Intro to resilience modelling, simulation, and visualization in Python with fmdtools.

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Overview

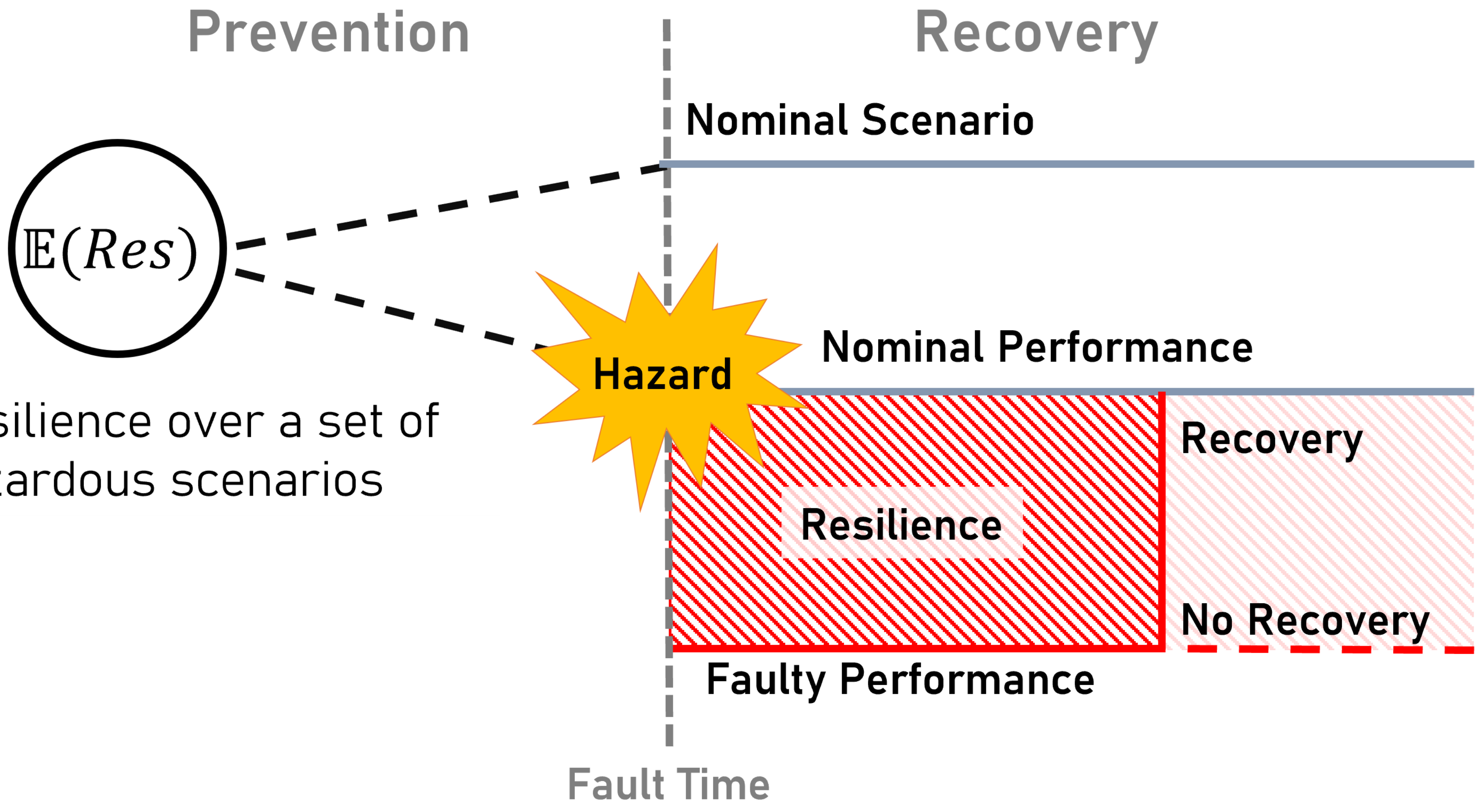
- **Overview of fmdtools**
  - Purpose
  - Project Structure
  - Common Classes/Functions
  - Basic Syntax
- **Coding Activity**
  - Example model: `examples/pump/ex_pump.py`
  - Workbook: `examples/pump/Tutorial_unfilled.ipynb`
    - Model Instantiation
    - Simulation
    - Visualization/Analysis

Prerequisites

- Ideally, some pre-existing Python and Git knowledge
- Anaconda distribution
  - Ideally this is already set up!
  - Download/install from: https://www.anaconda.com/products/individual
- A git interface
  - Github Desktop (graphical git environment)
  - git-scm (stand-alone CLI)

