PathSim

An Open-Source Python Framework for Digital Twin Applications in Fusion Fuel-Cycle Modeling

IAEA Workshop on Digital Engineering for Fusion Energy Research

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Why am I here?

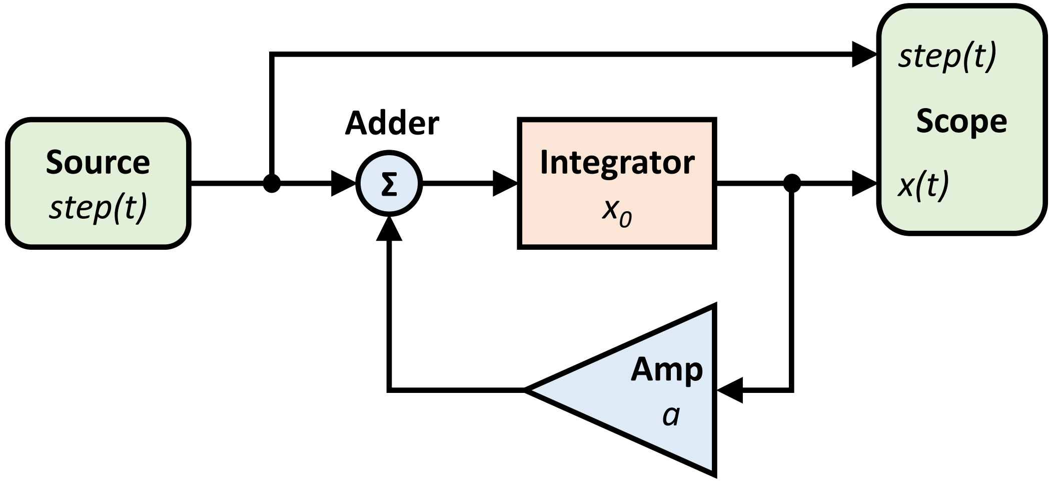
What is *PathSim*?

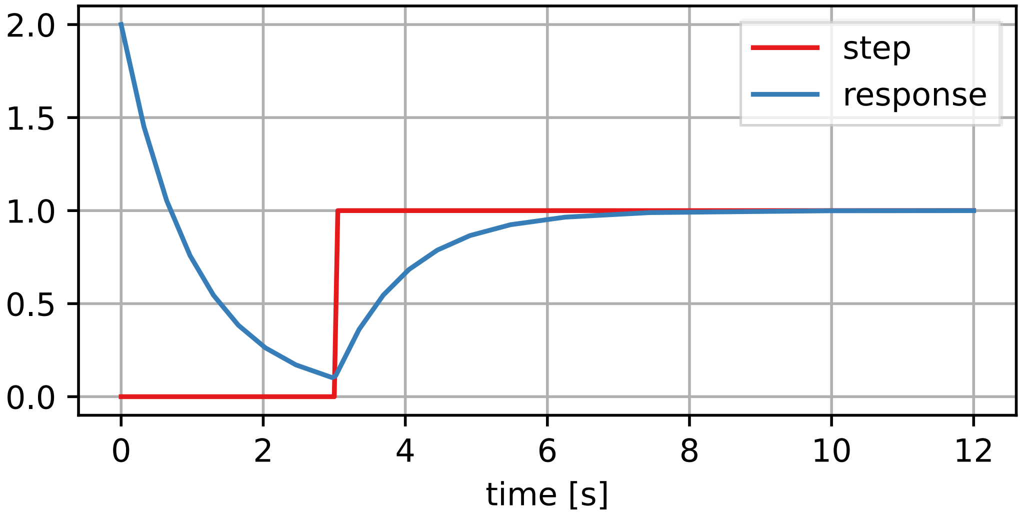
Where does it fit in?

How does it work?

Whats coming?

PathSim – Dynamical System Simulation in *Python*

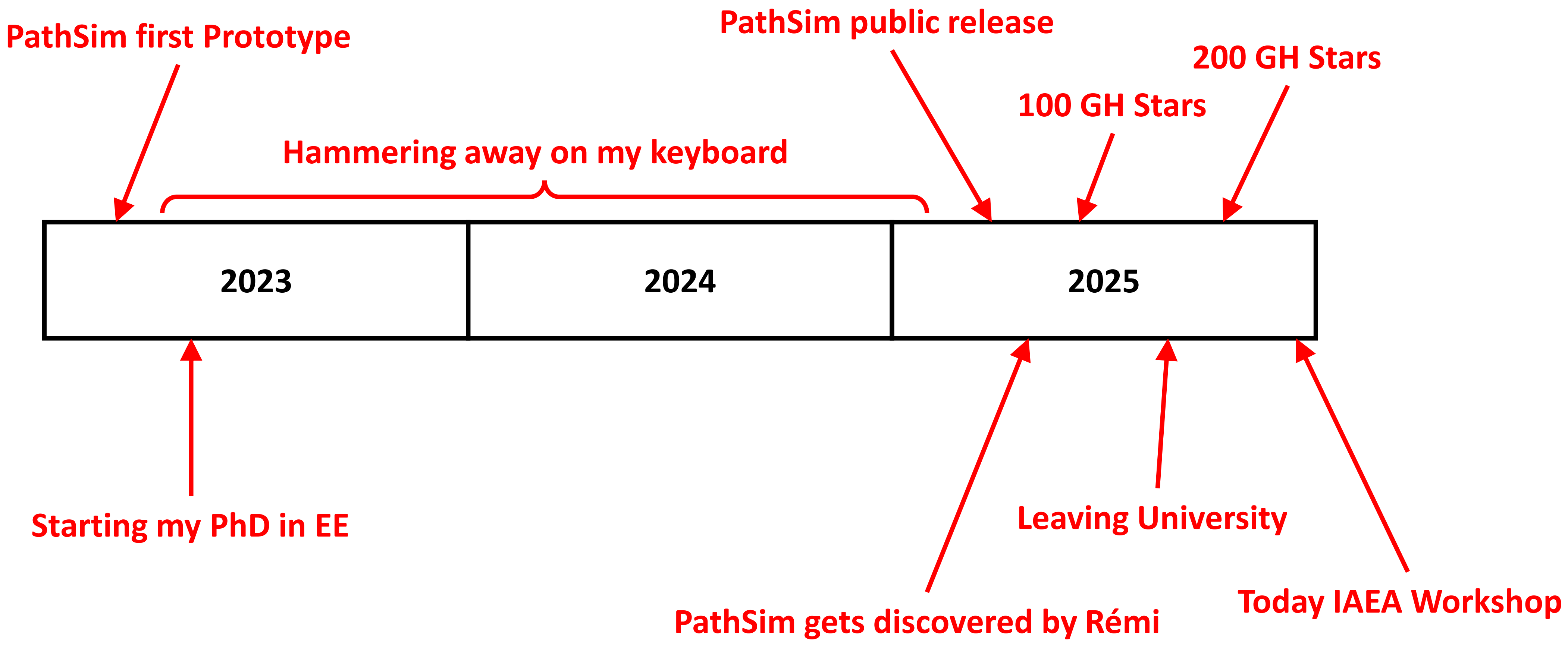




```
from pathsim import Simulation, Connection
from pathsim.blocks import (
    Source, Integrator,
    Amplifier, Adder, Scope
    )

#system parameters
a, x0, tau = -1, 2, 3

#step function
def step(t):
    return float(t>tau)

#blocks defining the system
src = Source(step)
itg = Integrator(x0)
amp = Amplifier(a)
add = Adder()
sco = Scope(labels=["step", "response"])

#add connections and initialize simulation
sim = Simulation(
    blocks=[src, itg, amp, add, sco],
    connections=[
        Connection(src, add[0], sco[0]),
        Connection(amp, add[1]),
        Connection(add, itg),
        Connection(itg, amp, sco[1])
    ], dt=0.01)

#run simulation for some time
sim.run(4*tau)

#plot the results
sco.plot()
```

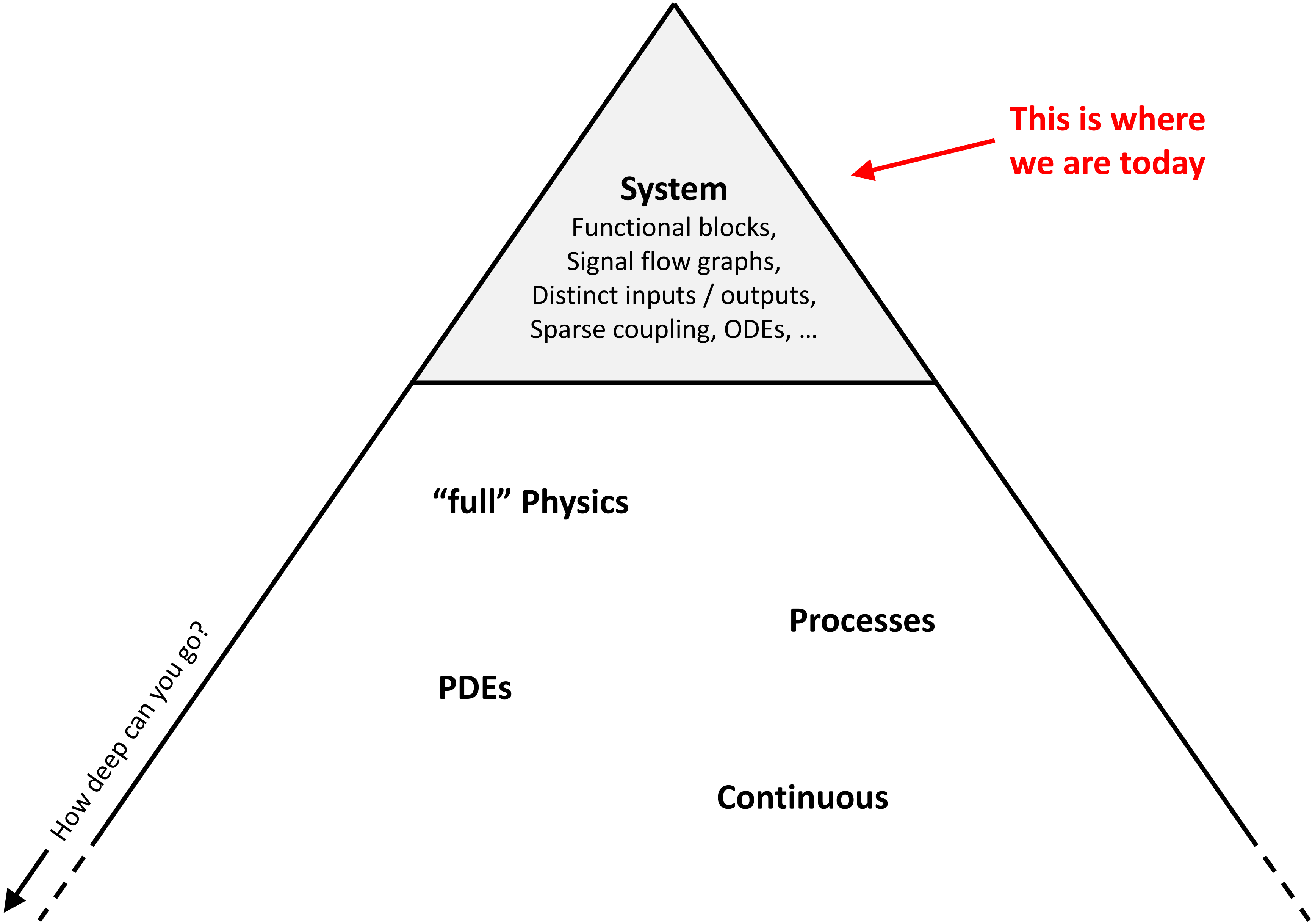
What am I doing here?

A Timeline


PathSim first Prototype
Hammering away on my keyboard
PathSim public release
100 GH Stars
200 GH Stars
2023
2024
2025
Starting my PhD in EE
PathSim gets discovered by Rémi
Leaving University
Today IAEA Workshop

System Level
vs.
Component Level

Abstraction Layers in Engineering



System

Functional blocks,
Signal flow graphs,
Distinct inputs / outputs,
Sparse coupling, ODEs, …

This is where we are today

“full” Physics

Processes

PDEs

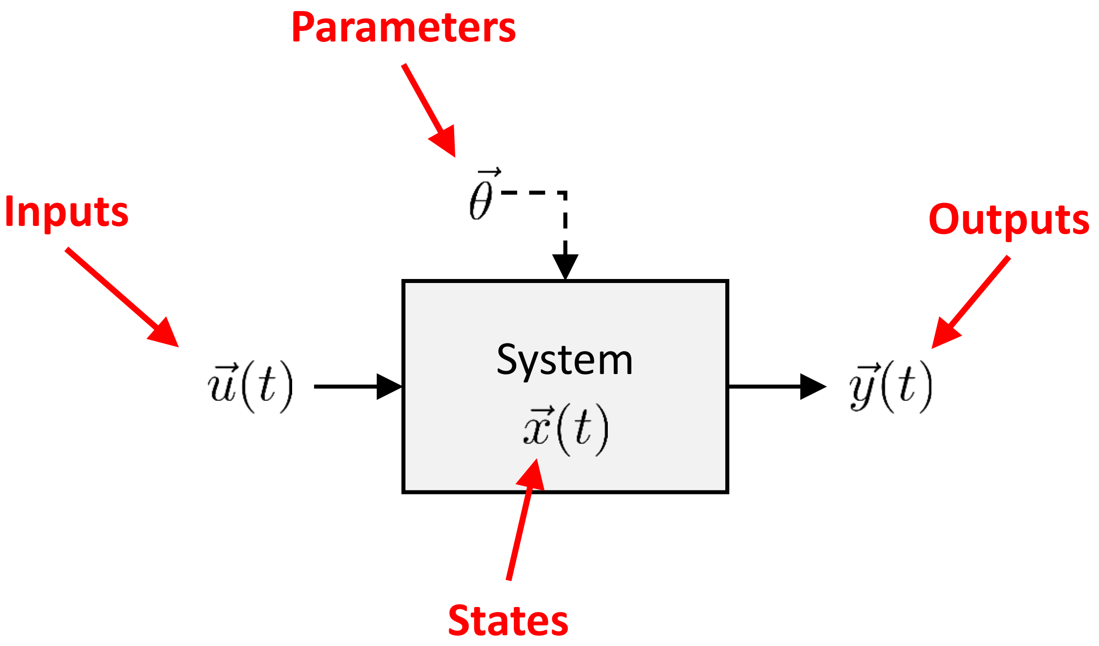
Continuous

How deep can you go?

