Massachusetts Institute of Technology
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Obtaining System- and Component-Level Insights from Importance Measures Using an Efficient Data-Driven Simulation Approach

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Summary
▶ Motivation
▶ Background
▶ Approach
▶ Conclusions
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“Risk” can describe different contexts

Risk can represent a performance shortfall

– Risk Analysis – science-driven way to make things *better*

Risk as an impact to safety

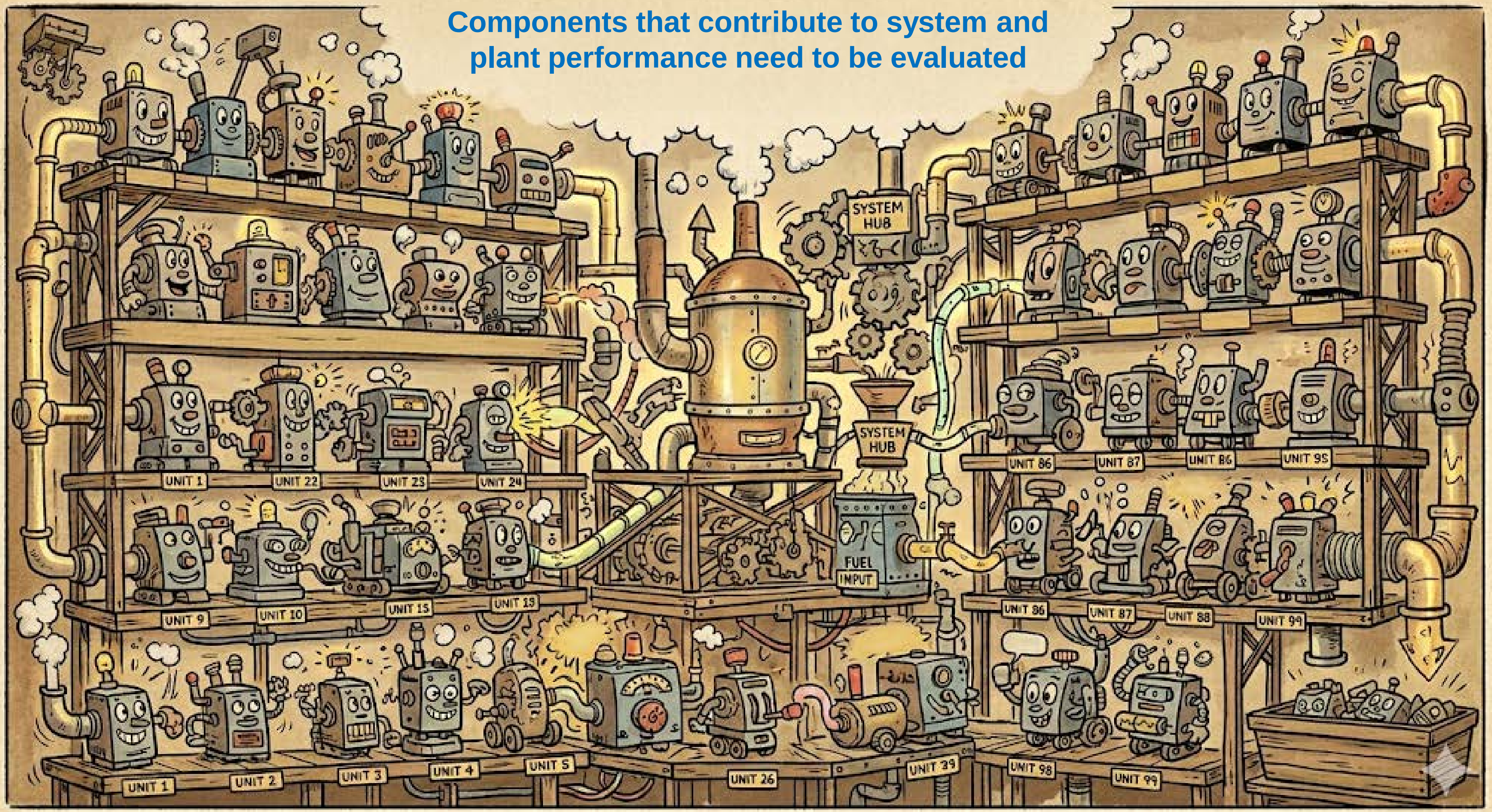
Computer simulation to evaluate complex systems

