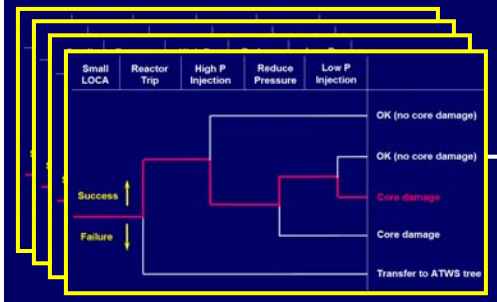
- **Reducing the logic in a fault tree gives:**
  - **Cutsets**, sets of failures that result in overall failure
    - PUMP A FAILS and PUMP B FAILS
      - Independently or by common cause
    - VALVE A FAILS and VALVE B FAILS and VALVE C FAILS
      - Independently or by common cause
    - TANK FAILS
  - **Probability that the function will fail**, derived from the cutsets and the failure probabilities of the basic events therein



Where do we get the numbers?

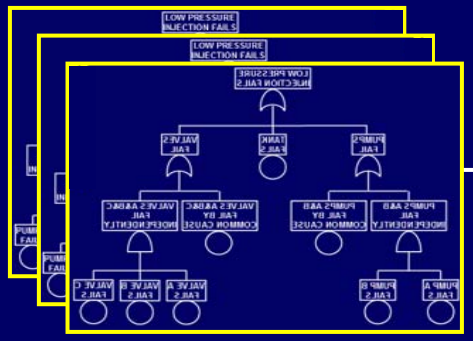
- **Operating experience data for:**
  - Frequency of many initiating events
  - Failure rates of plant equipment
  - Average availability of plant equipment
  - Probabilities of repair and recovery (e.g., restoration of offsite power)
- **Special methods:**
  - **Expert elicitation** for rare events (e.g., large LOCA frequency)
  - **Human reliability analysis** (e.g., operator fails to switch to recirculation)
  - **Common cause failure** modeling

How do we "solve" the PRA model?



CORE DAMAGE SEQUENCES:

- Small LOCA OCCURS & Reactor Trip SUCCEEDS & High Pressure Injection FAILS & Reducing Pressure SUCCEEDS & Low Pressure Injection FAILS
- … (may be several on each tree!)

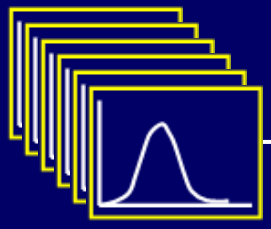


SYSTEM CUTSETS:

- PUMP A FAILS & PUMP B FAILS
- TANK FAILS
- … (may be several for each tree!)

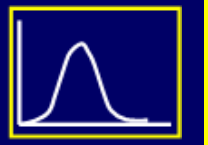
CORE DAMAGE CUTSETS:

- SMALL LOCA & HPI TANK FAILS & LPI PUMP A FAILS & LPI PUMP B FAILS
- SMALL LOCA & HPI PUMP A FAILS & HPI PUMP B FAILS & LPI TANK FAILS
- … (many combinations per sequence!)



FAILURE PROBABILITIES & INITIATING EVENT FREQUENCIES

- CORE DAMAGE FREQUENCY
- UNCERTAINTY ANALYSIS
- IMPORTANCE MEASURES
- SENSITIVITY STUDIES
- RISK INSIGHTS



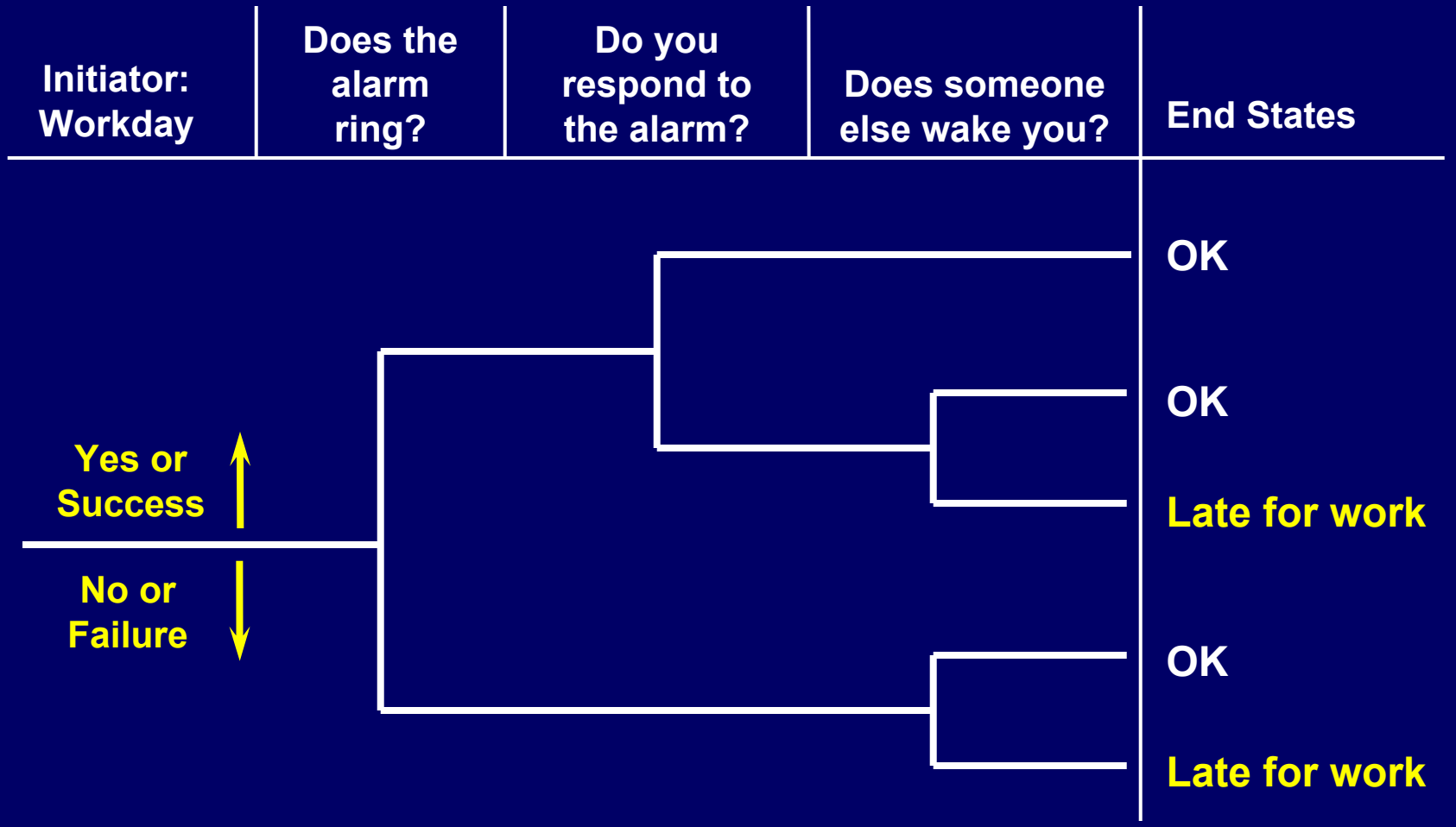
Example: Estimating the Frequency of Oversleeping