Naming Conventions that I repeatedly stumbled over

Name	Physics View	Systems View
System Modeling	• coupled PDEs on a shared mesh	• high level interconnected components • block diagrams, signal flow, ODEs/DAEs • hierarchical means subsystems
Component	• a physical domain (thermal, neutronics...)	• An abstract functional unit with I/O
Coupling	• field data exchange between solvers	• connecting outputs to inputs
Digital Twin	• High-fidelity simulation of a device • detailed model validated against experiments • Runs in hours/days on HPC	• Connected to live data, continuously updated • Used for prediction, monitoring, control • Runs fast enough for “real-time” use
Multi Physics	• Coupled PDE fields on shared geometry • Thermal field + neutron flux + stress tensor + ... • What's the spatial distribution?	• Multi-domain behavioral modeling • Heat flows, mass flows, signals between boxes • What's the aggregate behavior?

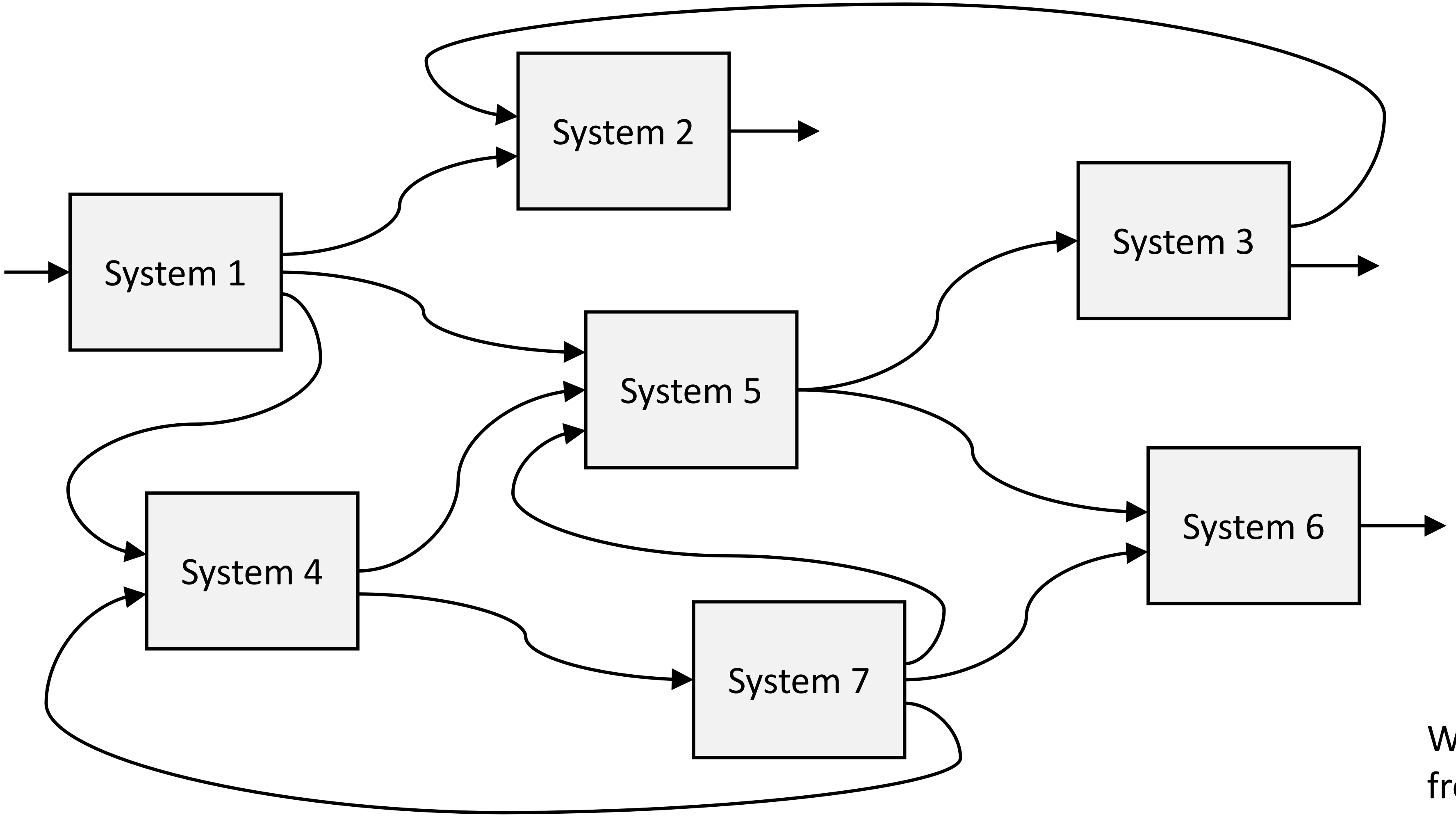
In the Signal-flow Paradigm



Inputs, outputs and internal states. Internal algebraic couplings, conditions (branching) and differential equations.

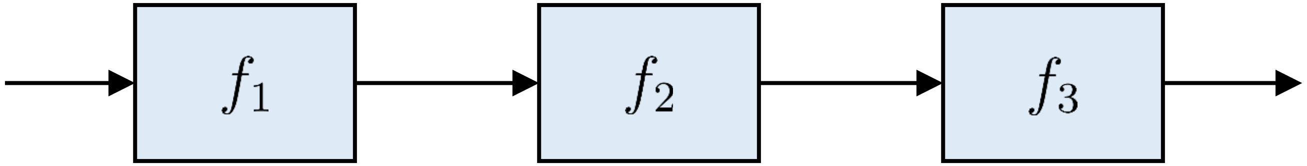
Goal: Prediction of the system behavior (outputs *y(t)* and states *x(t)*) across time, for given initial conditions x_0 and system inputs *u(t)*.

In the Signal-flow Paradigm – Complexity through Connections



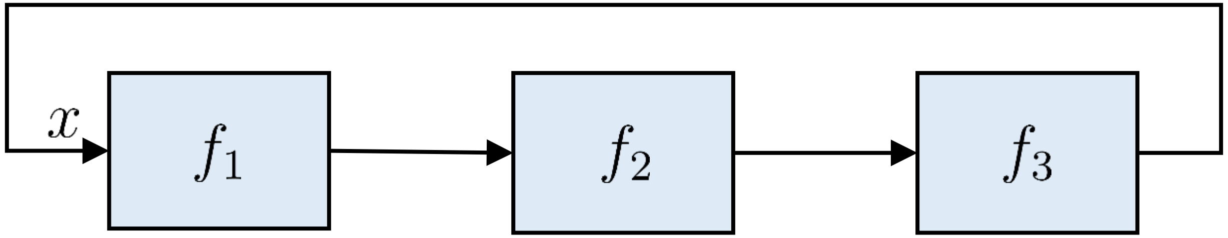
Weird things can happen from interconnected Systems…

In the Signal-flow Paradigm – Feedback Loops



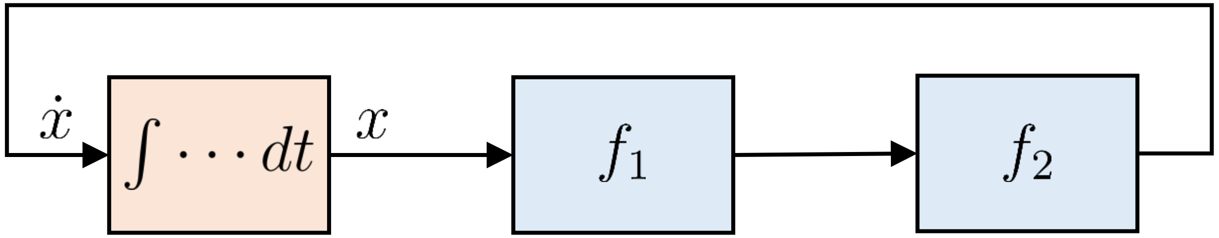
Algebraic Chains …

$$\ldots = f_3(f_2(f_1(\ldots)))$$



… with feedback are algebraic loops (fixed point problems) …

$$x = f_3(f_2(f_1(x)))$$

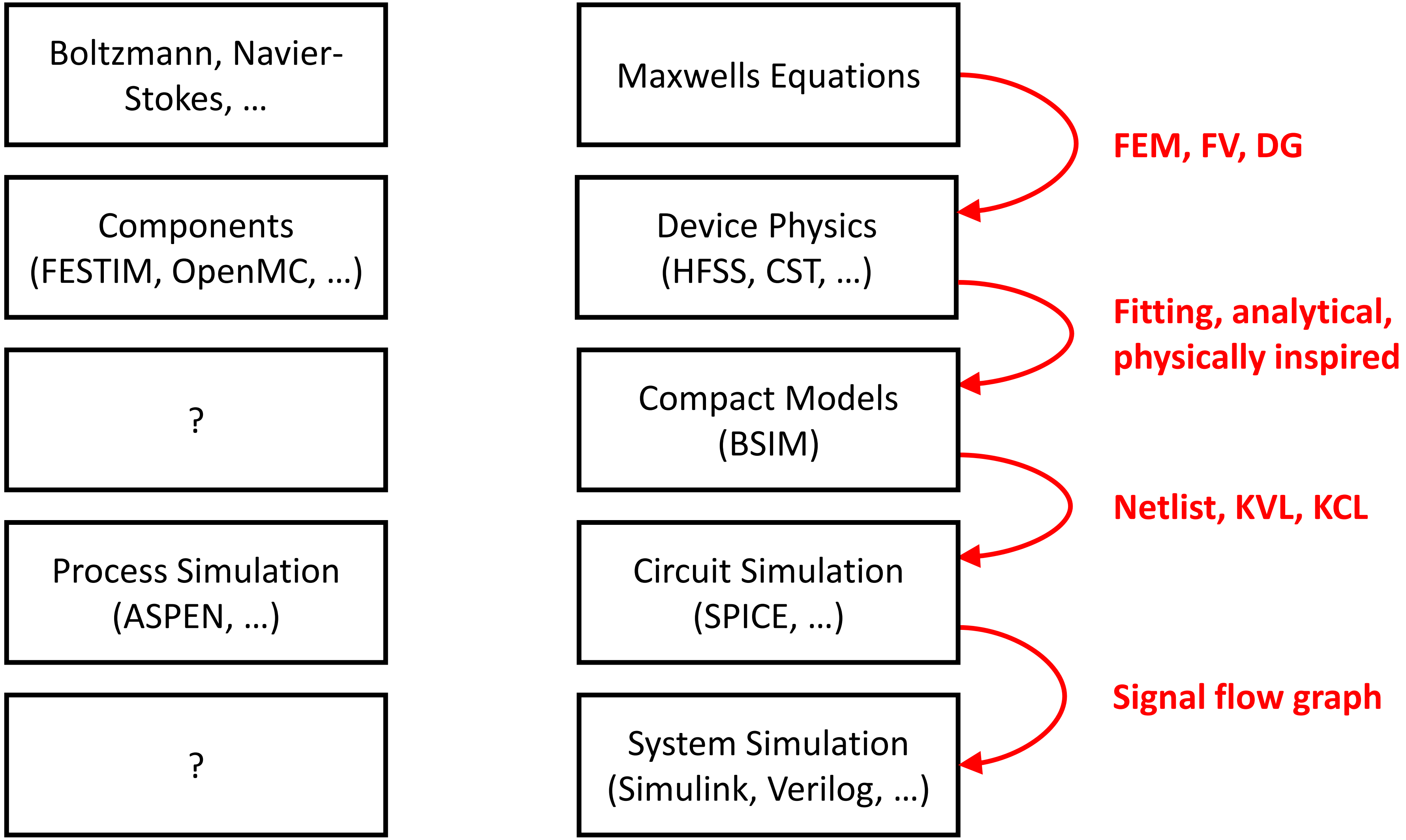


… broken by dynamic blocks are ODEs.

$$\dot{x} = f_2(f_1(x))$$

Where does *PathSim* fit in?