Motivation: Modelling System Resilience

Resilience means taking a **dynamic understanding of risk and safety**

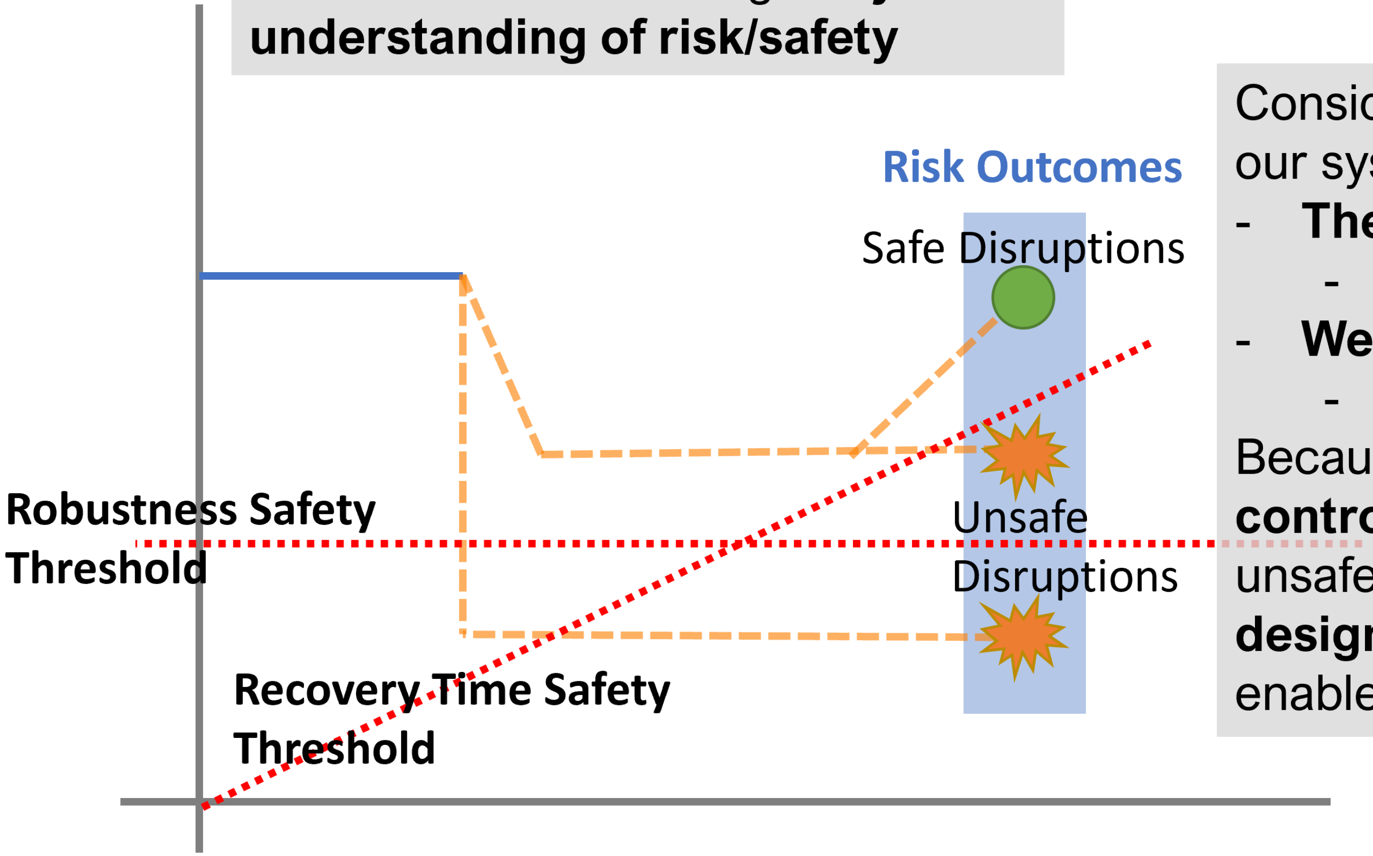


Expected Resilience: Resilience over a set of hazardous scenarios

Yodo, N., & Wang, P. (2016).

Why is Resilience Important?

Resilience means taking a **dynamic understanding of risk/safety**



Considering resilience is important when our system has dynamic attributes, e.g.:

- **The system state changes over time**
  - (e.g., position, velocity, etc)
- **We can control this state**
  - (e.g., operators, autopilot)

Because we can use it to determine **how to control the system to a safe outcome** in unsafe circumstances and what **design/operational features** we need to enable this control