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

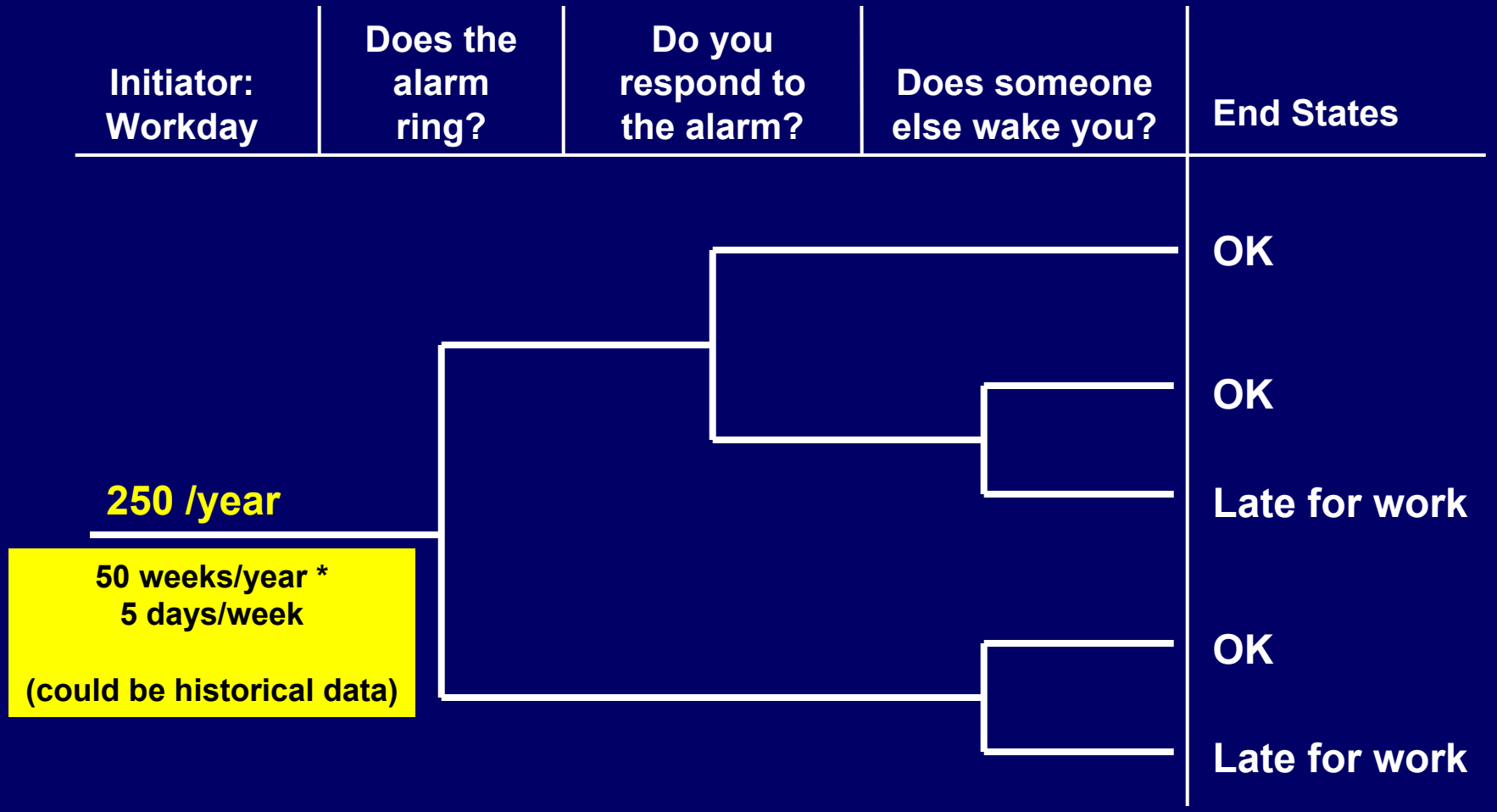
The Scenario

- **You wish to estimate the frequency of being late for work due to oversleeping**
- **After thinking about the problem a bit, you construct a simple event tree model**
  - Initiating event is the fact that it's a work day
  - Mitigating "systems" are an alarm clock and a backup person
- **You "solve" the model to arrive at an estimated "career damage frequency"**
  - Develop initiating event frequency
  - Determine branch probabilities (may need fault trees)
- **You re-analyze the problem to see the impact of adding a redundant alarm clock**