Abstractions in Modeling for Fusion (perceived by me (as an outsider)) and in EE



Boltzmann, Navier-Stokes, …

Components (FESTIM, OpenMC, …)

?

Process Simulation (ASPEN, …)

?

Maxwells Equations

Device Physics (HFSS, CST, …)

Compact Models (BSIM)

Circuit Simulation (SPICE, …)

System Simulation (Simulink, Verilog, …)

FEM, FV, DG

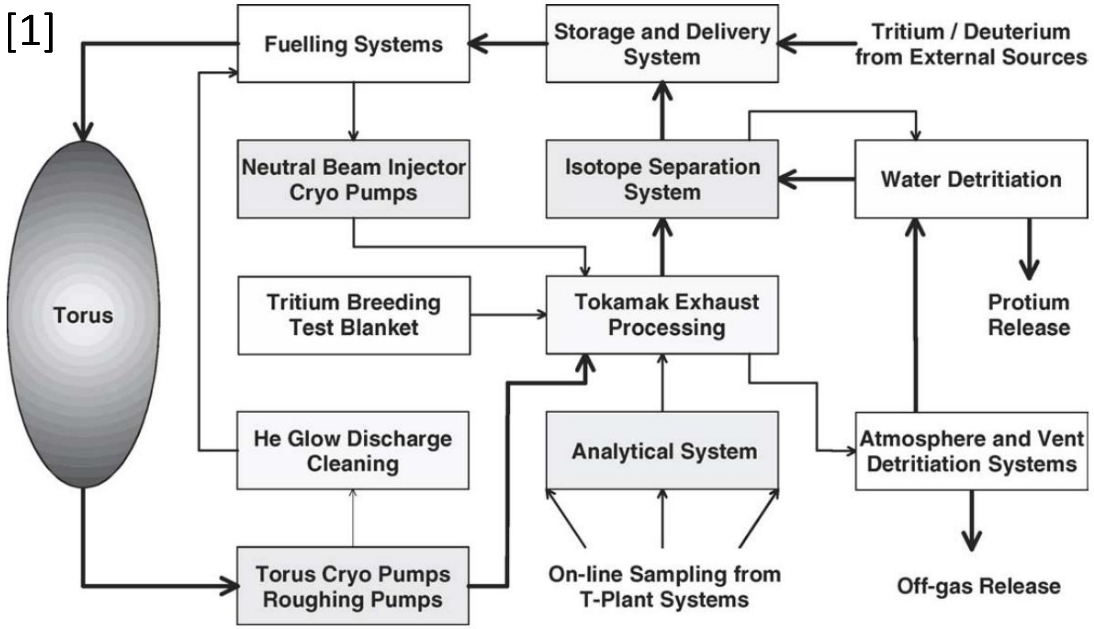
Fitting, analytical, physically inspired

Netlist, KVL, KCL

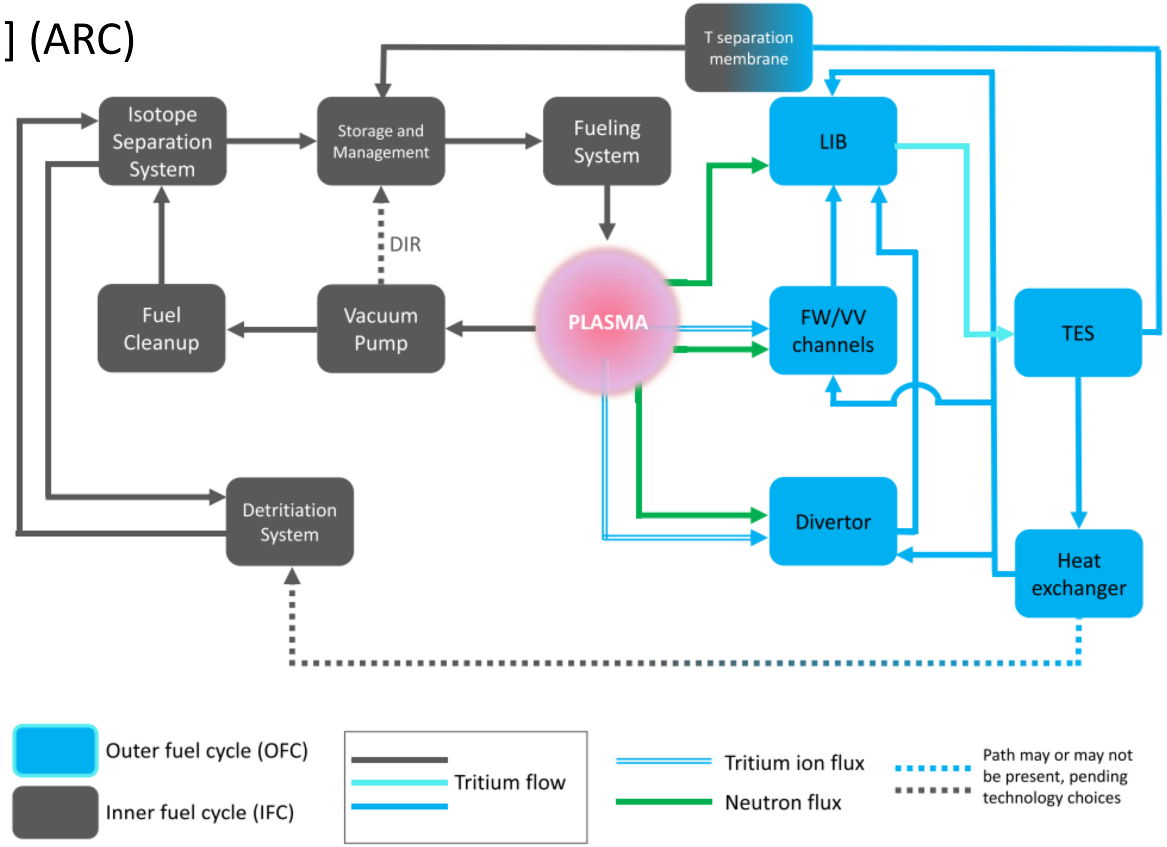
Signal flow graph

Where is the System Level in Fusion?

[1]


Fuelling Systems
Storage and Delivery System
Tritium / Deuterium from External Sources
Torus
Neutral Beam Injector Cryo Pumps
Isotope Separation System
Water Detritiation
Tritium Breeding Test Blanket
Tokamak Exhaust Processing
Protium Release
He Glow Discharge Cleaning
Analytical System
Atmosphere and Vent Detritiation Systems
Torus Cryo Pumps Roughing Pumps
On-line Sampling from T-Plant Systems
Off-gas Release

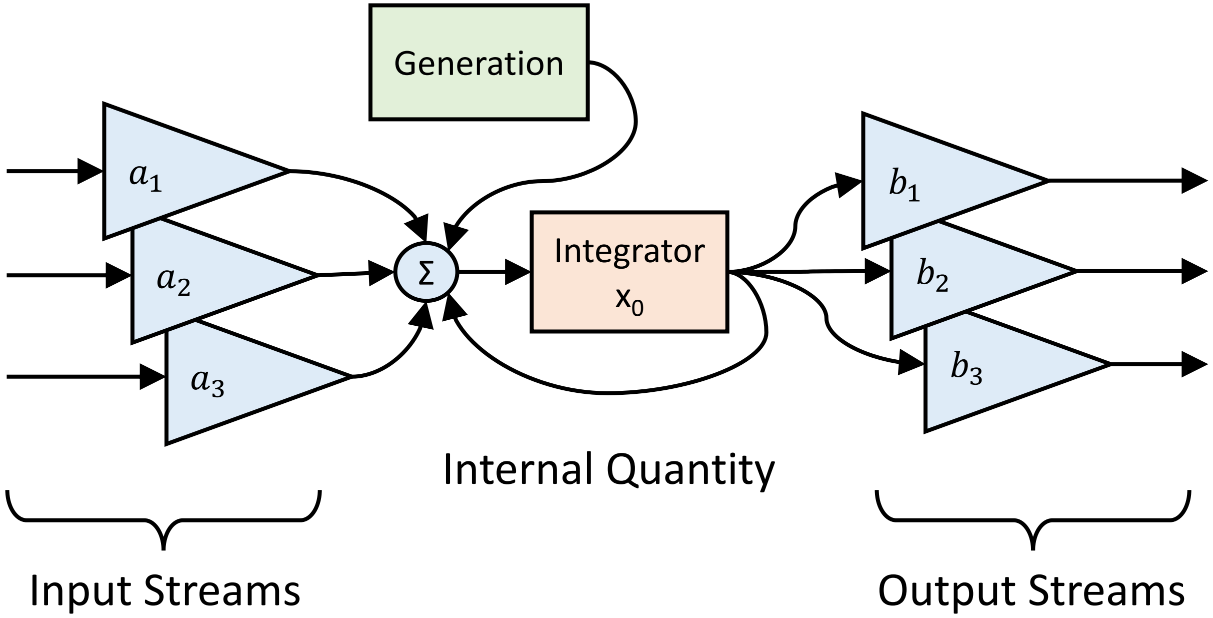
[2] (ARC)

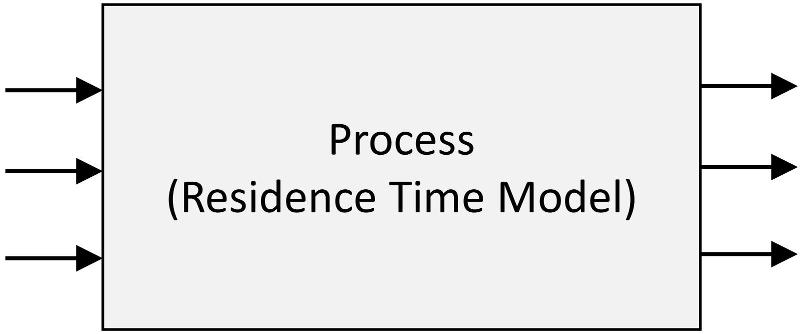


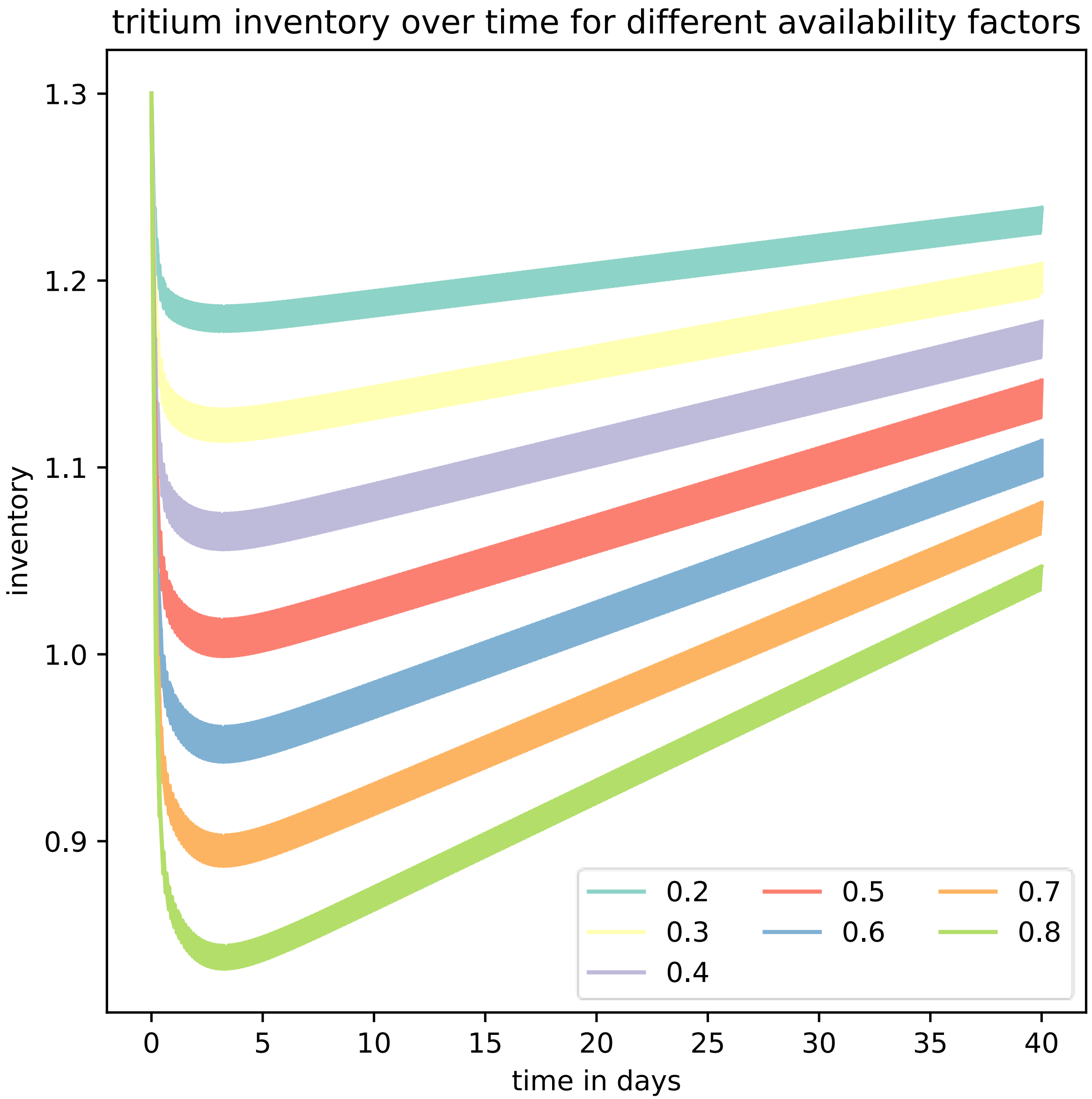
[1] ITER fuel cycle R&D: Consequences for the design