– Computational Risk Analysis (CRA)

Background

Off-normal scenarios = Initiating Events + Enabling Conditions

Components that contribute to system and plant performance need to be evaluated



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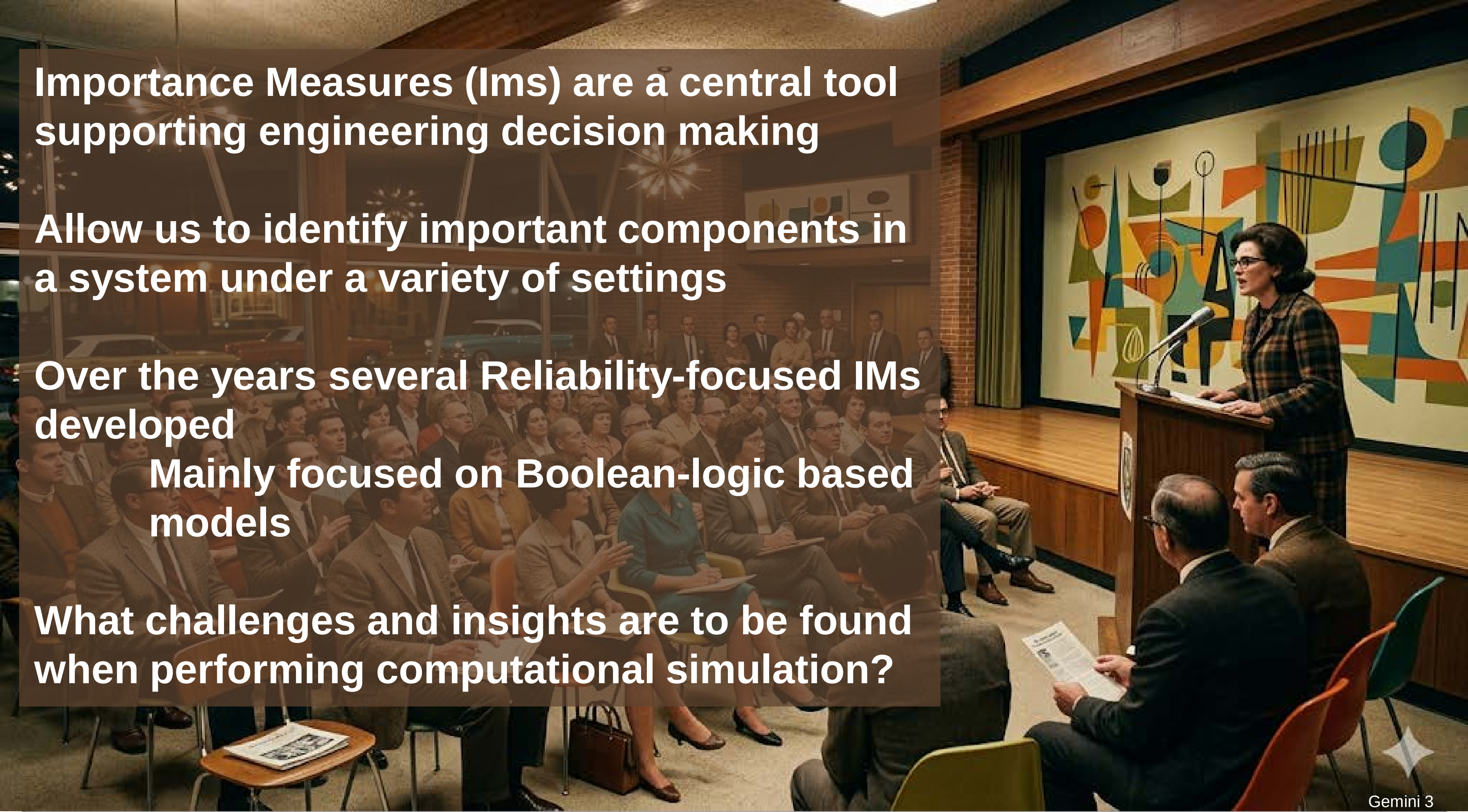
Importance Measures (Ims) are a central tool supporting engineering decision making

Allow us to identify important components in a system under a variety of settings

Over the years several Reliability-focused IMs developed

- Mainly focused on Boolean-logic based models

What challenges and insights are to be found when performing computational simulation?