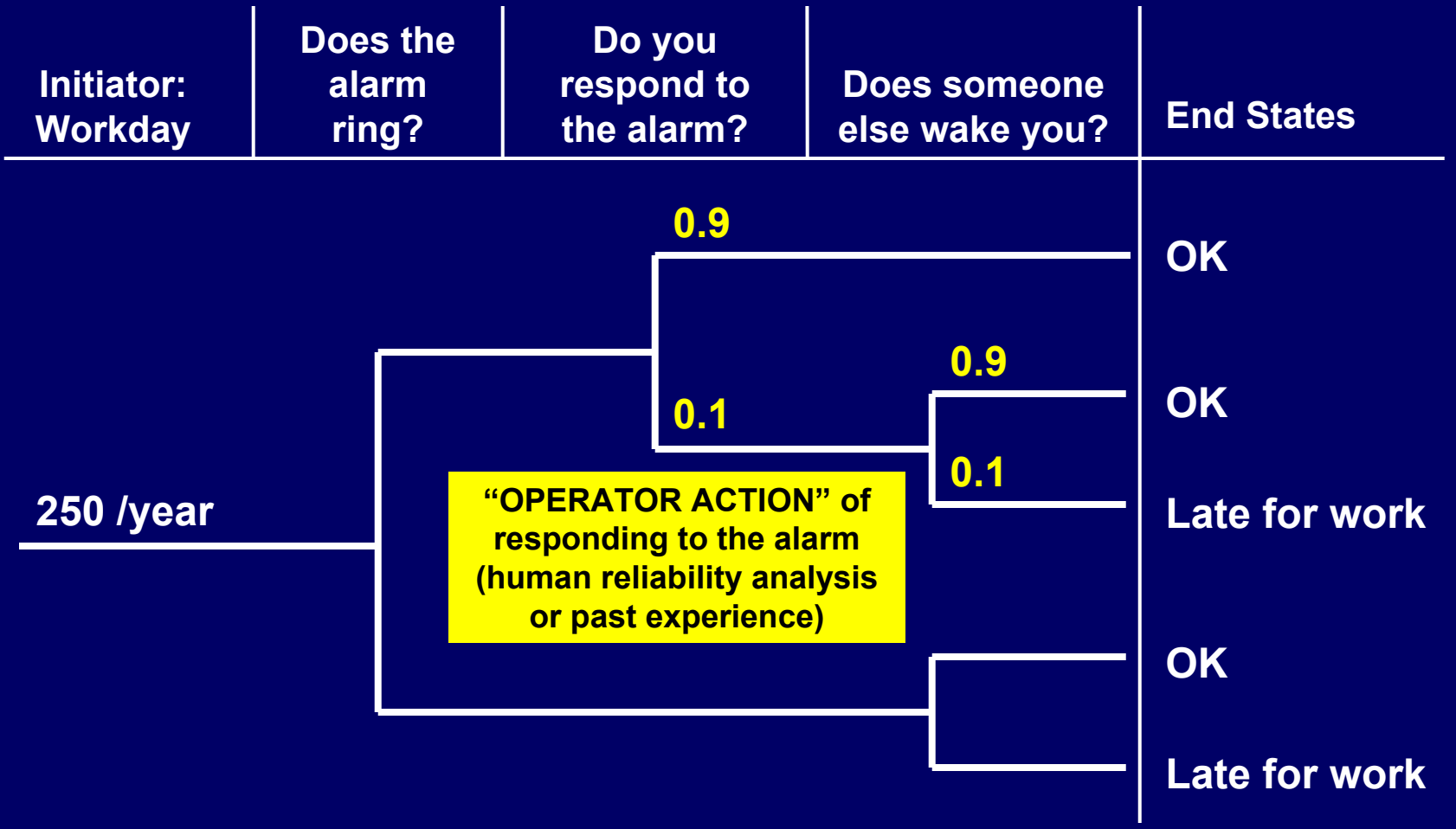
Sample Event Tree for Oversleeping



Estimating the Frequency of Oversleeping



Estimating the Frequency of Oversleeping



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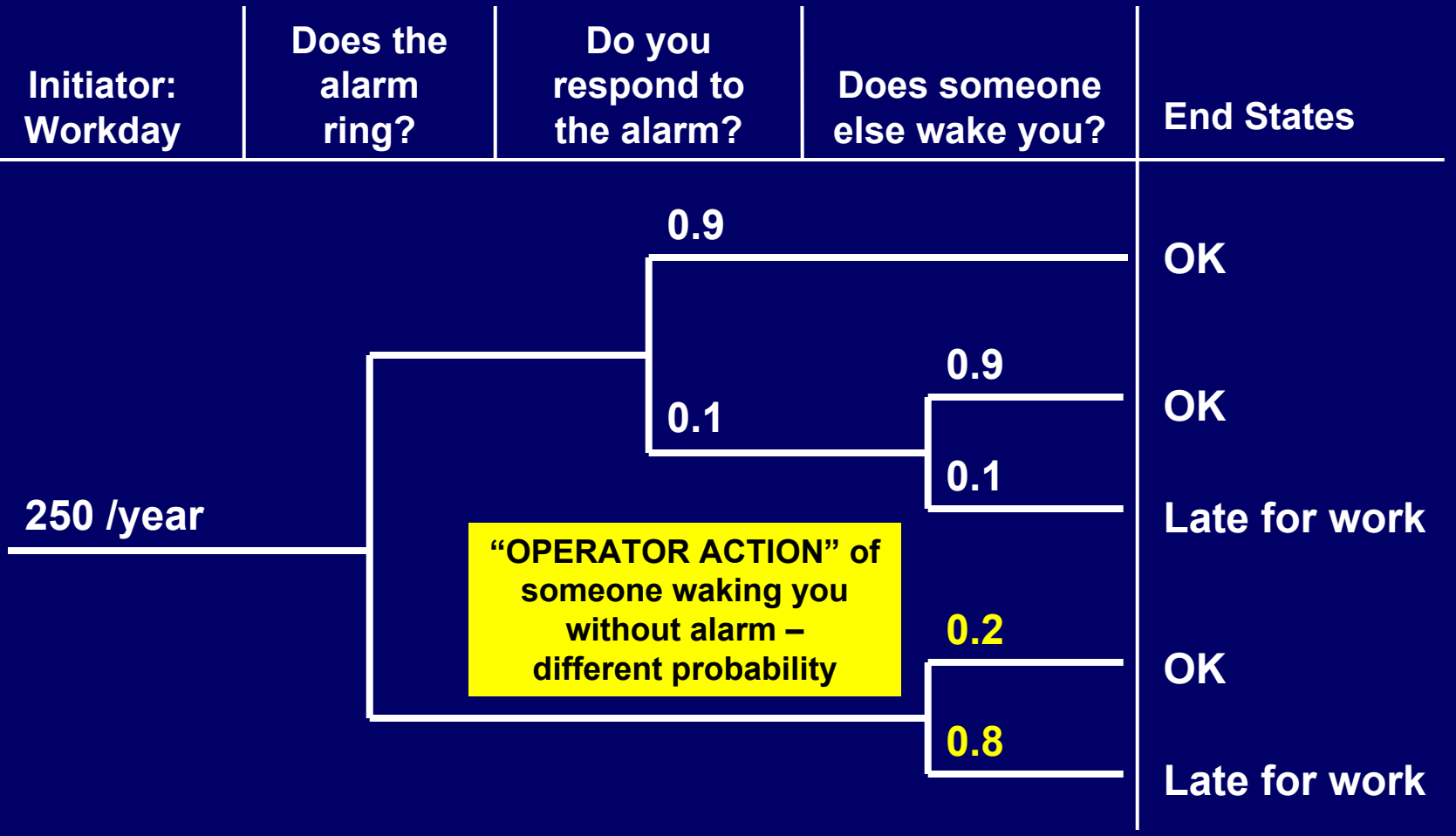
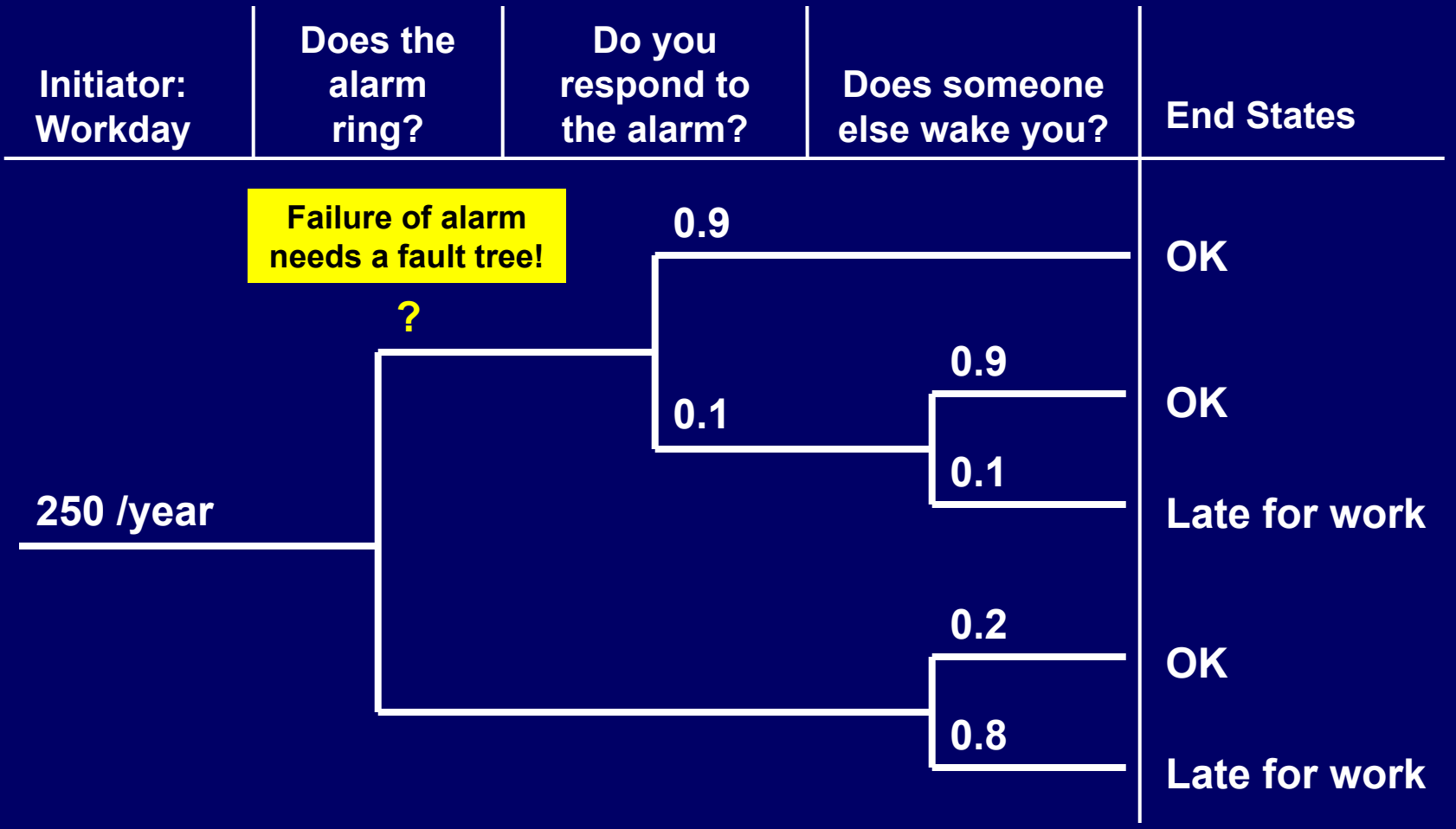
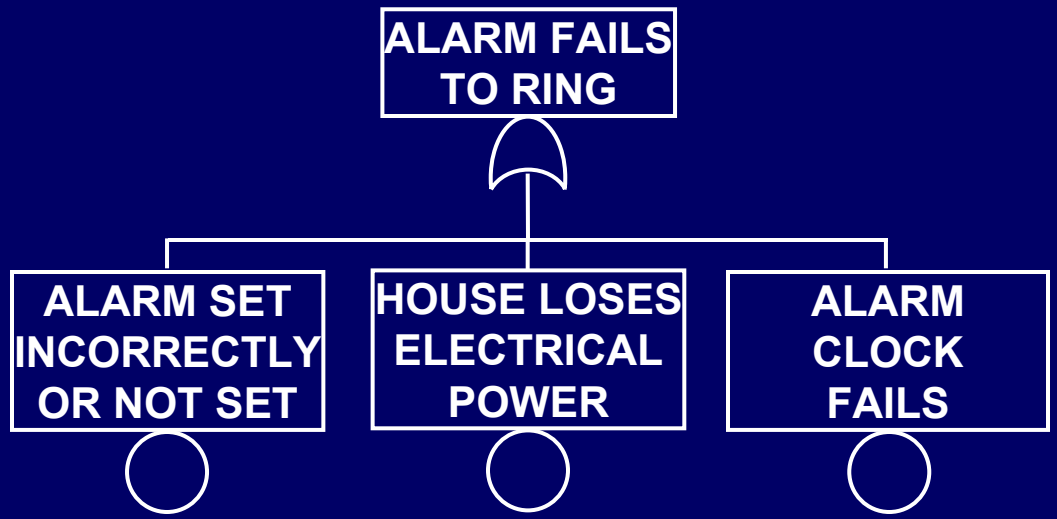