Enabling proactive design process

Idea: the system should be resilient-by-design

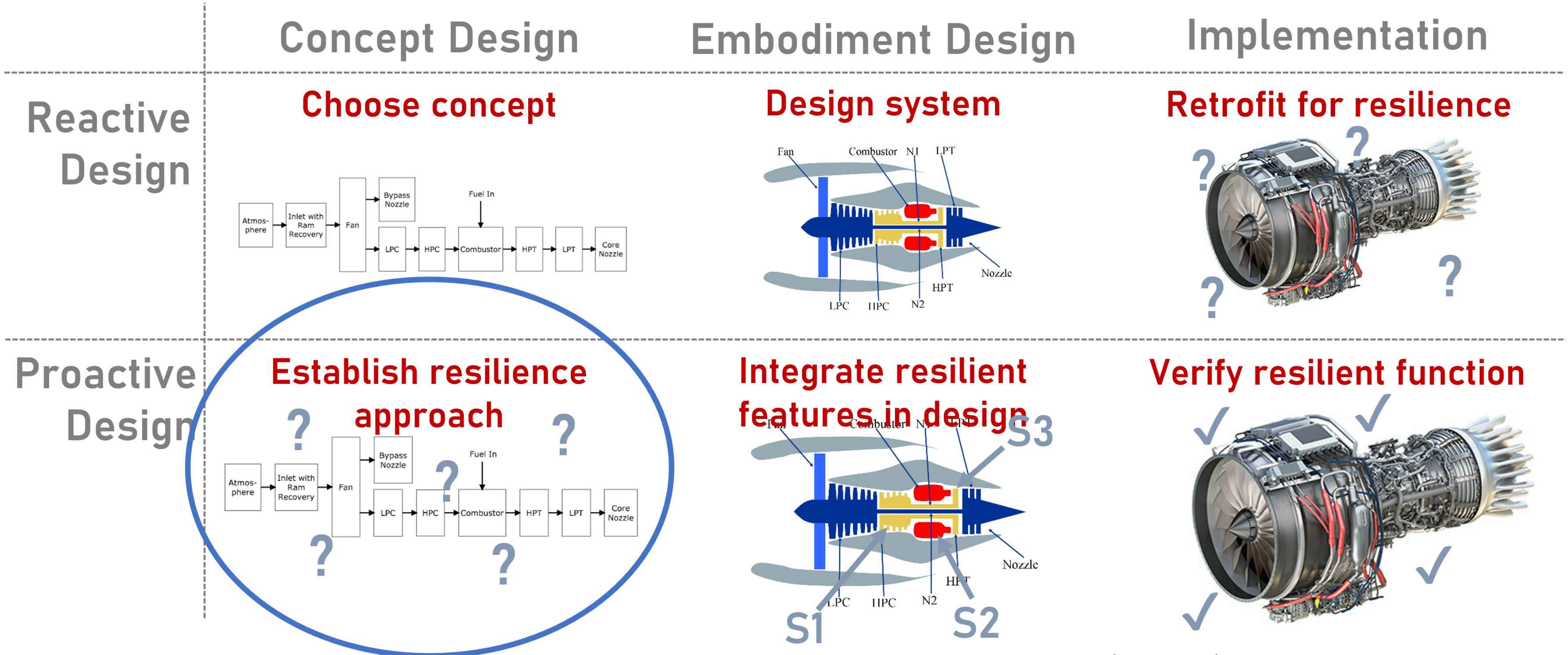


Image 1 & 2 Credit: User's Guide for the Commercial Modular Aero-Propulsion System Simulation (C-MAPSS)
Image 3 Credit: https://en.wikipedia.org/wiki/File:General_Electric_Passport.jpg

- Especially relevant to **new systems** when **we don't have data**

Why fmdtools? Possible Competitors:

- Uncertainty Quantification tools: (e.g. OpenCossan)
    - Doesn’t incorporate fault modelling/propagation/visualization aspects
- MATLAB/modelica/etc. Fault Simulation tools
    - Rely on pre-existing model/software stack--Useful, but often difficult to hack/extend (**not open-source**)
- Safety Assessment tools: (e.g. Alyrica, Hip-Hops)
    - Focused on quantifying safety, not necessarily resilience
    - As a result, use **different model formalisms**!

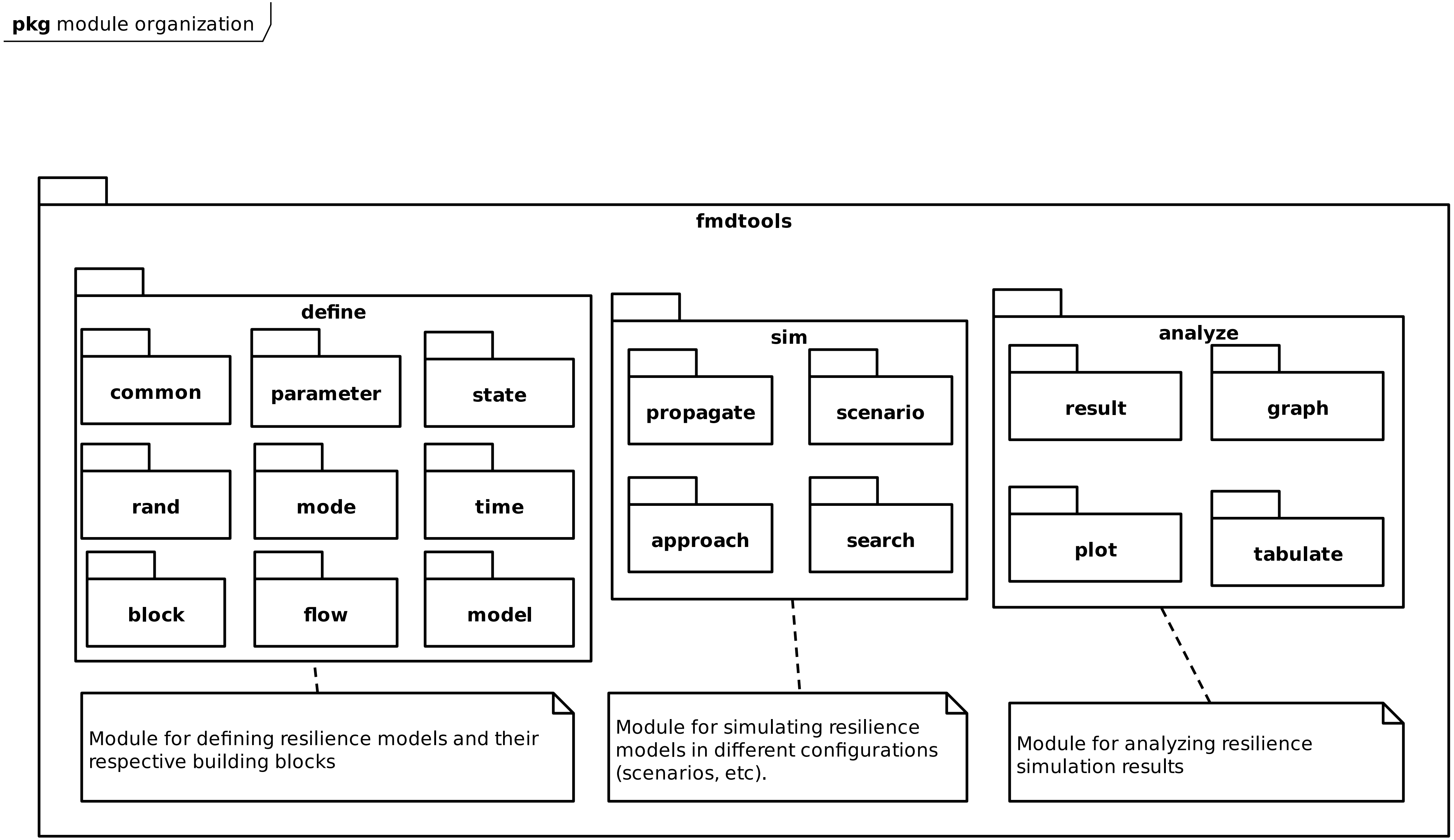
Why fmdtools? Pros:

