Process-Level Modeling and Simulation for HP's Multi Jet Fusion 3D Printing Technology

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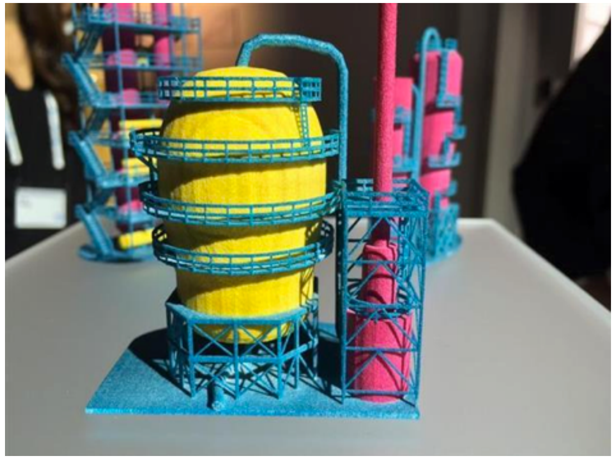
Introduction

- 3D Printing Technology (Additive Manufacturing)
  - Expected to revolutionize the way of production
    - Highly customized and complex parts
    - Small scale manufacturing (<1000 units)



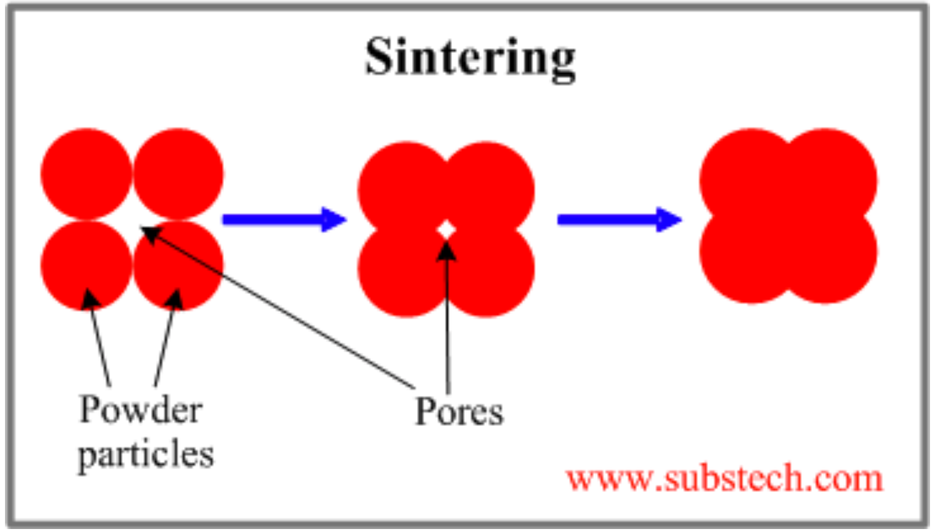
http://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/8283

http://www.3ders.org/articles/20160105-hp-reveals-more-multi-jet-fusion-3d-printer-expected-in-late-2016.html

Introduction

Techniques used for 3D Printing

- Sintering / Fusion
  - Process of compacting and forming a solid mass of material
  - By heat and/or pressure
  - Example of material: metals, ceramics, plastics

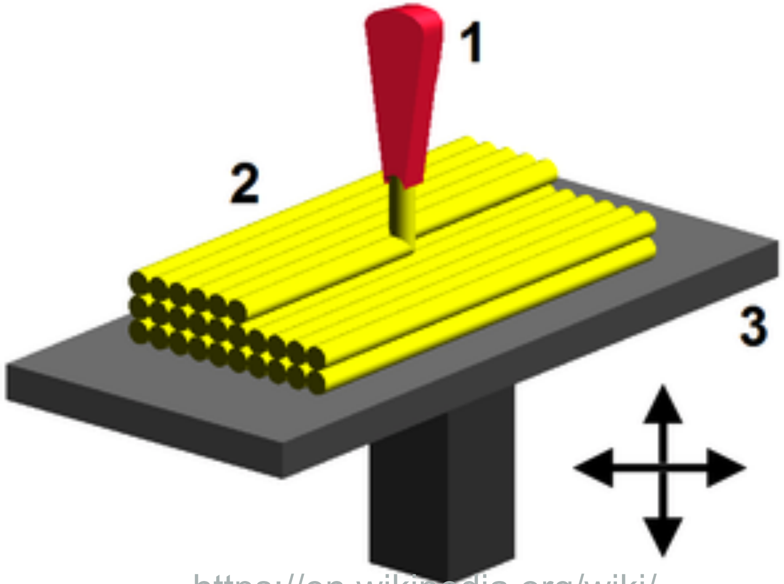


http://www.substech.com/dokuwiki/doku.php?id=sintering_of_ceramics

Introduction

Techniques used for 3D Printing

- Fused Deposition Modeling (FDM)
  - Laying down fused material with ejecting nozzle