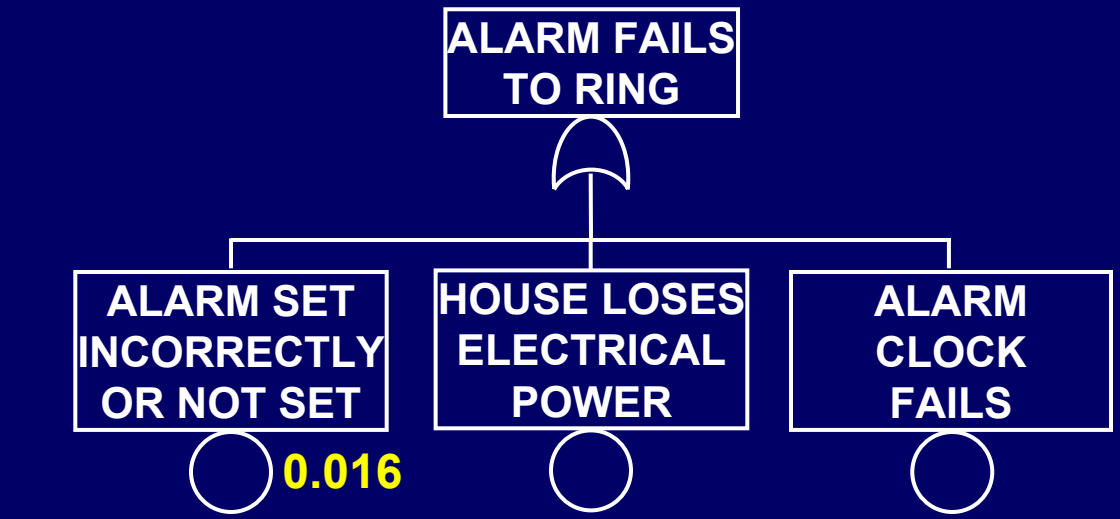
Estimating the Frequency of Oversleeping