- Highly Expressive, modular model representation.
  - faults from any component can propagate to any other connected component via **undirected propagation**
  - highly-extensible code-based behavior representation
  - class structure enables **complex models** representing human behavior and systems of systems
- Research-oriented:
  - Written in/relies on the Python stack
  - Open source/free software
- Enables design:
  - Models can be parameterized an optimized!
  - Plug-and-play analyses and visualizations

Why not fmdtools? Cons:

- You already have a pre-existing system model
  - fmdtools models are built in fmdtools
  - if you have a simulink/modelica model, you may just want to use built-in tools
- You want to use this in production
  - fmdtools is Class E Software and thus mainly suitable for research (or, at least, we don't gaurantee it)
  - Somewhat dynamic development history

What is fmdtools? A Python package for design, simulation, and analysis of resilience.



What is fmdtools? Repo Structure

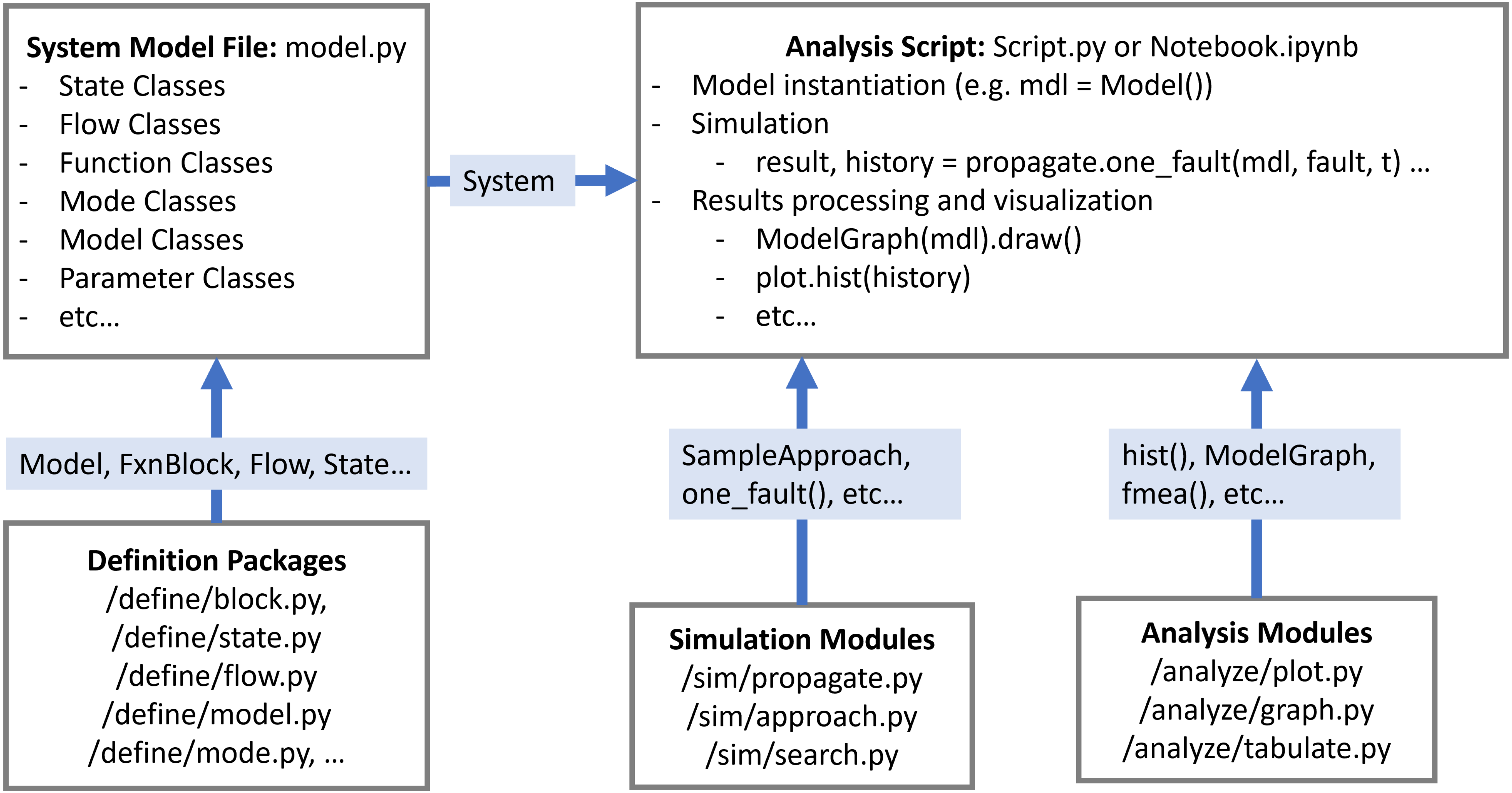
Repository (https://github.com/nasa/fmdtools/)