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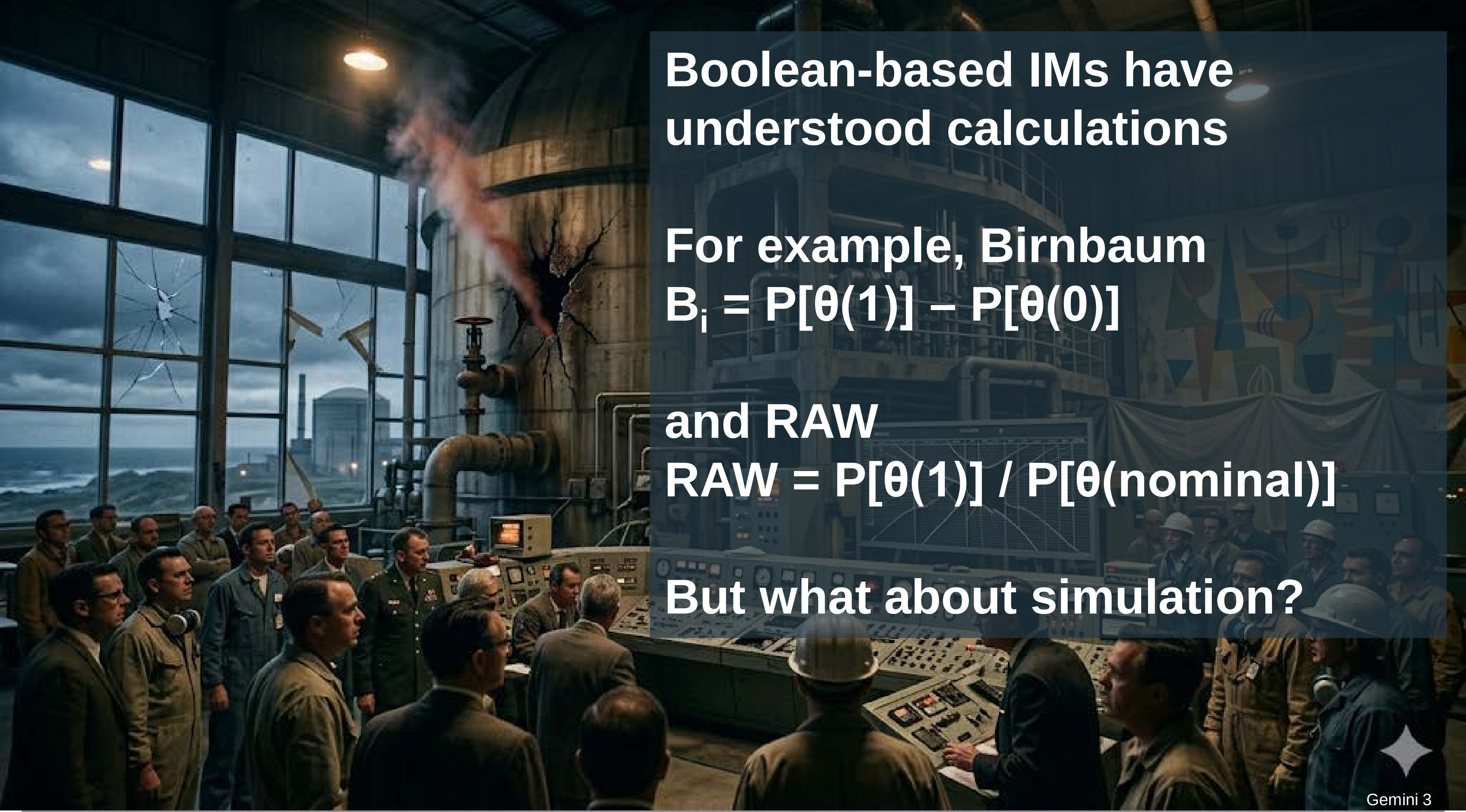