Sample Fault Tree for Alarm Failing to Ring

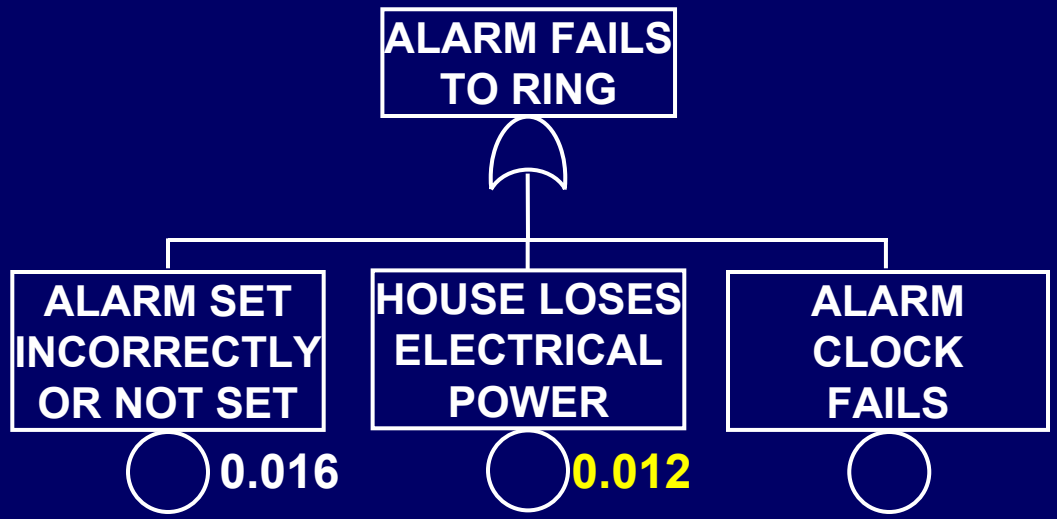


Estimating the Probability of Alarm Failing to Ring



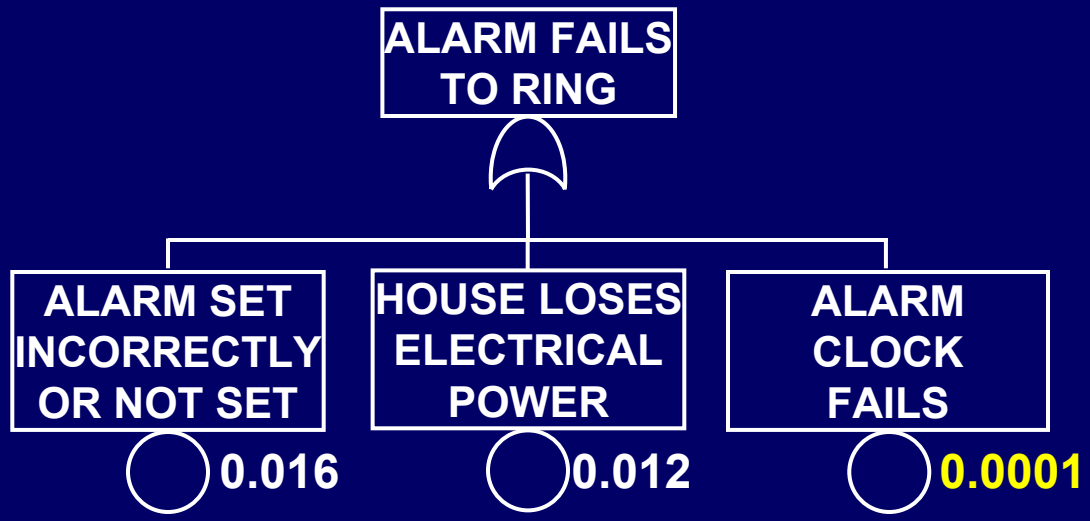
Your experience data:
4 times each work year
4/250 = 0.016

Estimating the Probability of Alarm Failing to Ring



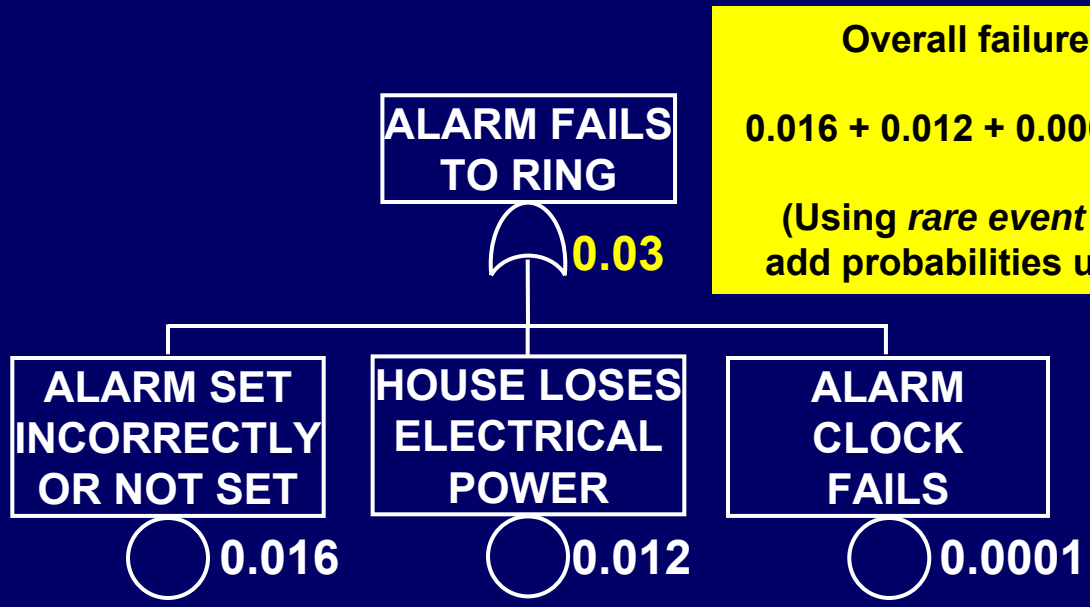
Your experience data:
3 work days per year
3/250 = 0.012

Estimating the Probability of Alarm Failing to Ring



Clock company's experience data:
1 failure in 10,000 demands
1/10000 = 0.0001

Estimating the Probability of Alarm Failing to Ring

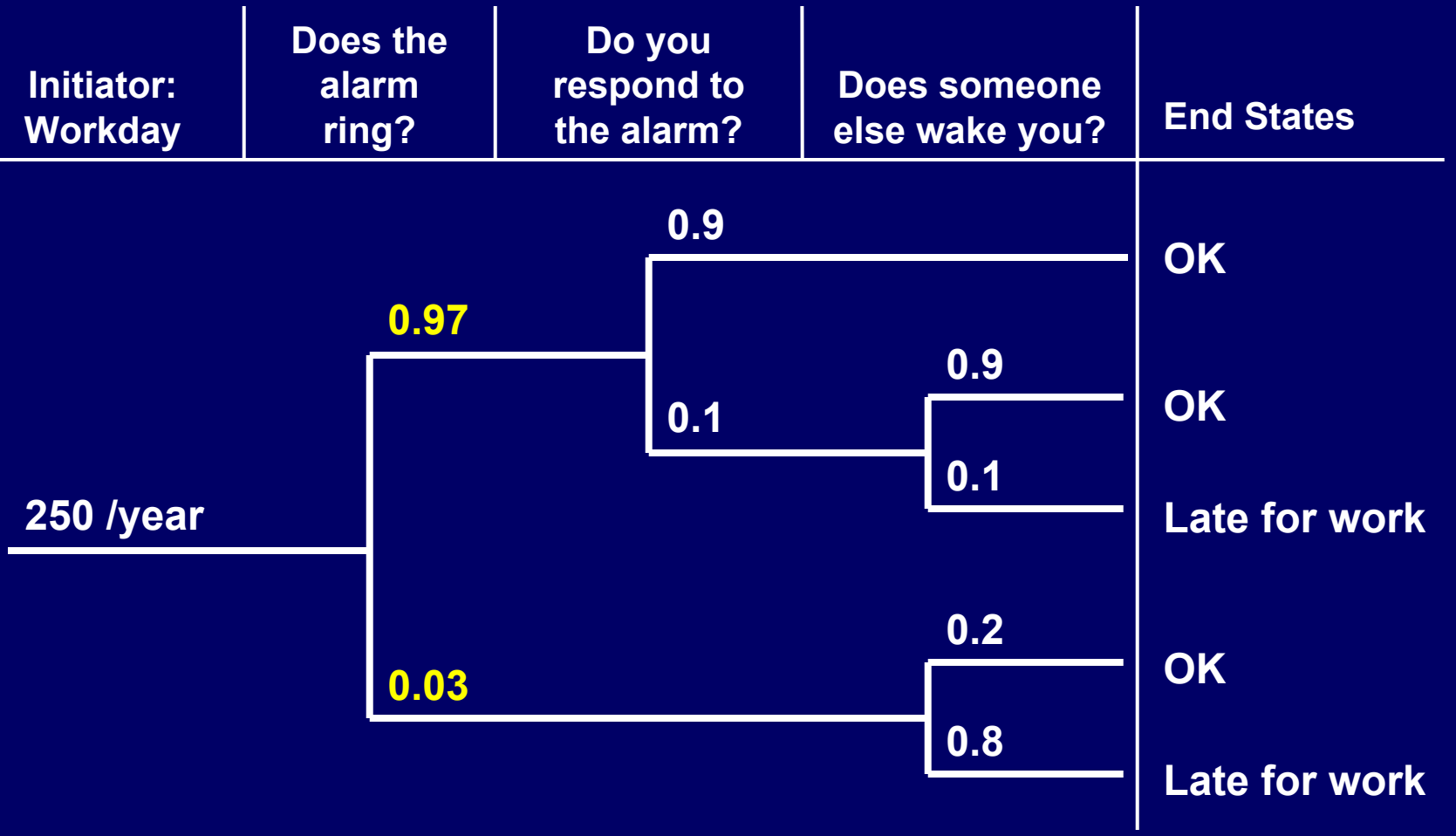


Overall failure probability:

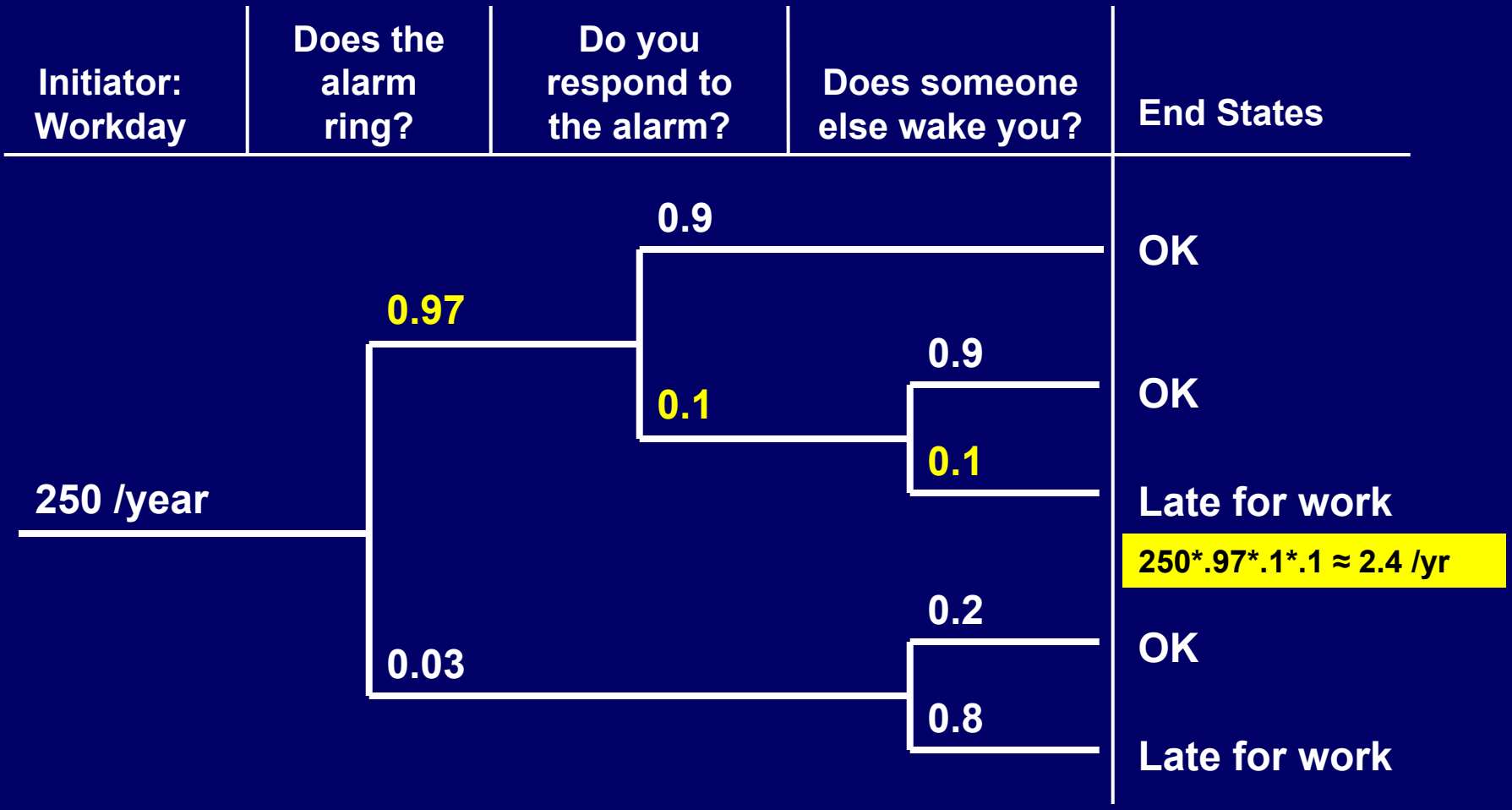
0.016 + 0.012 + 0.0001 = 0.0281 ≈ 0.03

(Using *rare event approximation*, add probabilities under "OR" gate)