- `/fmdtools` : installable package
- `/examples` : example models with demonstrative notebooks and tests
- `/docs` : resources for documentation
- `/tests` : stand-alone tests (and testing rigs)
- `README.md` : Basic package description
- `CONTRIBUTORS.md` : Credit for contributions
- `requirements.txt` : List of requirements
- ... and other configuration files

Activity: Download and Install fmdtools

- repo link: https://github.com/nasa/fmdtools/
- set up repo:
  - create `path/to/fmdtools` folder for repo
    - (usually in `/documents/GitHub`)
  - clone git into folder:
    - `git clone https://github.com/nasa/fmdtools.git`
    - can also use webpage
- package installation:
  - Open Python from anaconda (e.g., open Spyder)
  - Install with `pip install -e /path/to/fmdtools`

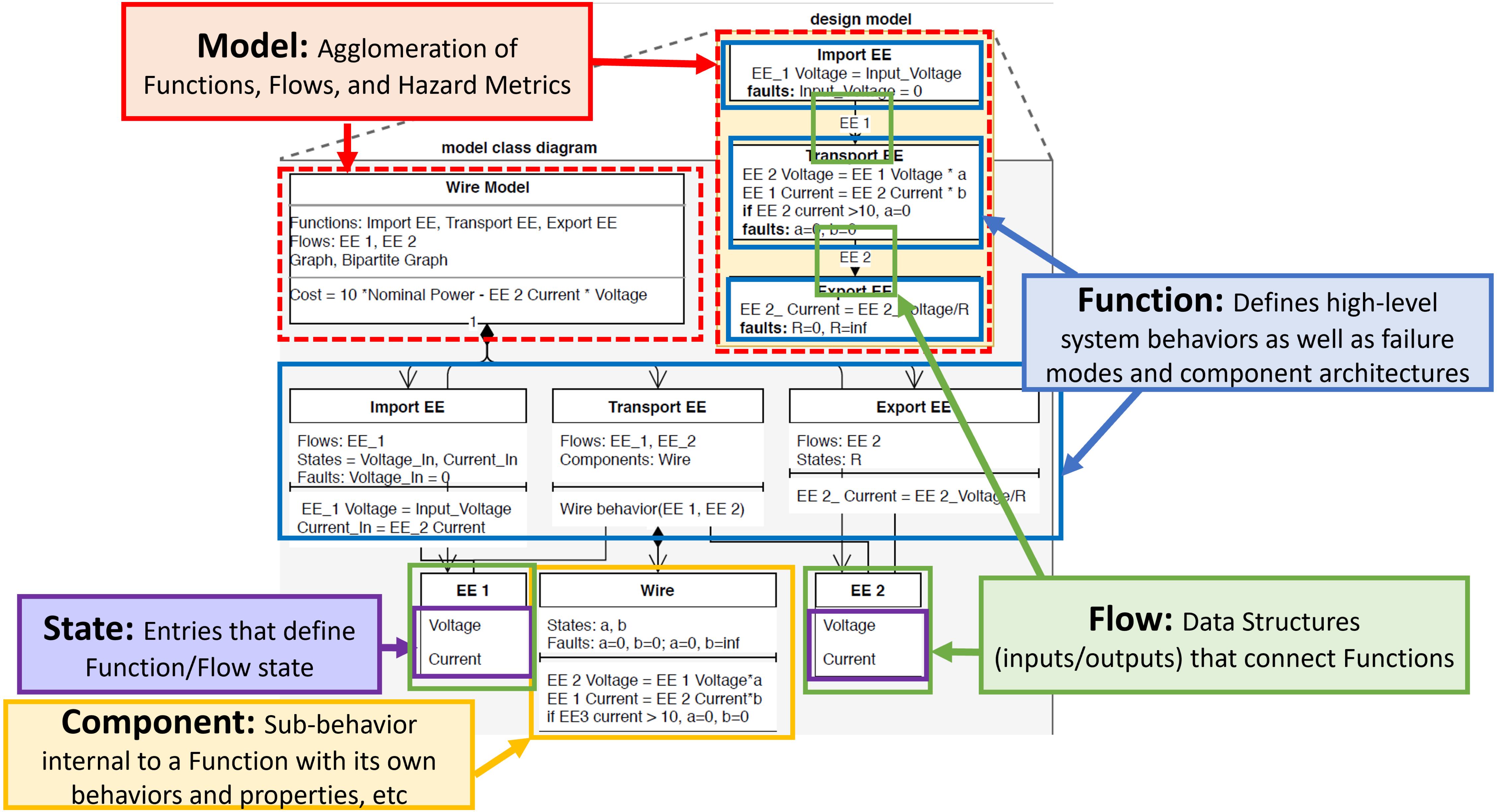
Analysis Workflow/Structure



Defining a Model

- What do we want out of a model?
  - What behaviors and how much fidelity do we need?
  - What functions/components and interactions make up the system?
    - Single function or multiple functions?
    - Is it controlled? Are there multiple agents?
- What type of simulation do we want to run?
  - Single-timestep vs multi-timestep vs network
- What scenarioss do we want to study and how?