Boolean-based IMs have understood calculations

For example, Birnbaum
$B_i = P[\theta(1)] - P[\theta(0)]$

and RAW
$RAW = P[\theta(1)] / P[\theta(nominal)]$

But what about simulation?

Approach

Event Model Risk Assessment using Linked Diagrams
EMRALD (github.com/idaholab/EMRALD)

Event Simulation

Time interval [0,mission time]

Simulates system and component states as function of time

Allows mixing physical and logical considerations

Potentially no restrictions on # of components and systems and the “type” of failure

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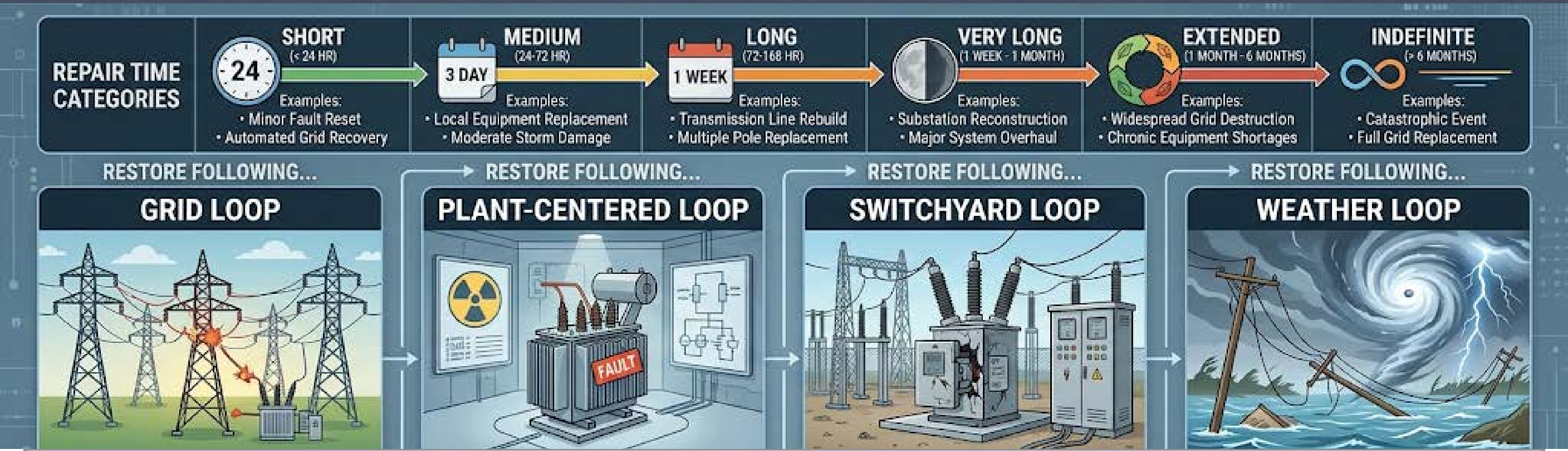
EMRALD