[2] Modeling and analysis of the tritium fuel cycle for ARC- and STEP-class D-T fusion power plants

What "we" already have (ARC fuel cycle with Residence Time Model)

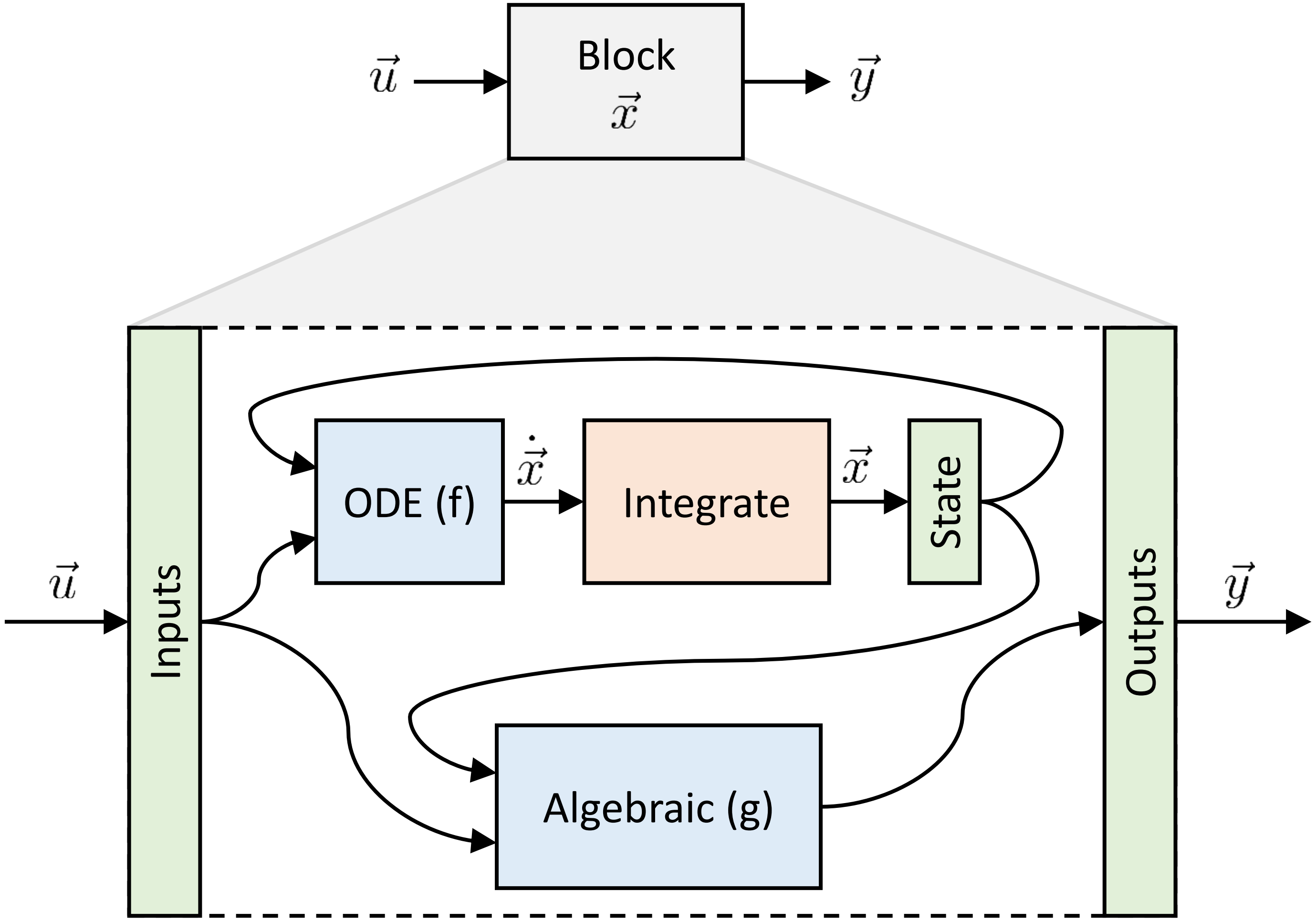






How does it Work?

Architecture – Blocks

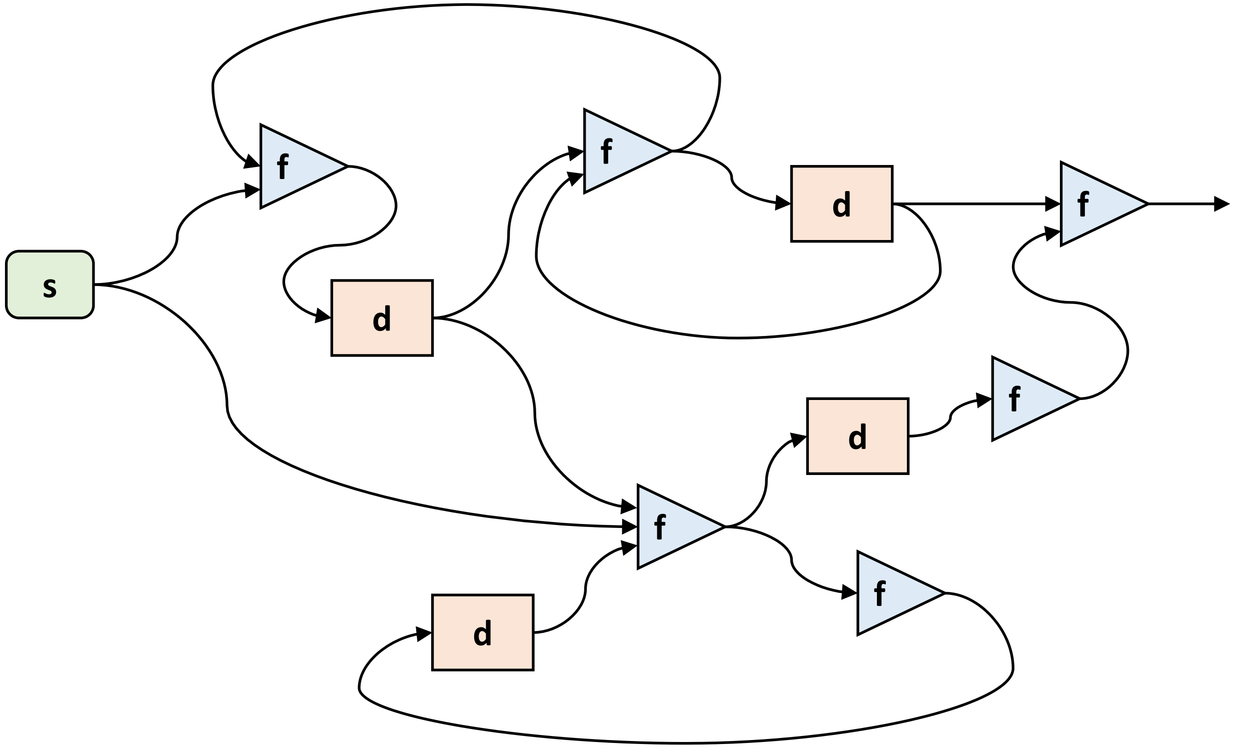


In *PathSim*, Blocks are systems with their own internal dynamics (which can be very complex)

$$\dot{\vec{x}} = f\left(\vec{x}, \vec{u}\right)$$

$$\vec{y} = g\left(\vec{x}, \vec{u}\right)$$

Architecture – Global System Funktion

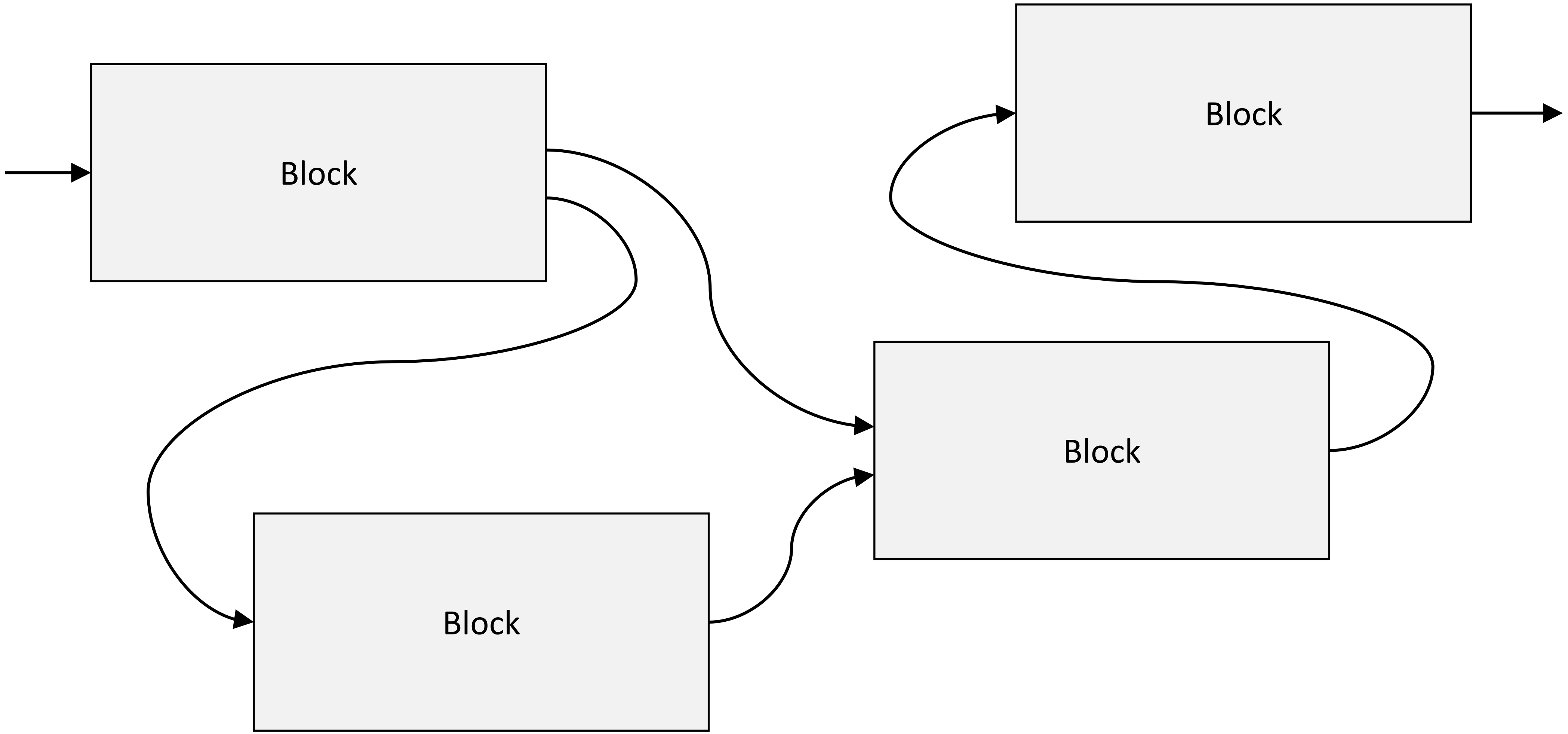


System topology is arbitrarily complex.