  - Failure modes and faulty behaviors
  - Disturbances and changes in parameters
  - What are the possible effects of hazards and how bad are they?
    - By what metrics?

Defining a Model



Demo Model Activity: examples/pump/ex_pump.py

Notice the definitions and structure:

- **States**: `WaterStates`, `EEStates`, `SignalStates`
- **Flows**: `Water`, `EE`, `Signal`
- **Functions**: `ImportEE`, `ImportWater`, `ExportWater`, `MoveWater`, `ImportSignal`
  - **Flows**
  - **Modes** (e.g., `ImportEEMode`, `ImportSigMode`)
    - Mode probability model
    - Actual modes in `faultparams` entry
  - others attributes, e.g., `Timer`
- **Model**: `Pump` connects functions, flows, and defines `end_classification`
- **Parameter**: `PumpParam` defines values we can change in the simulation

More Resources for Model Definition

- Note the docs for model definition in https://nasa.github.io/fmdtools/docs/fmdtools.define.html
- Other examples also can be helpful: https://nasa.github.io/fmdtools/docs/Examples.html

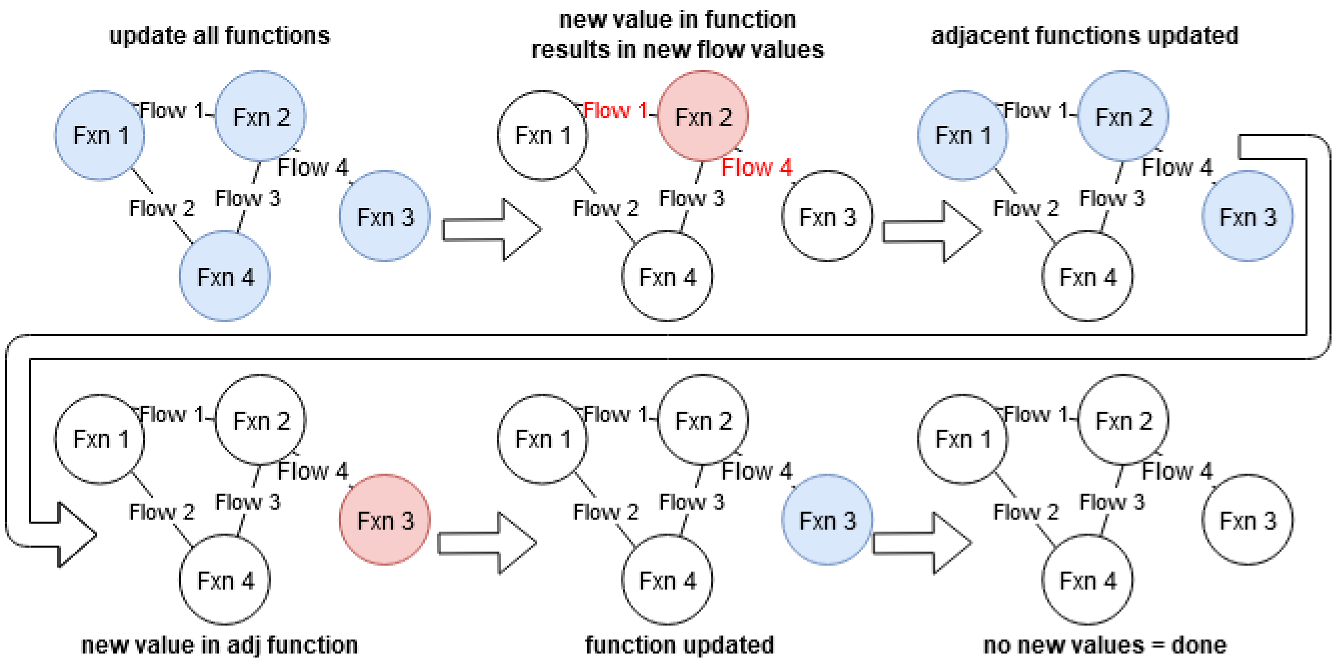
Notebook Activity:

Open `/examples/pump/Tutorial_unfilled.ipynb`:

- Instantiate the model
    - `mdl = Pump()`
- Explore structure
    - Try different parameters!
    - Change things!