Estimating the Frequency of Oversleeping



Estimating the Frequency of Oversleeping



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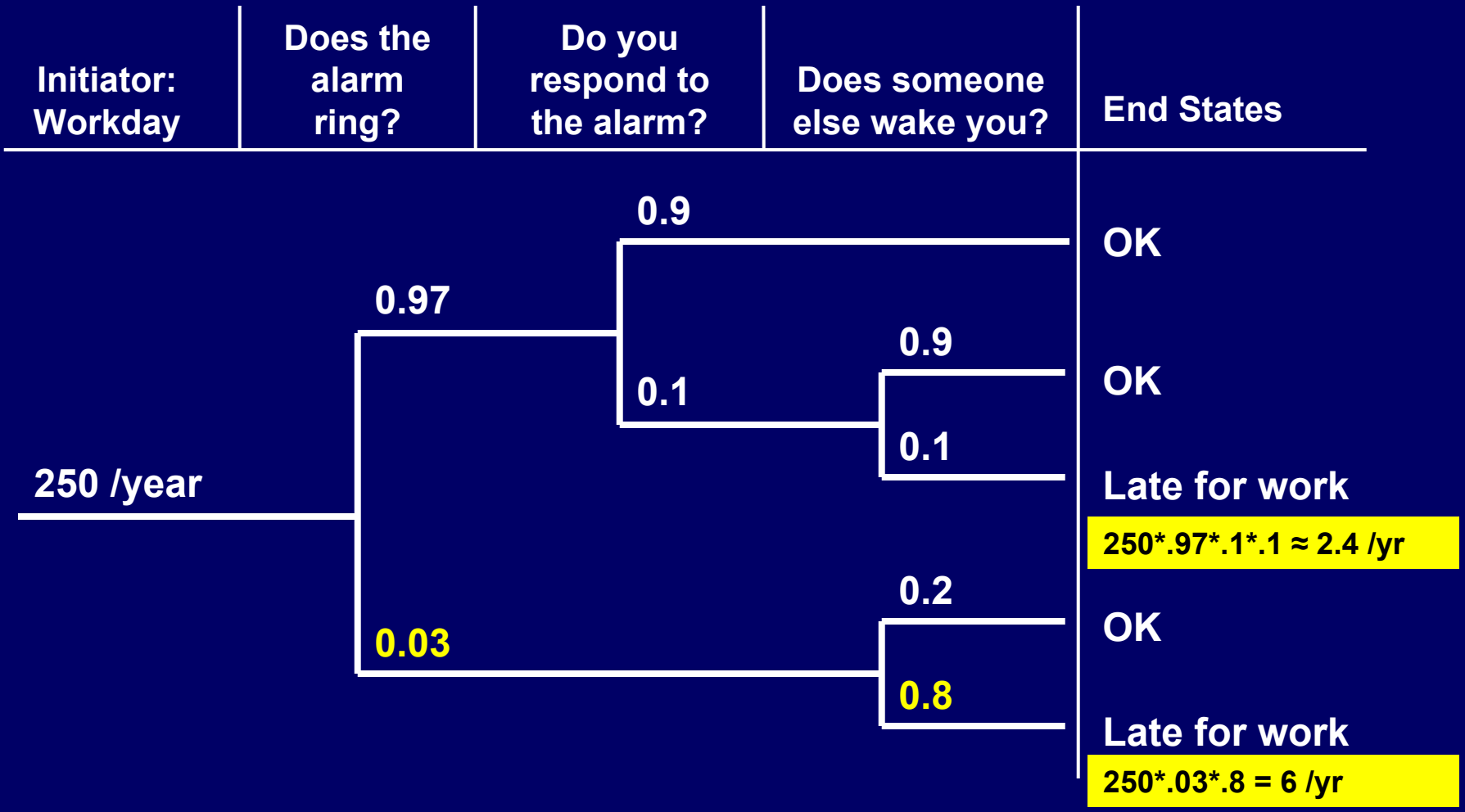
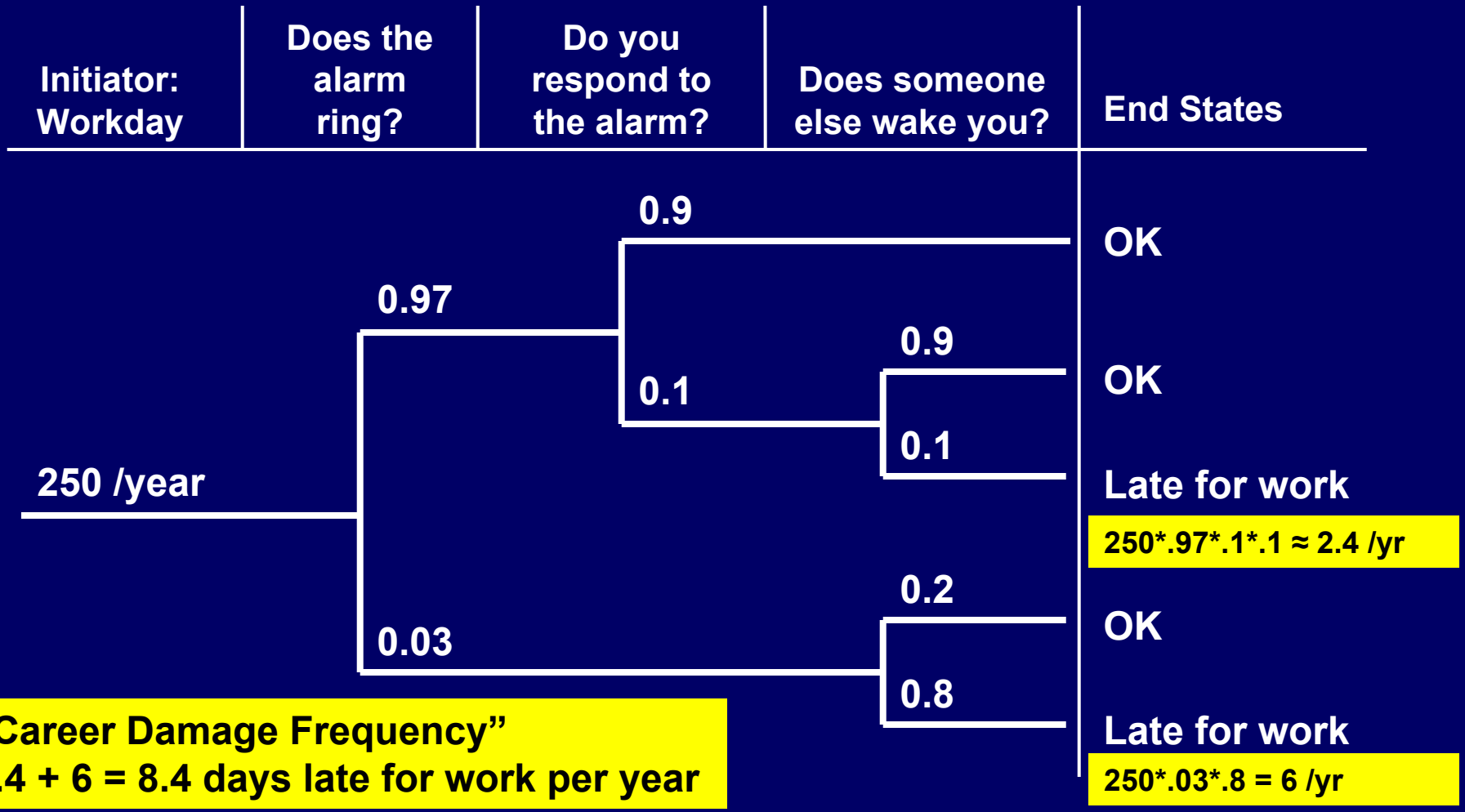