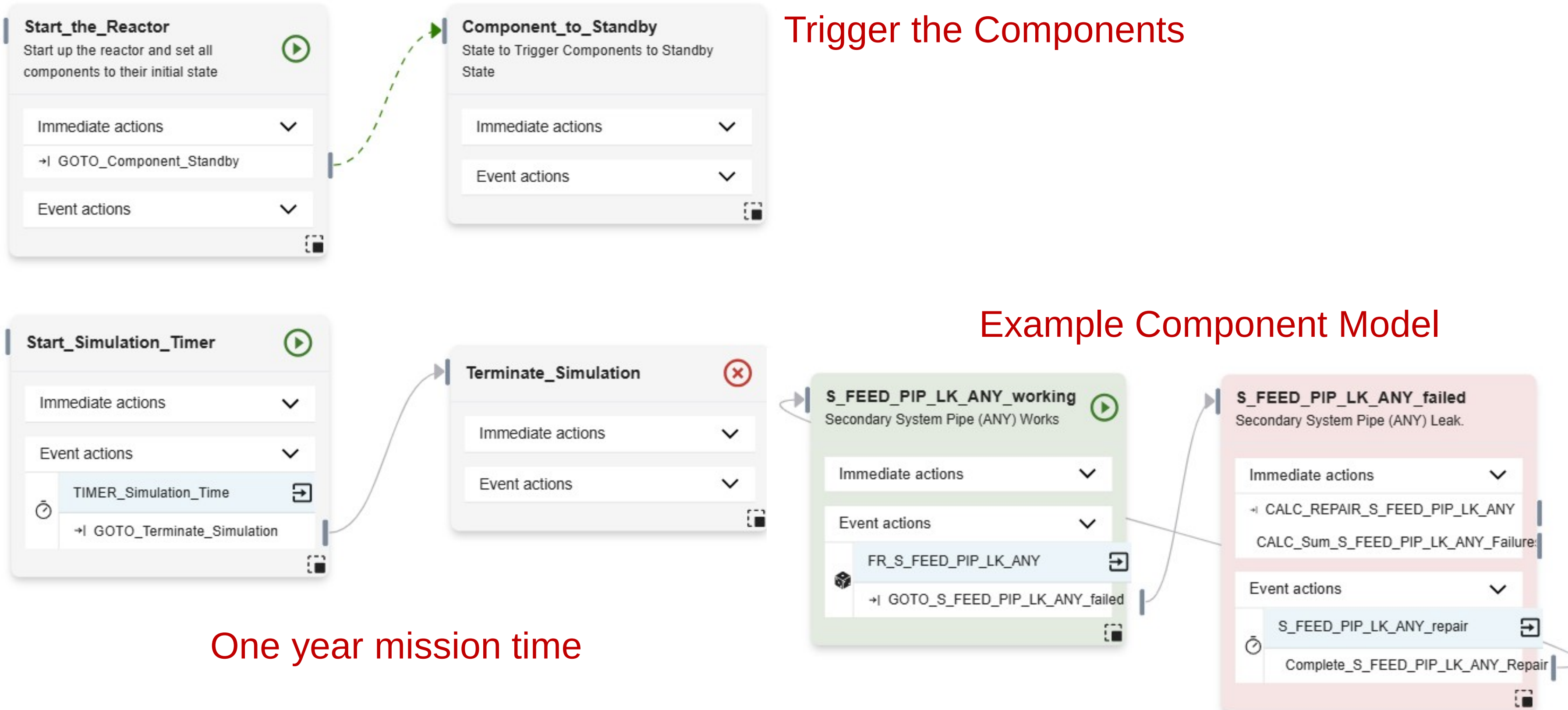
- A modeling approach using states
- A browser- based editor
- Simulation of detailed time-based systems & components evolution
- Calculation of state probabilities