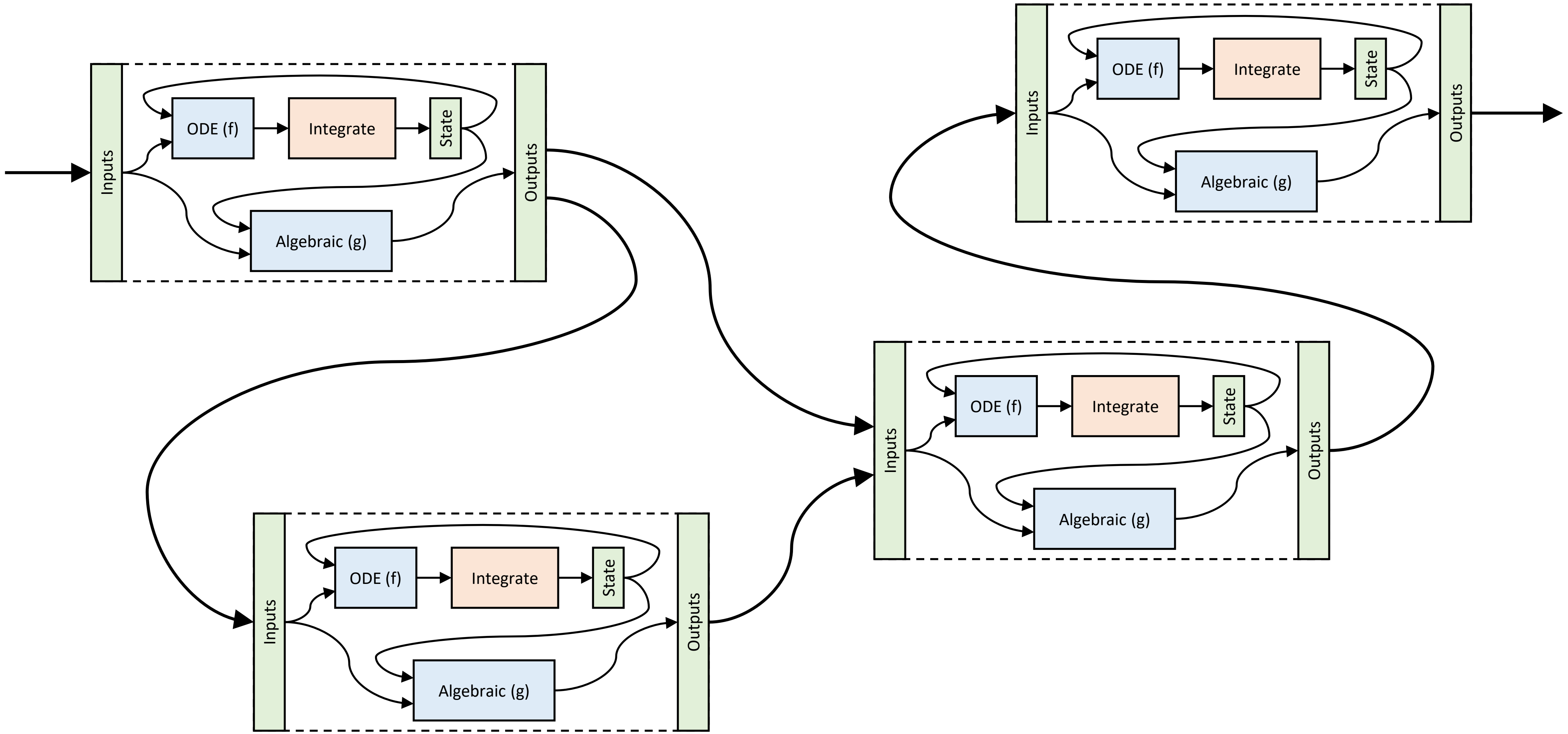
How is it constructed from all those blocks and connections?

$$F\left(\dot{\vec{x}}(t), \vec{x}(t), t\right) = 0$$

System Function Evaluation – Directed Graph



System Function Evaluation – Directed Graph



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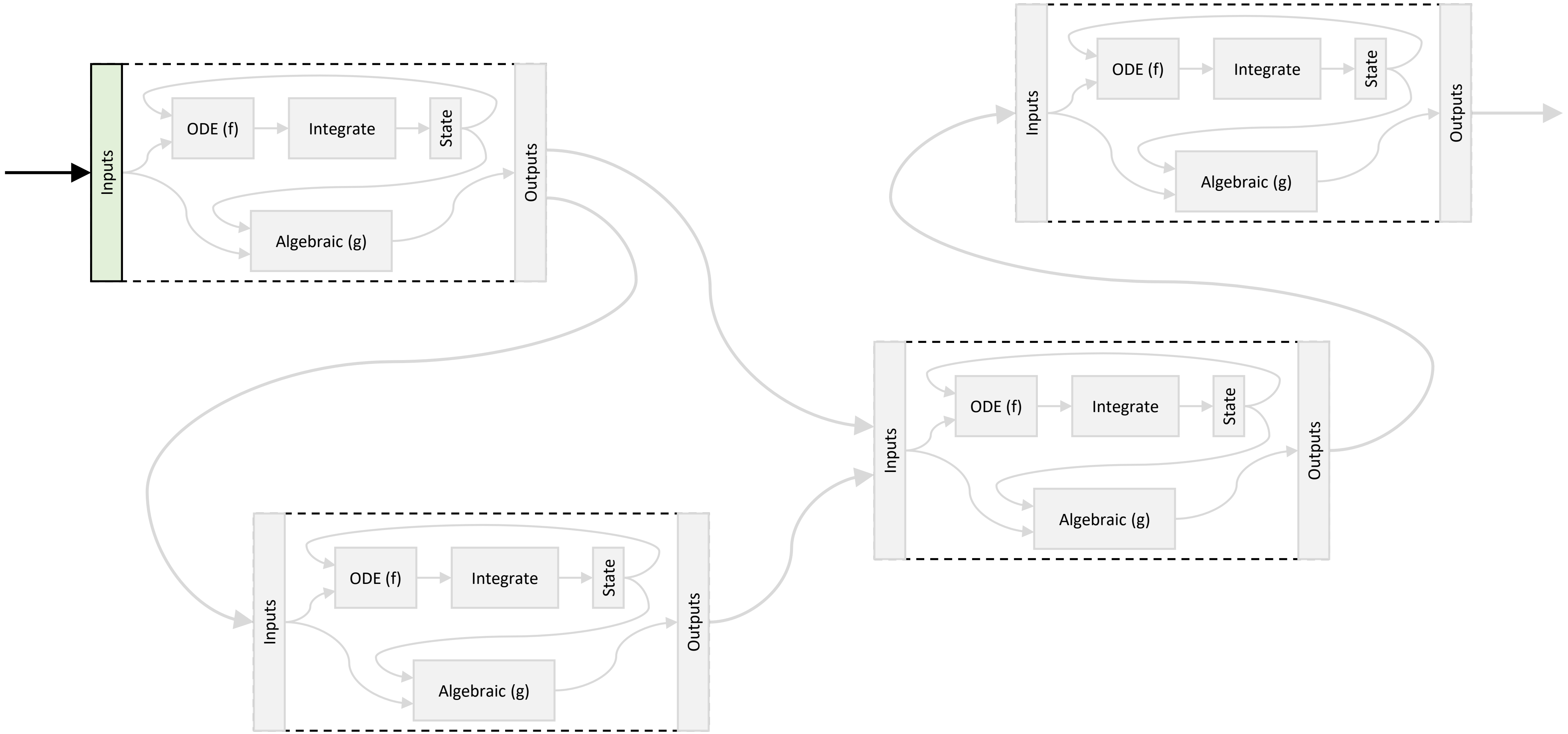

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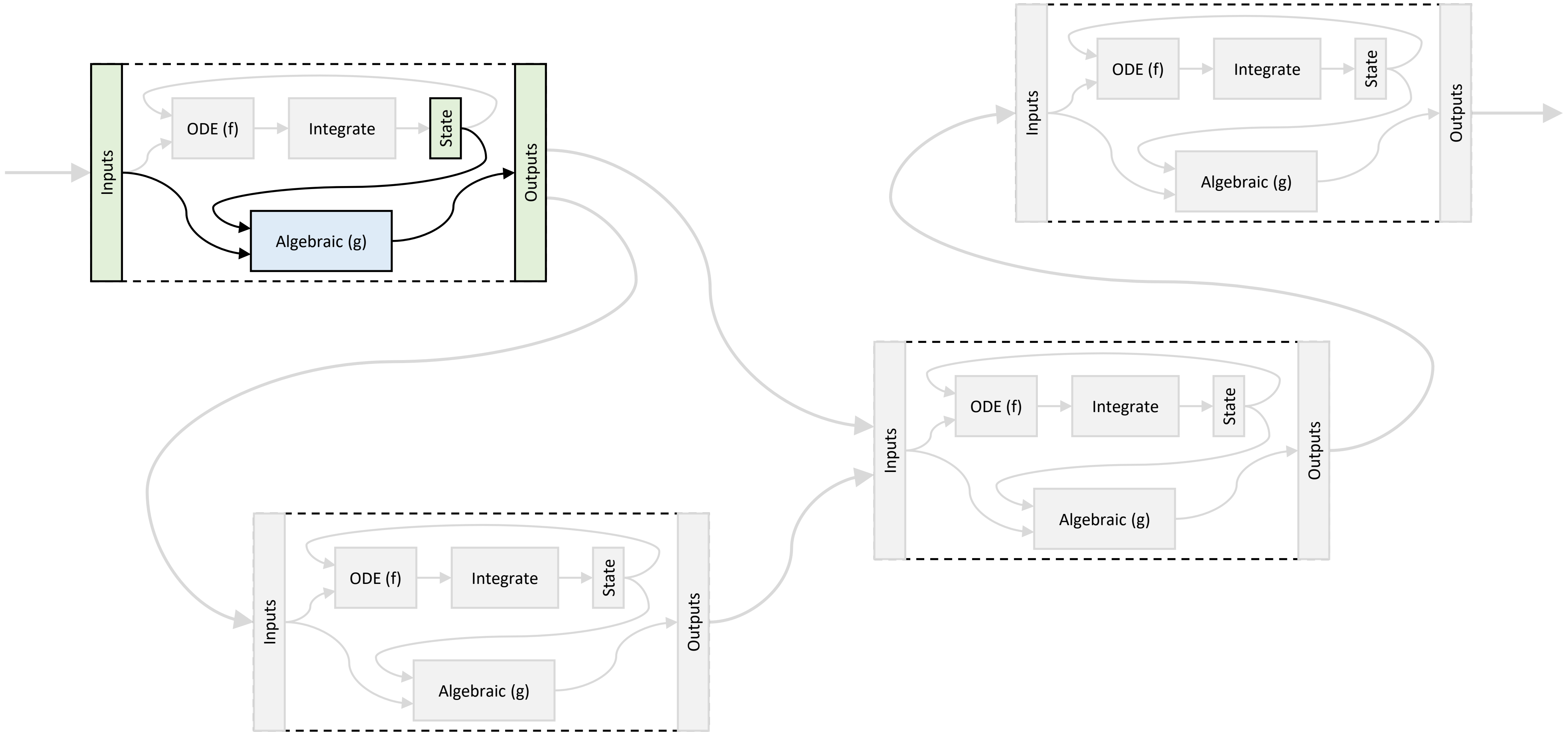