Estimating the Frequency of Oversleeping

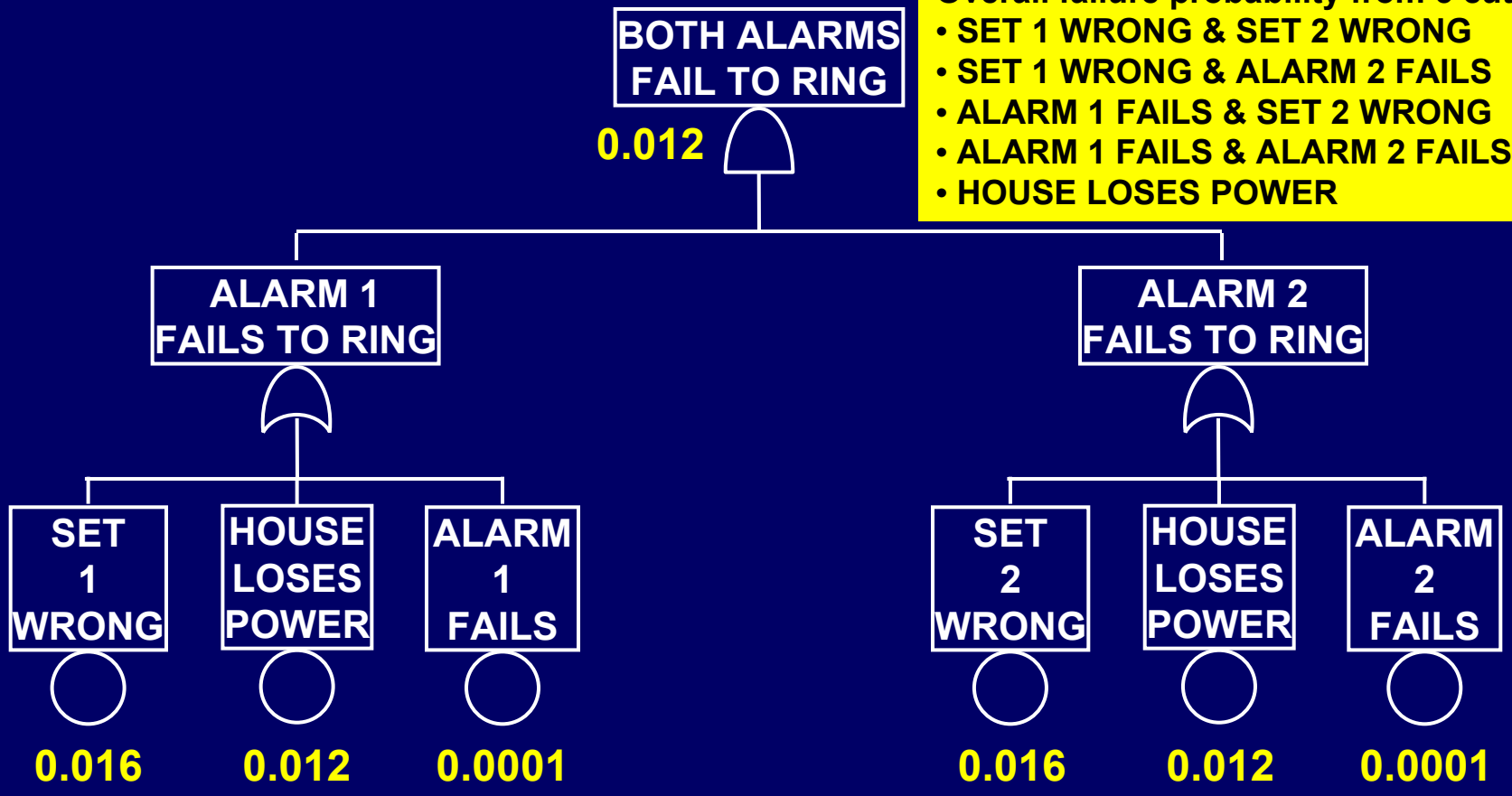


"Career Damage Frequency"
2.4 + 6 = 8.4 days late for work per year

What if we improve the design?

- **What happens if you set two alarms because you have a very important job interview?**
  - Theoretically improves the situation
    - **Both have to fail** for the "alarm fails to ring" event to be satisfied
  - Introduces other complexities
    - If both alarms depend on your home's electrical power, a **power outage makes the redundancy irrelevant**
    - If you set one wrong or forget to set it, the **likelihood of setting the other wrong is affected** (dependency)

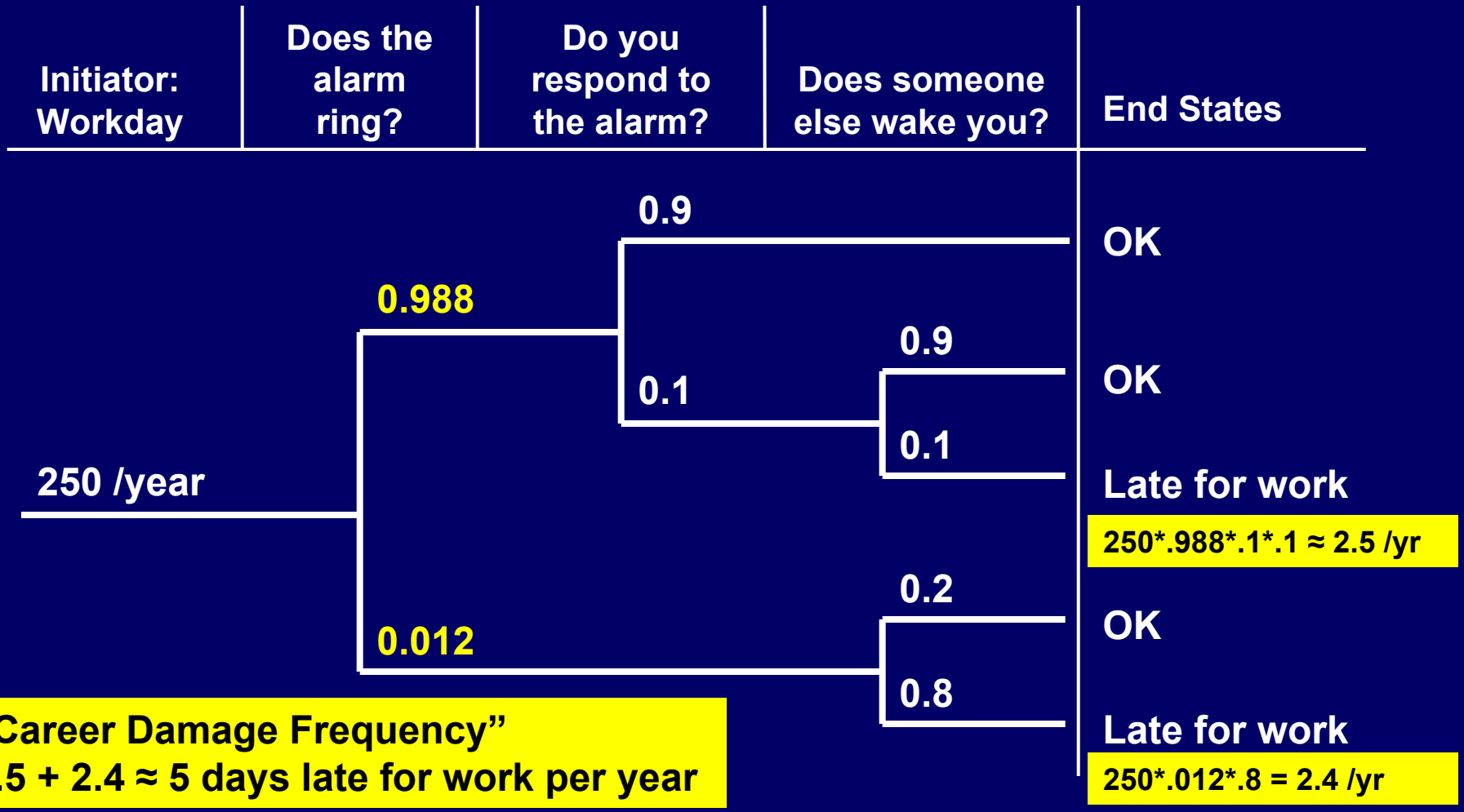
Estimating the Probability of 2 Alarms Failing to Ring



Overall failure probability from 5 cutsets:

- **SET 1 WRONG & SET 2 WRONG**
- **SET 1 WRONG & ALARM 2 FAILS**
- **ALARM 1 FAILS & SET 2 WRONG**
- **ALARM 1 FAILS & ALARM 2 FAILS**
- **HOUSE LOSES POWER**

Estimating the Frequency of Oversleeping (2 Alarms)



"Career Damage Frequency"
2.5 + 2.4 ≈ 5 days late for work per year

Career Damage Frequency Results

- **One alarm clock – ~8 late days per year**
  - 2.4 days when the alarm rings, you fail to properly respond, and nobody else hears the alarm and wakes you
  - 6 days when the alarm fails, and nobody else wakes you
- **Two alarm clocks – ~5 late days per year**
  - No noticeable change for 1st scenario
    - Alarm reliability almost 1.0 in either case
  - Major impact is on 2nd scenario
    - Failure of two alarms is less likely, but overall alarm failure is dominated by house power – extra plug-in alarms won't help!
- **Results can help you minimize risk of being late**
  - Shows "**where the risk is coming from**" – which sequences
  - May need more than one improvement to reduce overall CDF to an acceptable level

Notes on the Example

- **Simplified example – not a complete guide to PRA modeling!**
- **A "real" PRA may have:**
  - Dependencies that mean you can't just multiply event tree branch probabilities as we did
  - Common cause failure modeling
  - Ways to remove logically impossible combinations
- **However, we saw that there is a logical way to model events and failures and estimate parameter data.**
- **As a bonus, we saw that redundant equipment helps, but only up to a point!**