Example: Component restoration times

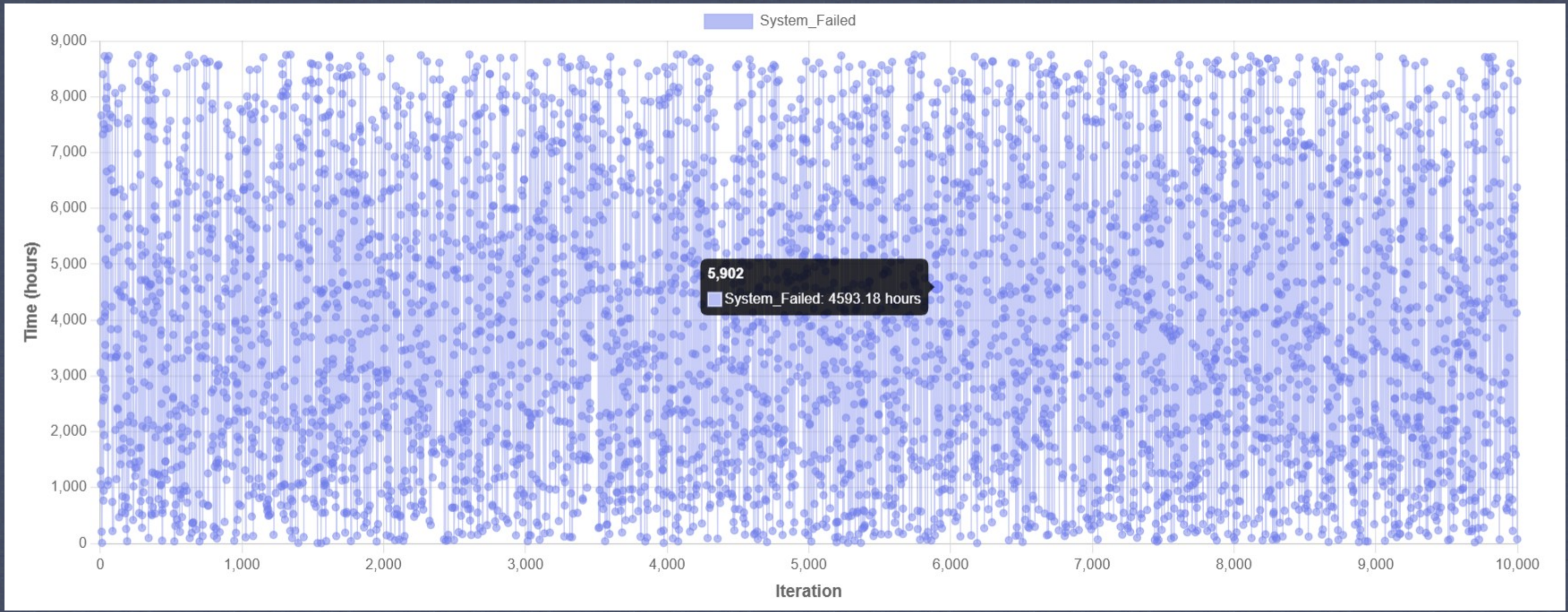
- When component fails, the time-to-restore is represented
- Key components cause the facility to lose power production