https://en.wikipedia.org/wiki/Fused_deposition_modeling

Introduction

Techniques used for 3D Printing

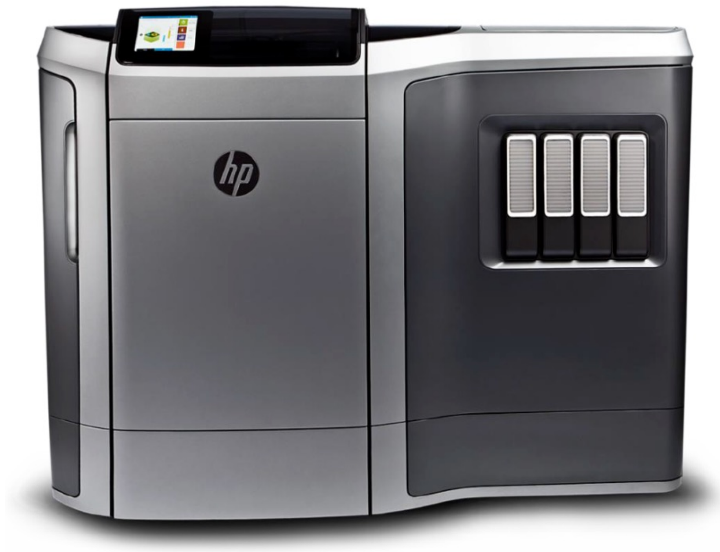
- Selective Laser Sintering (SLS)
  - Heating powder material by focusing laser to shape the object

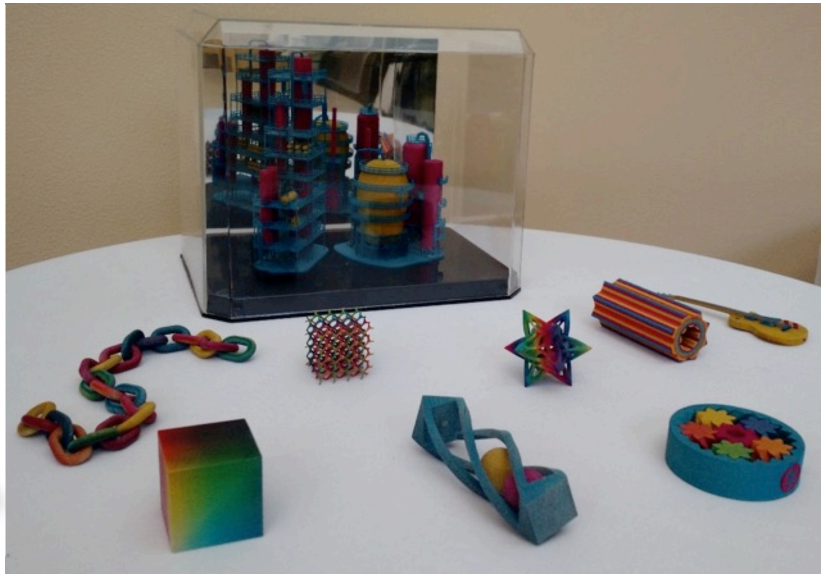
https://en.wikipedia.org/wiki/Selective_laser_sintering

Introduction

HP's Multi Jet Fusion (MJF) 3D Printing Technology

- Fast and inexpensive technology
- Can provide new levels of quality (different colors, strengths, flexibility, conductivity, etc.)