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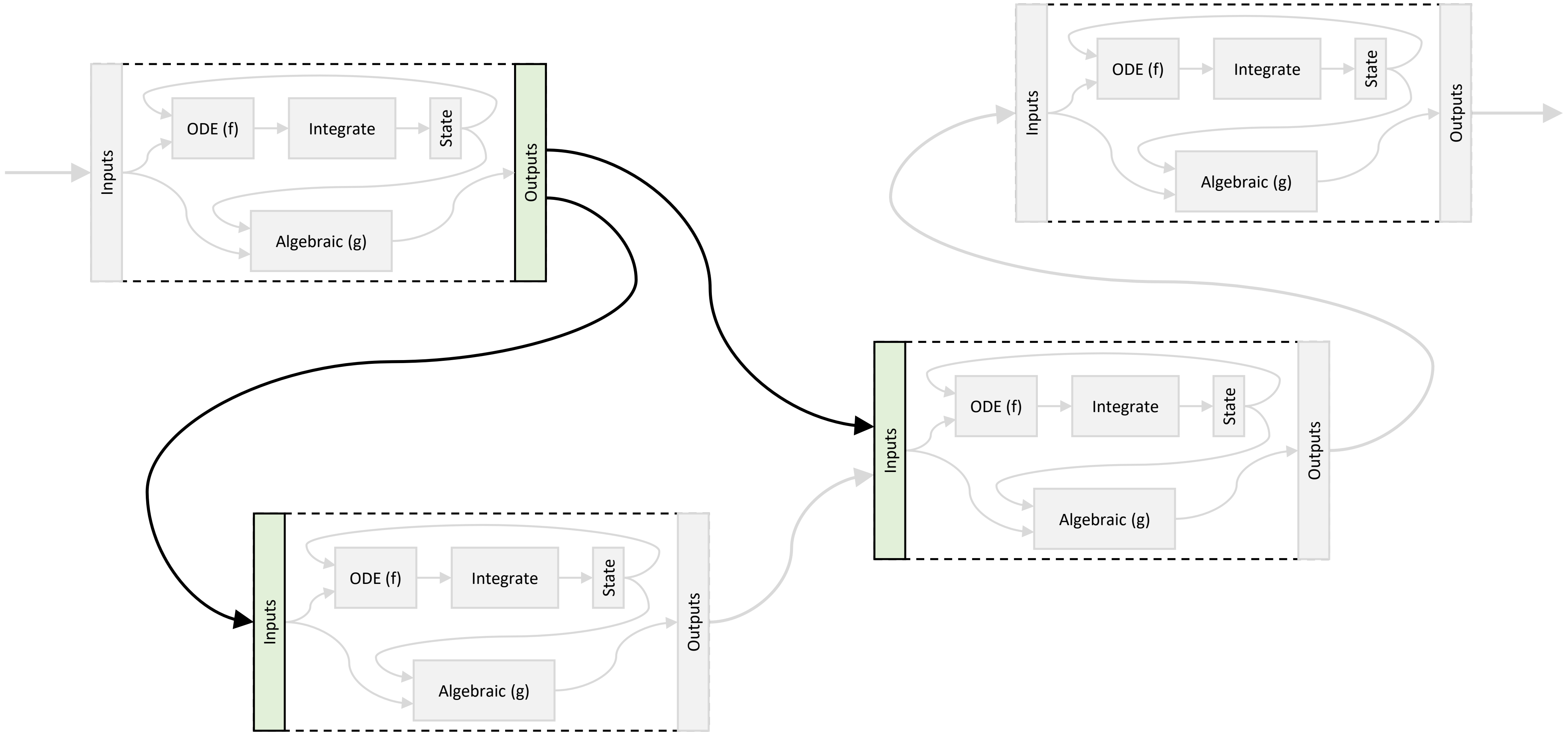
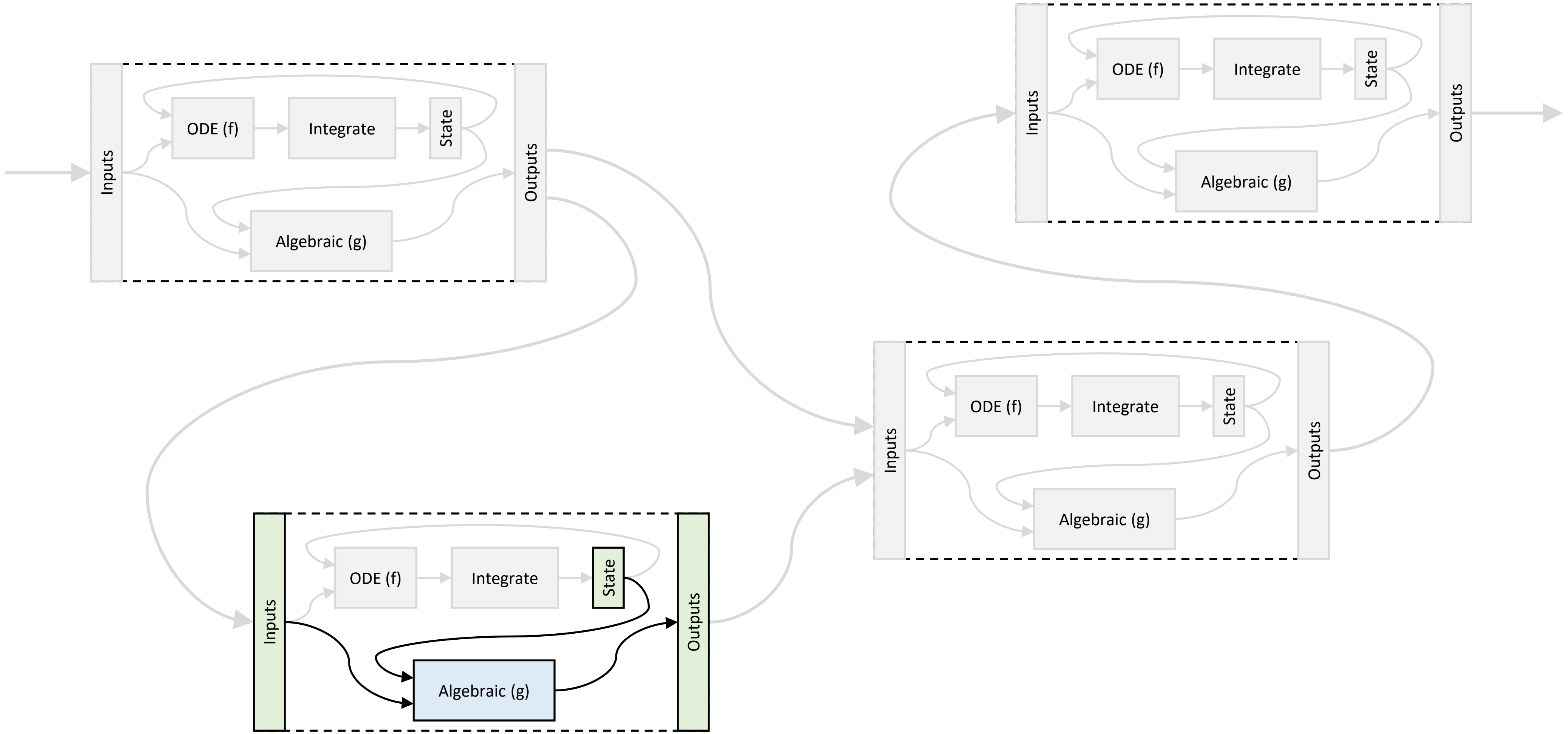


System Function Evaluation – Directed Graph



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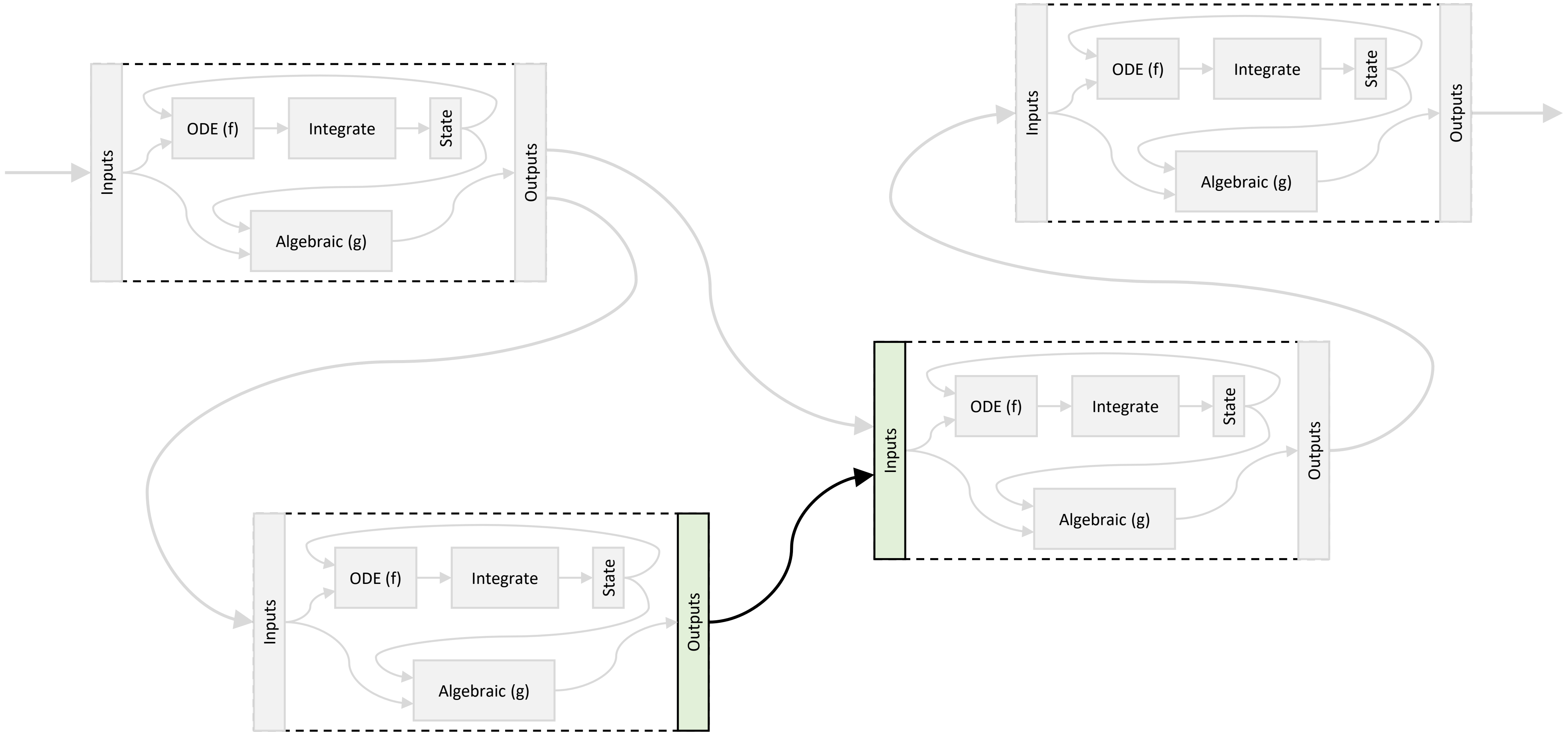

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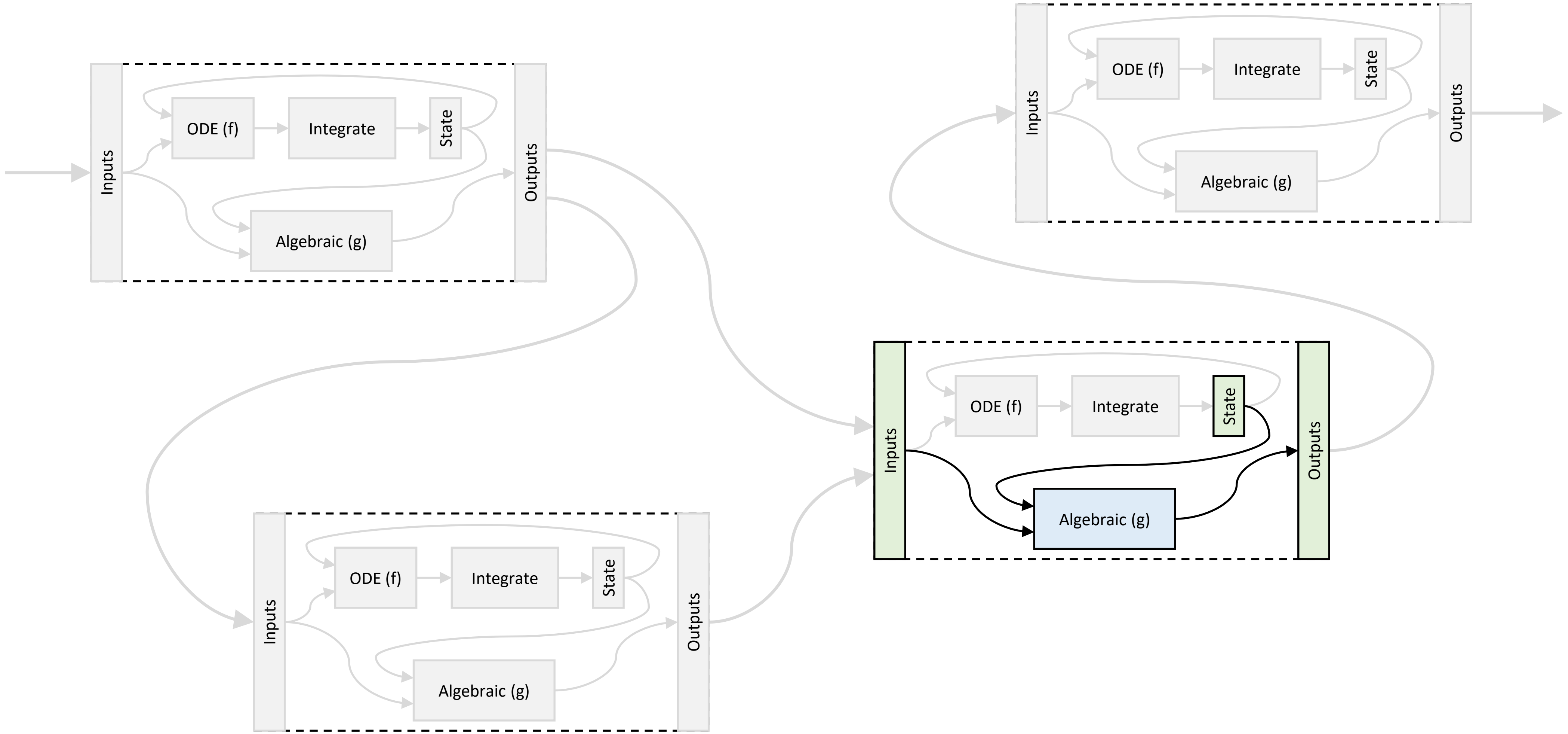