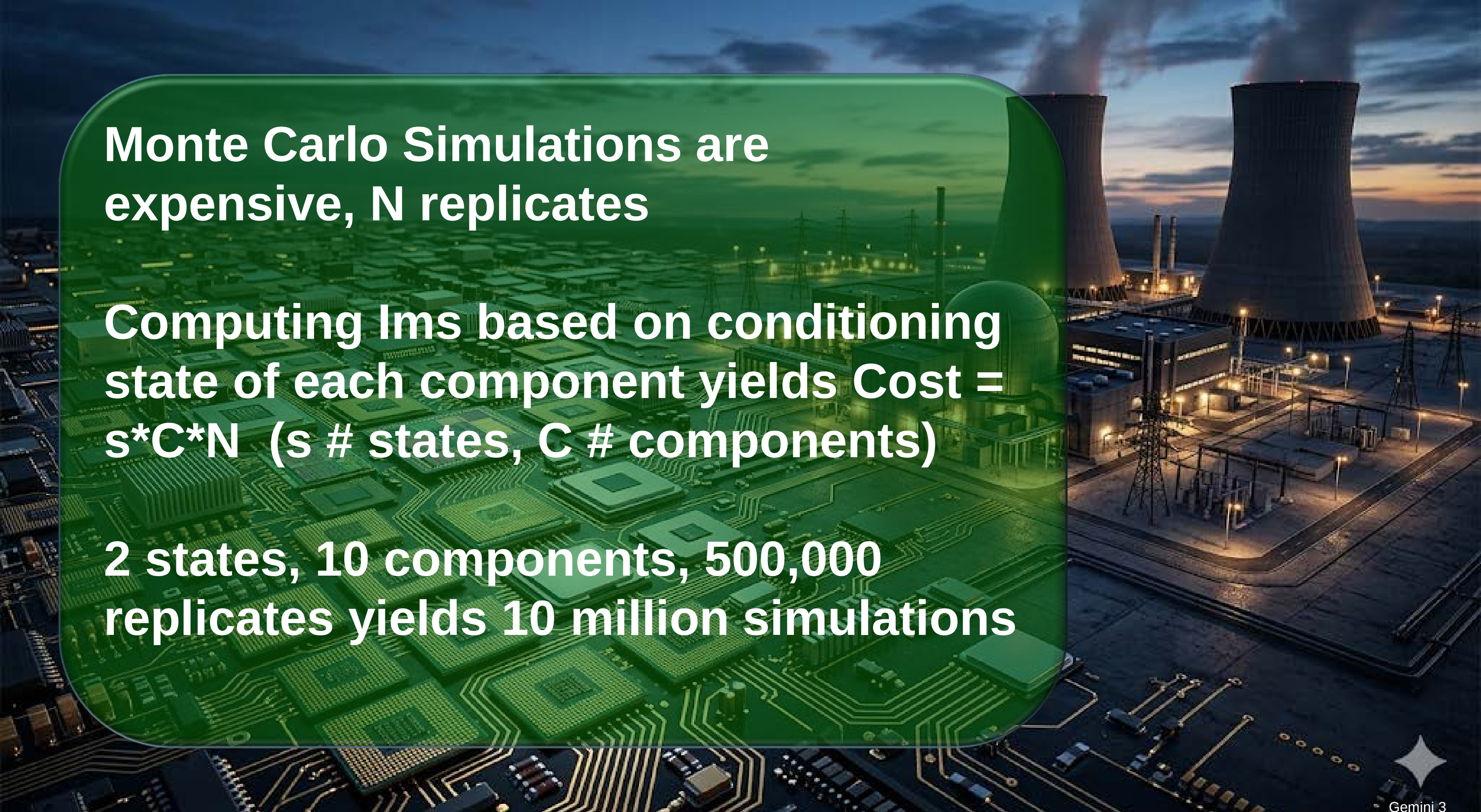


EMRALD diagram



Simulating reliability





Monte Carlo Simulations are expensive, N replicates

Computing Ims based on conditioning state of each component yields Cost = s*C*N (s # states, C # components)

2 states, 10 components, 500,000 replicates yields 10 million simulations

Our Goal

Calculate Ims from the simulation without adding additional cost

«Given already calculated data» approach

Avoid having to run calculations specific to IM calculations in the simulation engine

Example: Birnbaum

Estimate P[θ(1)] and P[θ(0)] from simulation results

- n_i = #-times component i fails in all simulations
- f_i^1 = number of times in which system fails in this set
- $N-n_i$ = #-times component i does not fail
- N = total number of simulations
- f_i^0 = number of times in which system works in this set