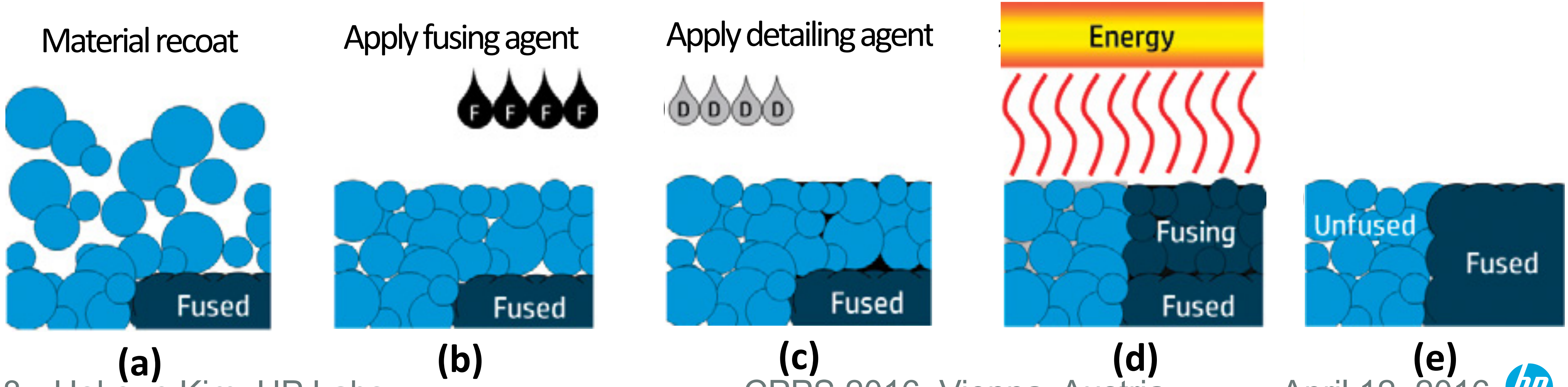




Introduction

HP's Multi Jet Fusion (MJF) 3D Printing Technology

- Process Details
  - Selectively apply fusing/detailing agent that amplifies/reduces fusion effect
  - Apply energy on the whole area, **layer-by-layer production** (significantly faster than point-by-point production with FDM/SLS)



Introduction

HP's Multi Jet Fusion (MJF) 3D Printing Technology

- Video clip for demonstration of MJF 3D Printer (USA Today, Oct, 2014)

Motivation

- HP's Multi Jet Fusion 3D Printer as a Cyber-Physical Production System (CPPS)
  - Printing process, mechanical parts (cyber part)
  - Build material layer (physical part)
- Need for modeling & simulation tool
  - To provide modeling and simulation tools for prediction of **quality of printed part that is determined during 3D printing process**
  - To give guidance for future materials/processes development and optimization
  - For fundamentally understanding Multi Jet Fusion technology

Motivation

- Current widely used 3D printing simulation technique
  - Finite Element Method (FEM)
    - A numerical method to find approximate solutions for parti... ons (PDEs) by dividing large problem int... t
  - Pros and c...

We needed a proper tool for process-level simulation that can **simulate cyber part as well**, and that is **much faster to simulate >100 layers** in a reasonable simulation time

    - ...en when simulating a single layer of material on a ...ea ($1cm^2$)
    - - Difficult to simulate cyber part (e.g. control of printing process)
  - Not proper for process-level simulation for printing a 3D object with hundreds or thousands layers