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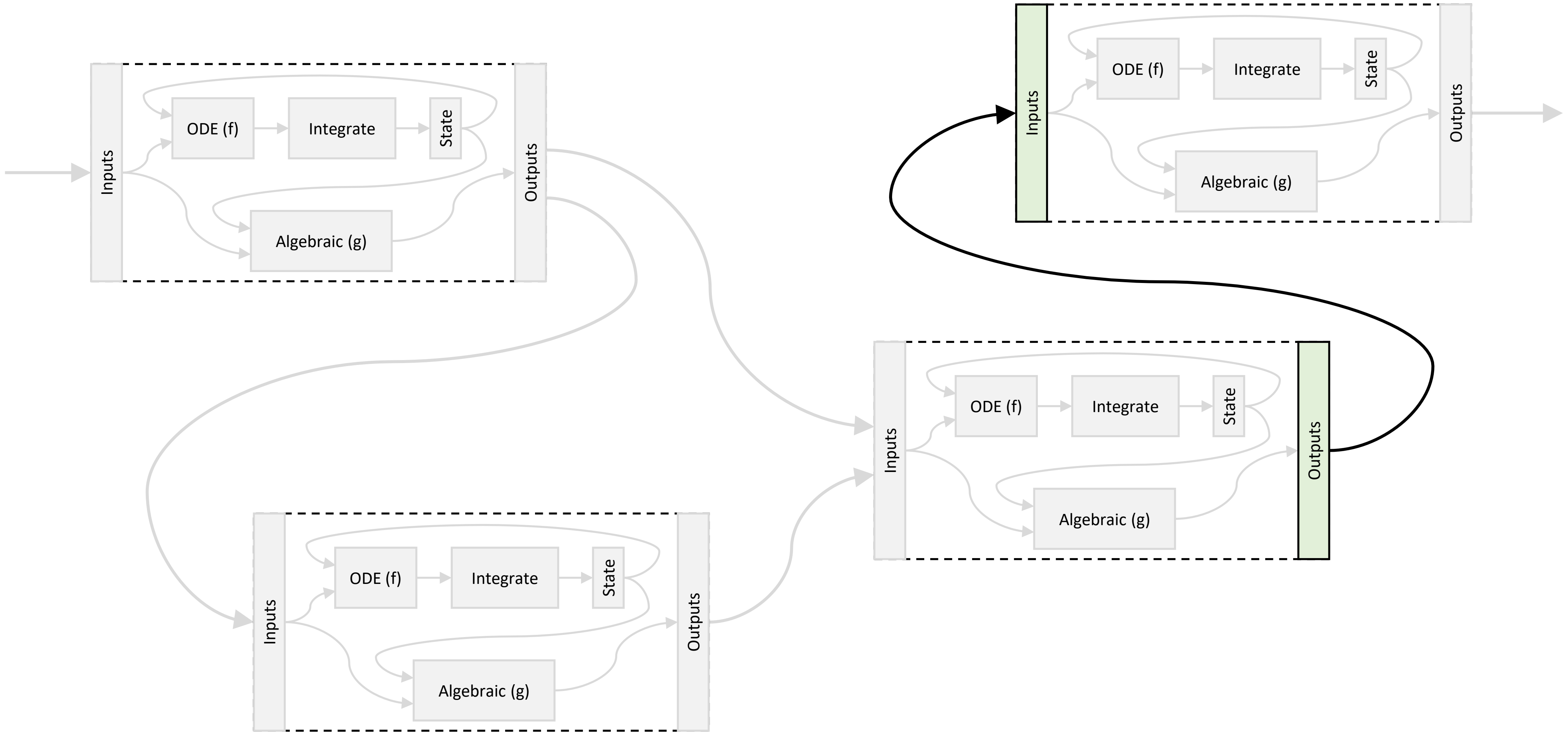
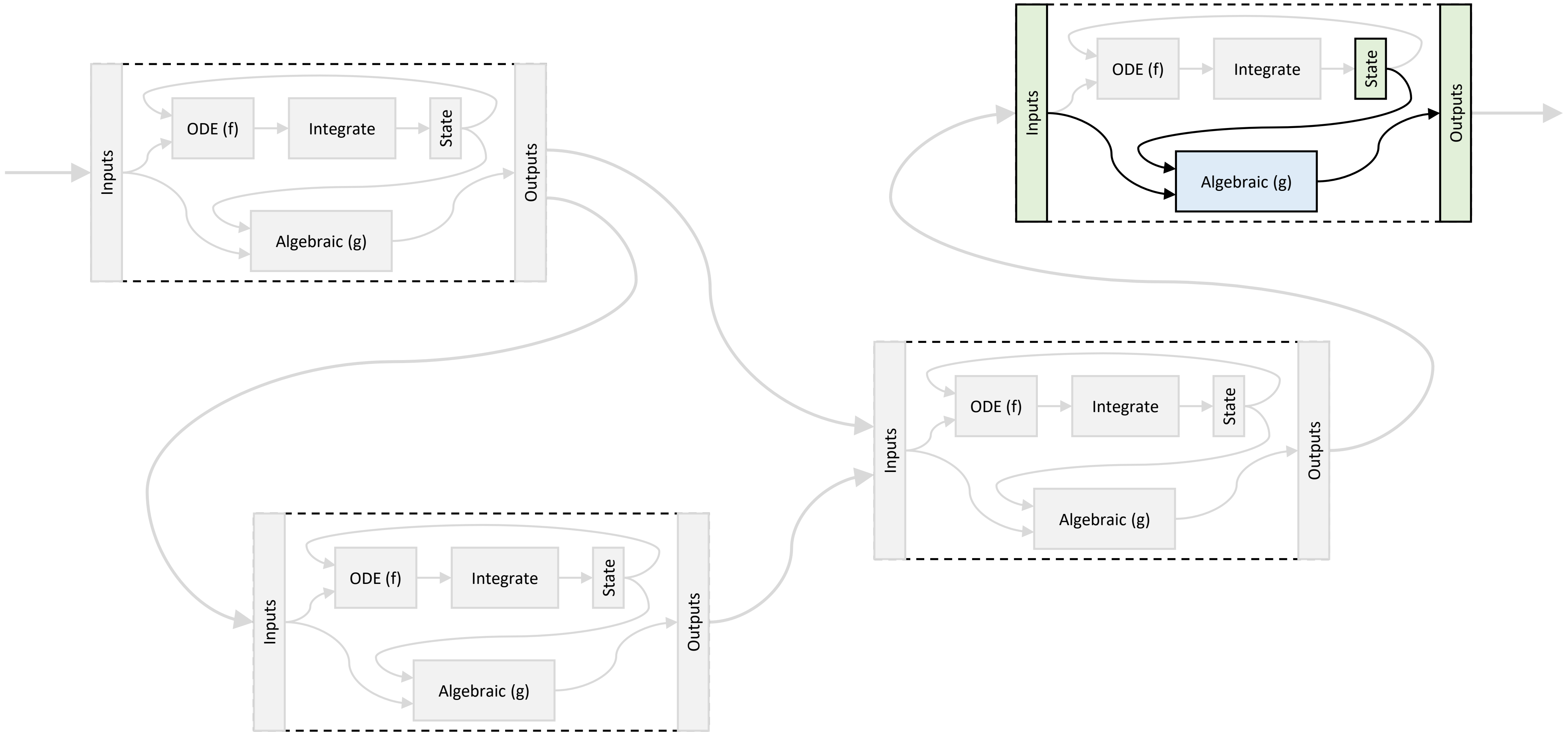
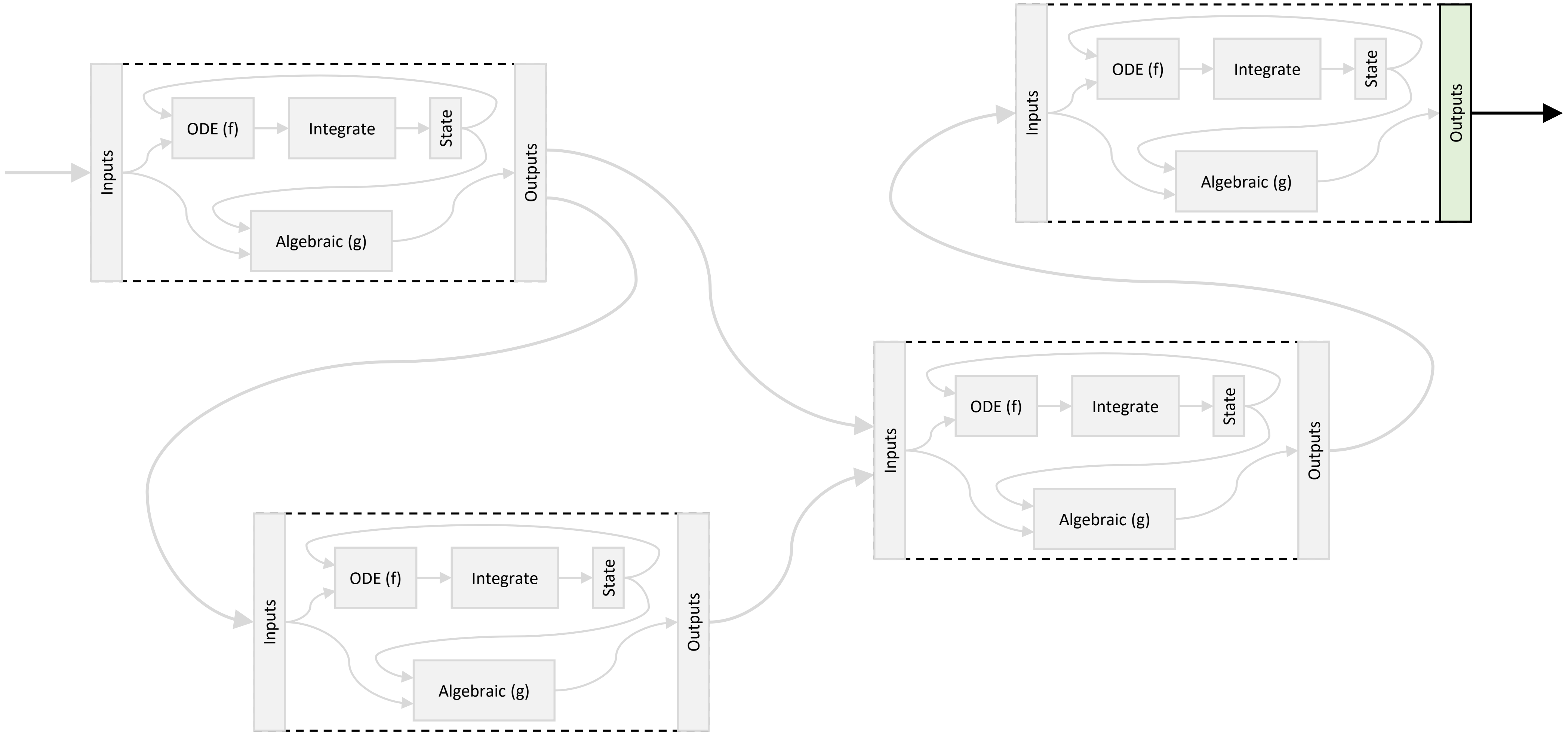