An estimate of the Birnbaum importance is

$$B_i = f_i^1 / n_i - f_i^0 / (N-n_i)$$

This can be extracted directly from the system simulation

Law of large numbers ensures asymptotic consistency

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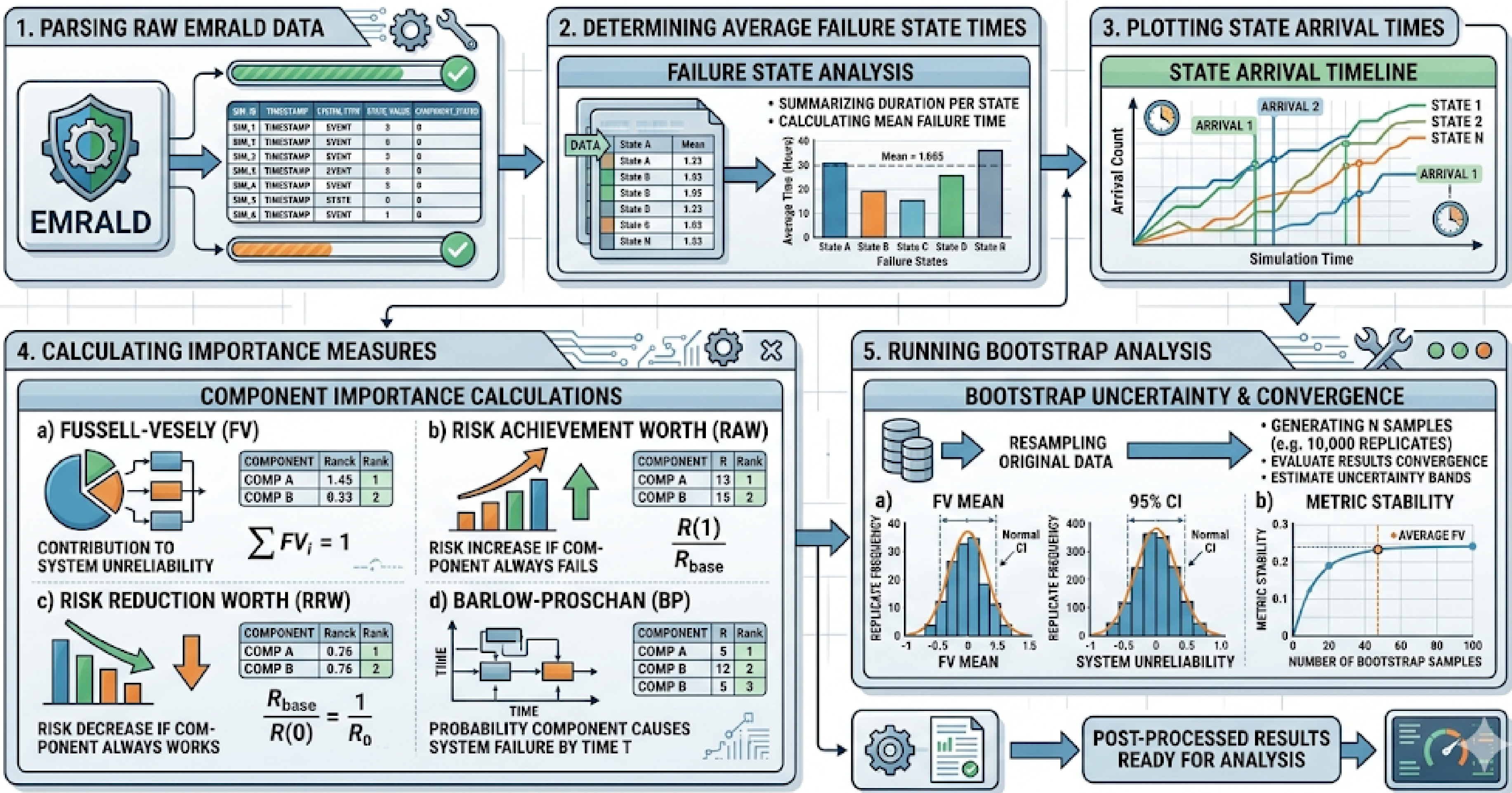
What is important in the system?

Importance measures from simulation…

Borgonovo, E. and C. Smith (2025), “Importance measures from complex reliability simulations,” In 35th European Safety and Reliability Conference (ESREL 2025) and the 33rd Society for Risk Analysis Europe Conference (SRA-E 2025), pp. 330–337.

https://rpsonline.com.sg/proceedings/esrel-sra-e2025/pdf/ESREL-SRA-E2025-P8909.pdf

EMRALD SYSTEM SIMULATION: DATA POST-PROCESSING WORKFLOW



Conclusions

In Summary

- **We have proposed a way to compute reliability importance measures from complex computer simulations**
  - No need to run conditional simulations yields a notable reduction in computational burden
- **We find asymptotically consistent IM estimates**
- **Results show applicability of the method to match traditional IMs**
- **Approach allows estimation and paves the way to chose the proper importance measure for the application at hand**
  - Safety significance, resilience, performance, maintenance...
- **Got Files?**
  - https://github.com/emanueleborgonovo/ReliabilityImportanceMeasures


THANK
YOU!
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