Background

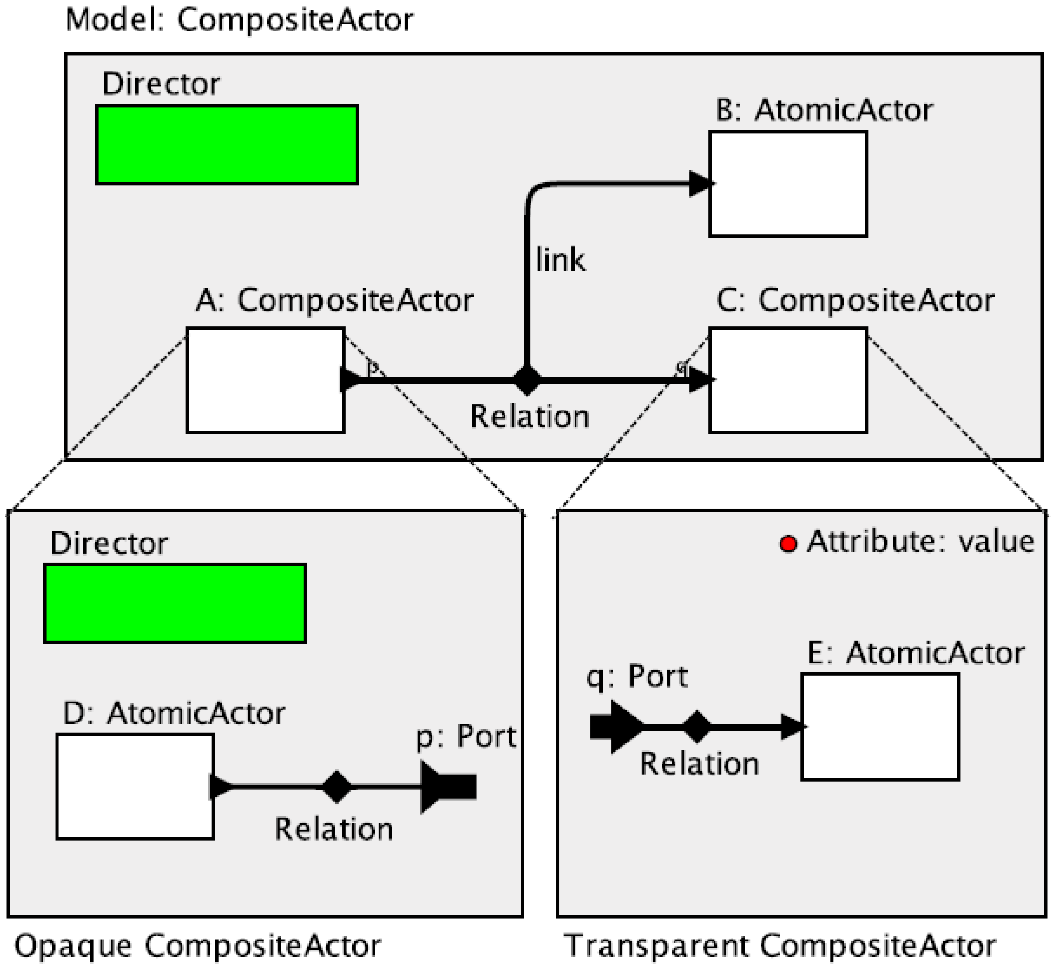
What is Ptolemy II?

- An open-source software for research on cyber-physical systems
  - Developed at UC Berkeley since1996 (its predecessor, Ptolemy Classic started in 1990)
  - Supports modeling of both the cyber part (computation, communication) and physical process (continuous dynamics)
  - Quite stable, easy to learn and use (supports GUI, one can build a model by drawing components)
  - Based on actor-oriented design
  - More information on http://ptolemy.org

Background

Actor-Oriented Design in Ptolemy II

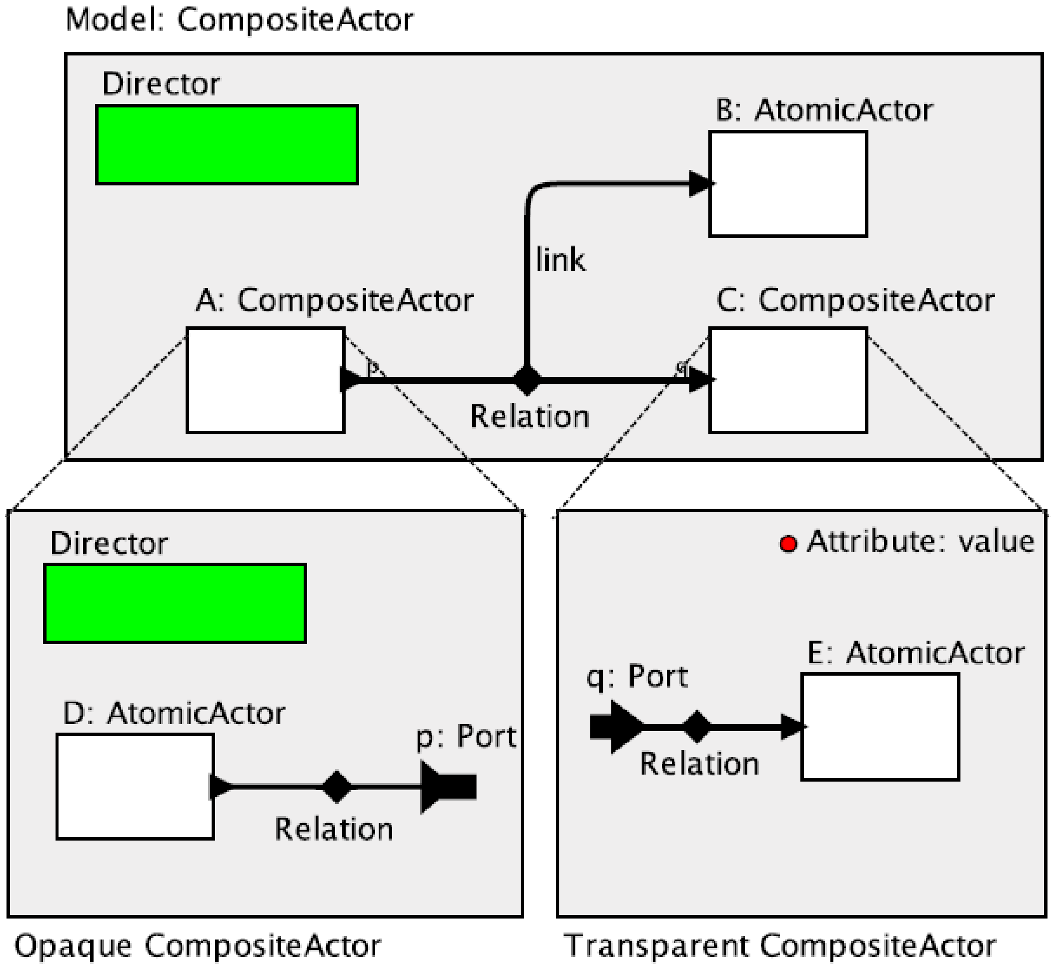
- Actors
  - Concurrently executed components
  - Interact with other actors through input/output ports connected to each other
  - Can model computation, communication, physical processes, etc.