      What does the model directory look like?
    - `dir(mdl)`

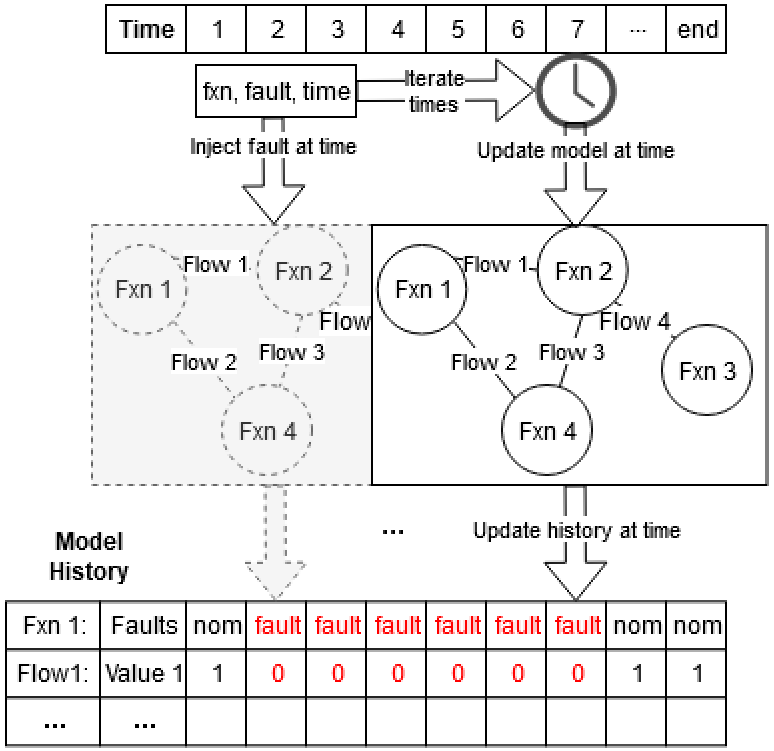
Simulation Concepts: Static/Undirected Propagation



In a single timestep:

- Functions with `static_behavior()` methods simulate until behaviors converge (i.e., no new state values)
- Functions with `dynamic_behavior()` run once in defined order

Simulation Concepts: Propagation over Time



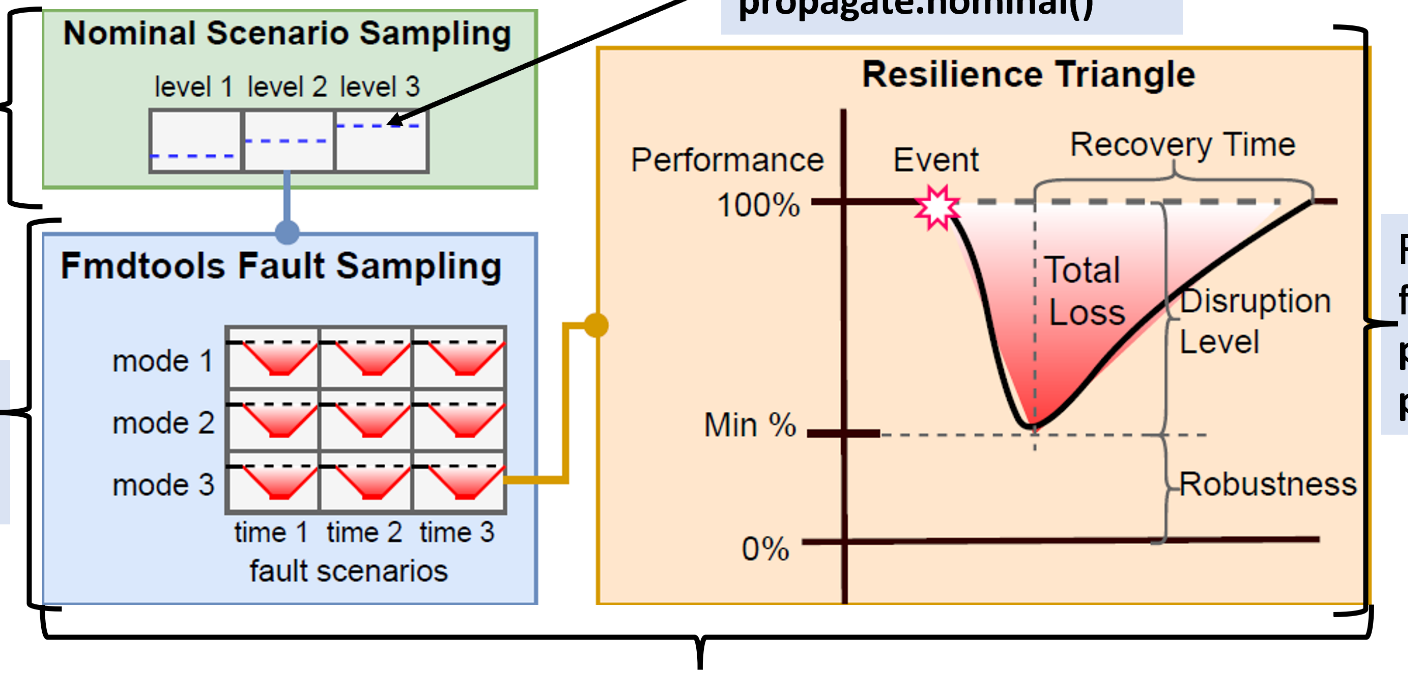
- Model increments (simulated + history updated) over each time-step until a **defined final time-step** or **specified indicator returns true**.