System Function Evaluation – Directed Graph



System Function Evaluation – Directed Graph



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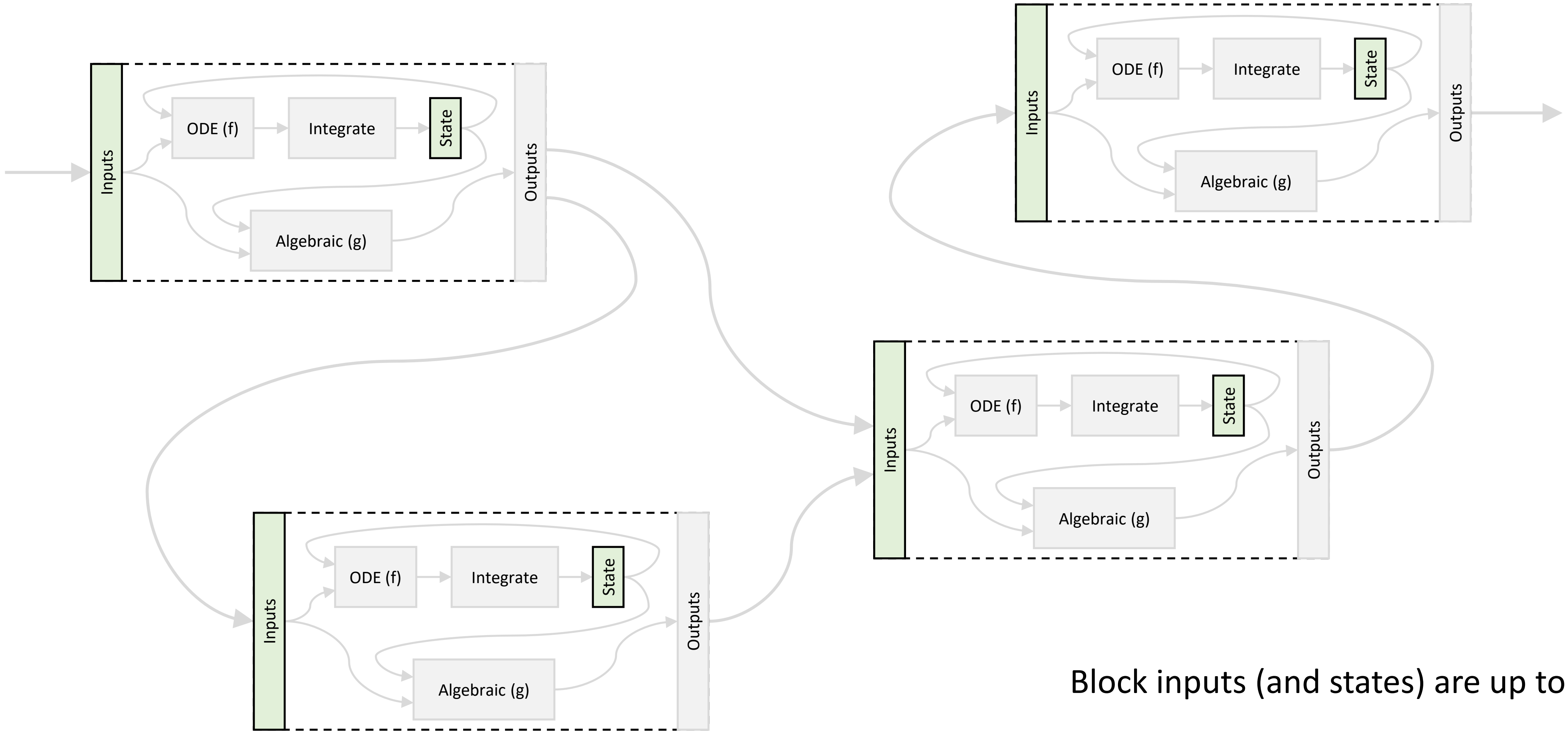
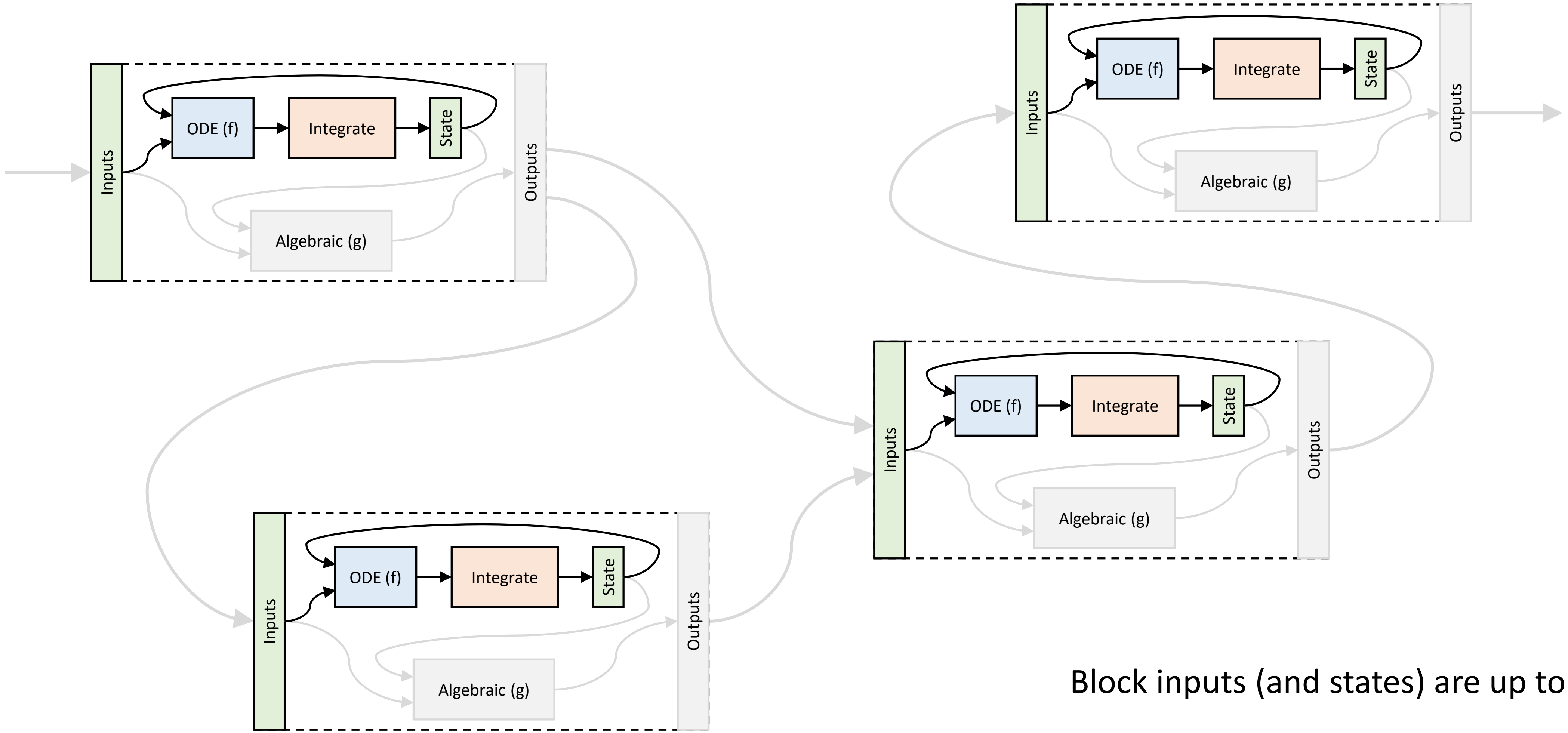


Block inputs (and states) are up to date …

System Function Evaluation – Integration Timestep



Block inputs (and states) are up to date …

… so the integrators can do their update

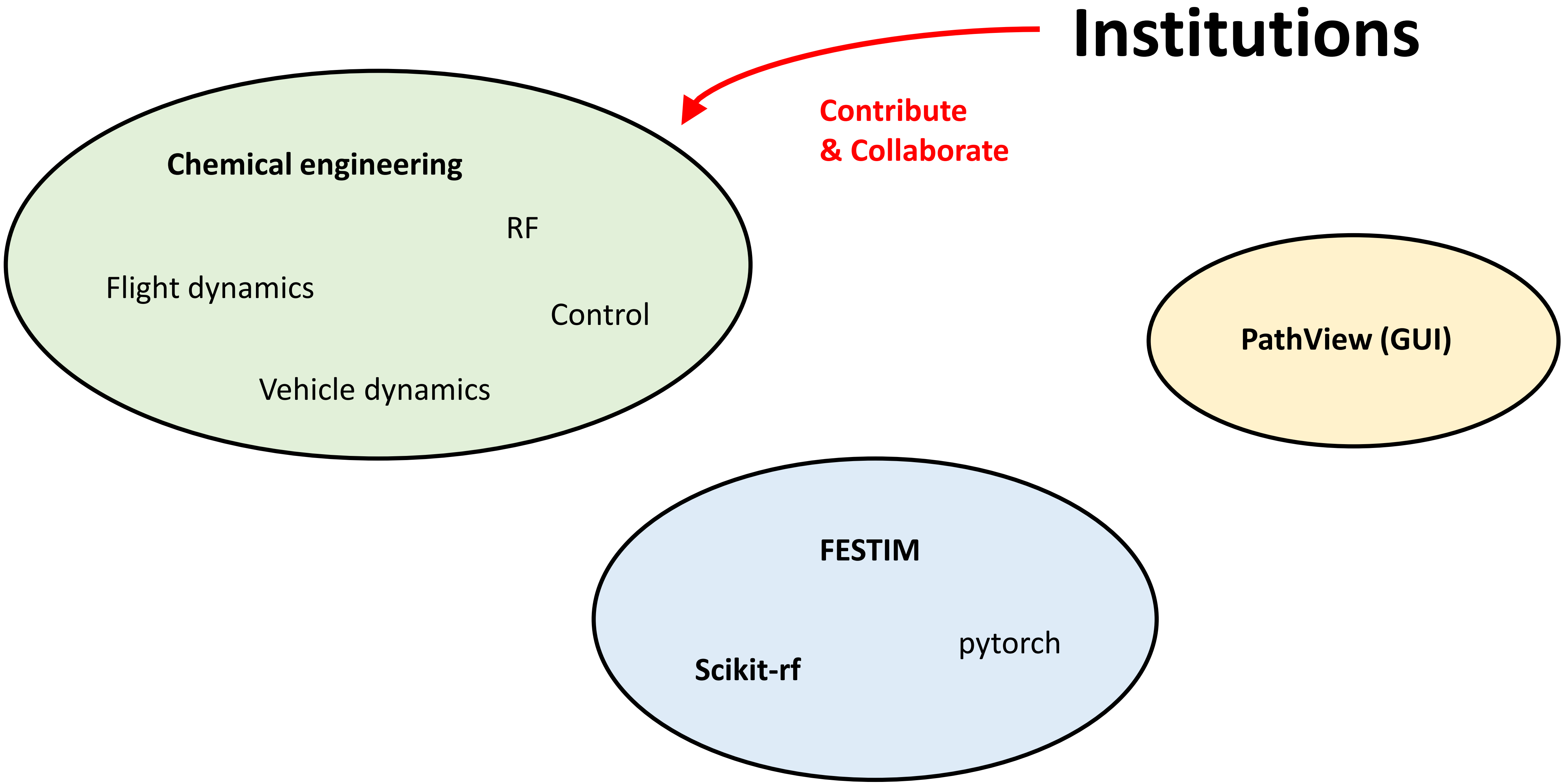
(Hot) Takeaway

Fusion needs system level tools that bring together all the device level analysis and modeling efforts.

Here is one that does this.

Whats coming?

Toolboxes, Integrations and Extensions … Ecosystem?



Institutions

Contribute
& Collaborate

Chemical engineering

RF

Flight dynamics

Control

Vehicle dynamics

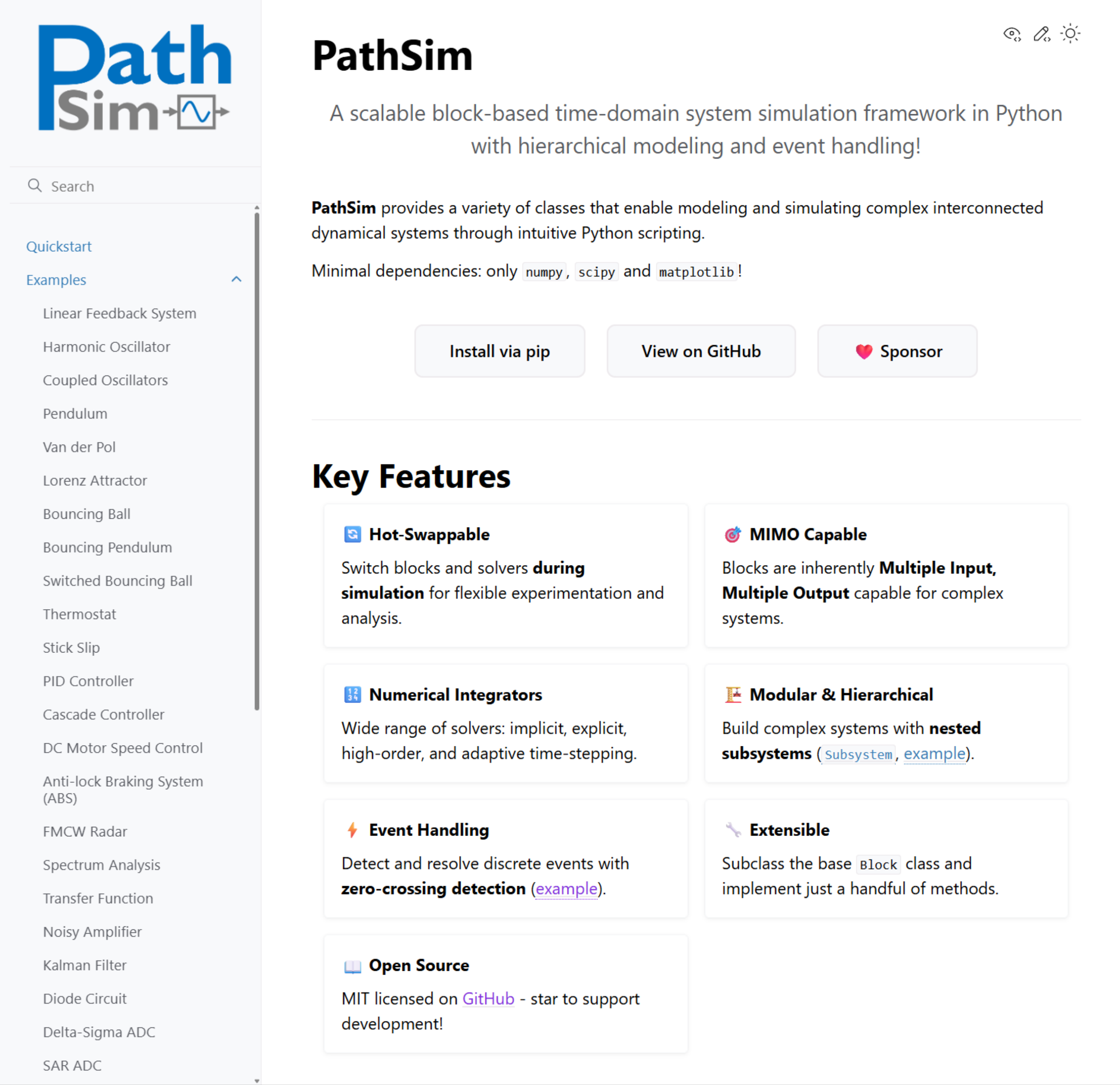
PathView (GUI)

FESTIM

Scikit-rf

pytorch

Where to find it?



PathSim

A scalable block-based time-domain system simulation framework in Python with hierarchical modeling and event handling!

PathSim provides a variety of classes that enable modeling and simulating complex interconnected dynamical systems through intuitive Python scripting.

Minimal dependencies: only `numpy`, `scipy` and `matplotlib`!

Key Features

Hot-Swappable

Switch blocks and solvers **during simulation** for flexible experimentation and analysis.

MIMO Capable

Blocks are inherently **Multiple Input, Multiple Output** capable for complex systems.

Numerical Integrators

Wide range of solvers: implicit, explicit, high-order, and adaptive time-stepping.

Modular & Hierarchical

Build complex systems with **nested subsystems** (`Subsystem`, example).

Event Handling

Detect and resolve discrete events with **zero-crossing detection** (example).

Extensible

Subclass the base `Block` class and implement just a handful of methods.

Open Source

MIT licensed on GitHub - star to support development!

pathsim.org