Background

Actor-Oriented Design in Ptolemy II

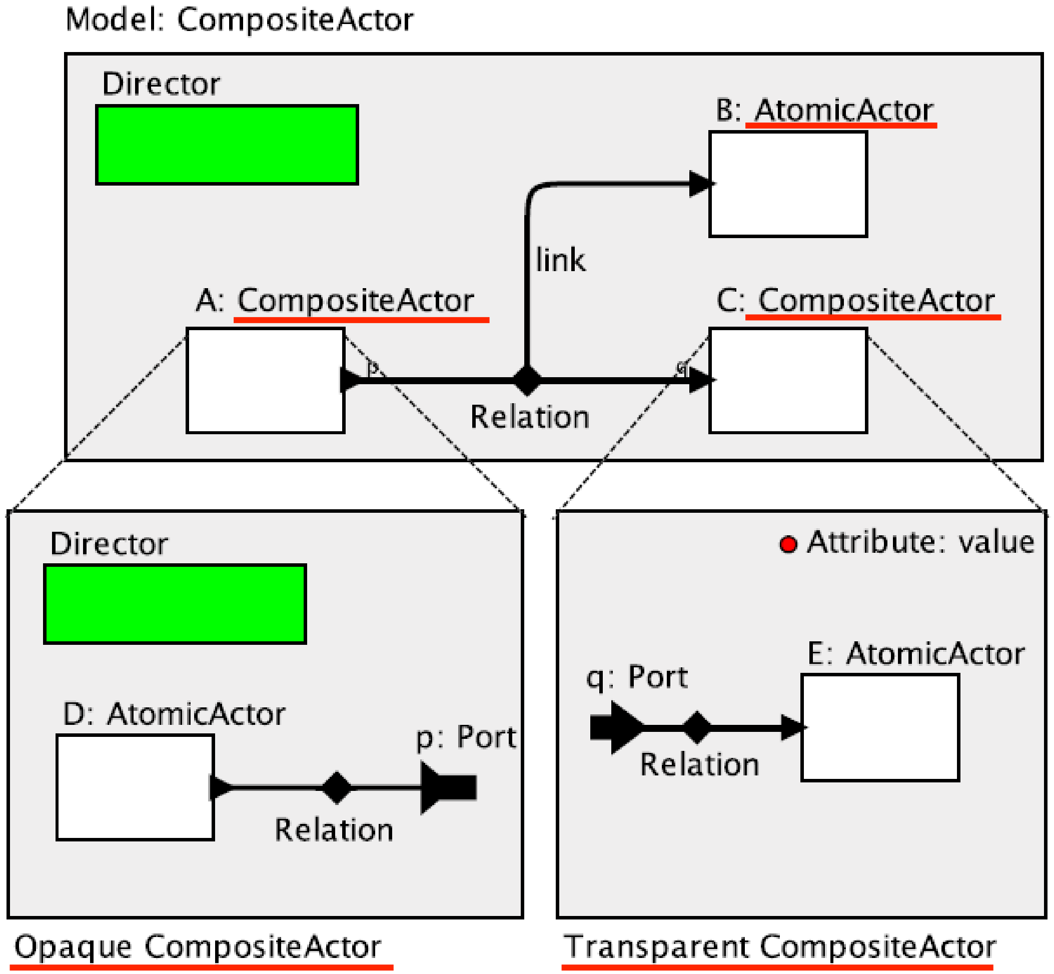
- Directors
  - Implement Models of Computation (MoCs)
  - Orchestrate behavior of actors, for example, when each actor should be executed (=fired)