Simulation Concepts: Types of Simulations

Performance over a set of possible operational parameters
propagate.nominal_approach()

Resilience over a set of fault modes
propagate.approach()

Nominal performance
propagate.nominal()



Resilience to a single fault or hazard
propagate.one_fault()
propagate.sequence()

Resilience to a set of fault modes over a set of operational parameters
propagate.nested_approach()

For more info, (syntax/arguments), see documentation for `fmdtools.sim.propagate`

Simulation Concepts: Sampling Approaches

These classes define **multi-run simulations** which can be used to quantify uncertain performance/resiliences:

- **SampleApproach**: Which faults to sample and when
  - Relies on **mode** information encoded in the model
  - Simulated using `propagate.approach()`
- **NominalApproach**: Nominal parameters or random seeds to sample
  - Can be simulated in `propagate.nominal_approach()`
  - Can be simulated in conjunction with faults using `propagate.nested_approach`

See docs for: `fmdtools.sim.approach`

Simulation Concepts: Things to Consider

Static/Dynamic propagation: How function states propagate to each other in a single time-step and multiple time-steps

- Undirected graph representation—states can effect all other connected states, and vice versa, in any order

Stochastic Propagation: Whether and how stochastic states are instantiated over time

- e.g. do we run with the "default" values of parameters, or do we sample from a random number generator?

Breadth of Scenarios: How hazards are represented as discrete scenarios to simulate

- What set of joint faults do we use? How many times are sampled?
- Operational scenarios and joint operational/fault scenarios

Activity: Simulate the Model

Run fault propagation methods:

- `propagate.nominal()`
- `propagate.one_fault()`
- `propagate.approach()`

What do the results look like? Explore data structures:

- `analyze.result.Result`
- `analyze.result.History`

Explore:

- What happens when you change `SampleApproach` parameters?
- What happens when you change `Model` parameters?
- How do these methods compare in terms of computational time?

Analysis Modules

plot.py

Behavioral/Statistical Plotting
- **hists()**: Plots behavior of given states over time in a set of scenarios
- **metric_dist()/_from():** Histograms of modelled metrics
- **nominal_vals_1d/2d/3d():** Simulation metric(s) in terms of input parameters
- **nominal/nested_factor_comparison():** Comparison of simulation statistics over given factors

matplotlib

graph.py

Visualization of simulation results on the model graph
- **Graph:** Base class for graph display methods, with methods like
    - **draw():** Show graph at state
    - **draw_from():** shows graph statesat a given time-step

-**ModelGraph, ASGGraph, etc:** Subclasses that create graph structures for specific fmdtools classes

NetworkX
Network Analysis in Python

tabulate.py

Display and export of simulation results as tables
- **fmea()**: FMEA-like assessment with faults, probabilities, and costs.
- **metricovertime():** total metric, rate, and expected metrics of scenarios over time
- **nominal/nested_factor_comparison():** Table of simulation statistics over factors
- others…

pandas

result.py

Logging, processing, and save/load for simulation results
- **Result**: Class for storing results from a simulation specified in desired_result argument, e.g.:
    - endclass (from find_classification)
    - graph (graph view)
    - model values (user-defined)
- **History**: Class for storing simulation histories specified using track argument

See docs for: `fmdtools.analyze`

Analysis Activity

Visualize the results:

- Show model graph
- Show nominal performances
- Show performances in a nominal scenario
- Make a scenario-based fmea

Explore:

- How can you show only the parameters you want? Or change the formatting?
- What does the behavior under other faults look like?
- What other analyses can you perform with these results?

Conclusions/Summary

- **fmdtools** is an environment for designing resilient systems
  - `/define` enables model definition
  - `/sim` is used to define simulations
  - `/analyze` is used to analyze and visualize simulation results
- I hope you agree that it has some powerful features!
  - Modelling expressiveness and clarity
  - Types of simulations that can be run
  - Powerful but easy-to-leverage plug-and-play analyses

Further Reading/Links

- More advanced topics (see examples):
  - Search and optimization
  - Human/AI Modelling
  - Systems-of-Systems modeling
  - Modelling Stochastic Behavior
  - ... and more
- Model Development Guide: Has best practices for developing models in a strategic way (especially helpful for compelx models)
- Overview Paper:
  - Hulse, D., Walsh, H., Dong, A., Hoyle, C., Tumer, I., Kulkarni, C., & Goebel, K. (2021). fmdtools: A fault propagation toolkit for resilience assessment in early design. International Journal of Prognostics and Health Management, 12(3).