Background

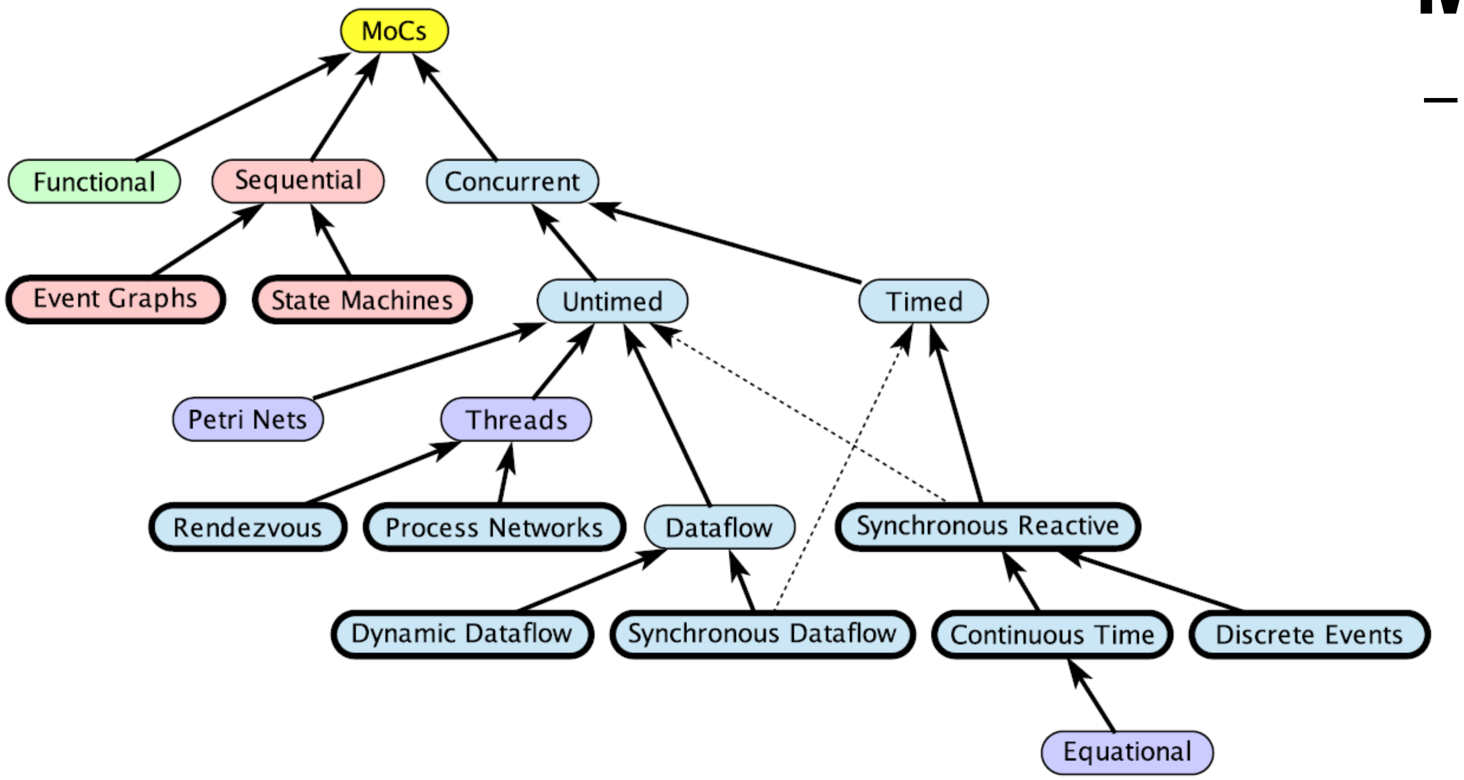
Actor-Oriented Design in Ptolemy II

- Actor hierarchy
  - An actor can have sub-actors (composite actor)
  - Atomic actor = non-composite actor
  - A composite actor can have its own director (opaque composite actor)
  - Actors in a transparent composite actor are governed by the upper-level director



Background

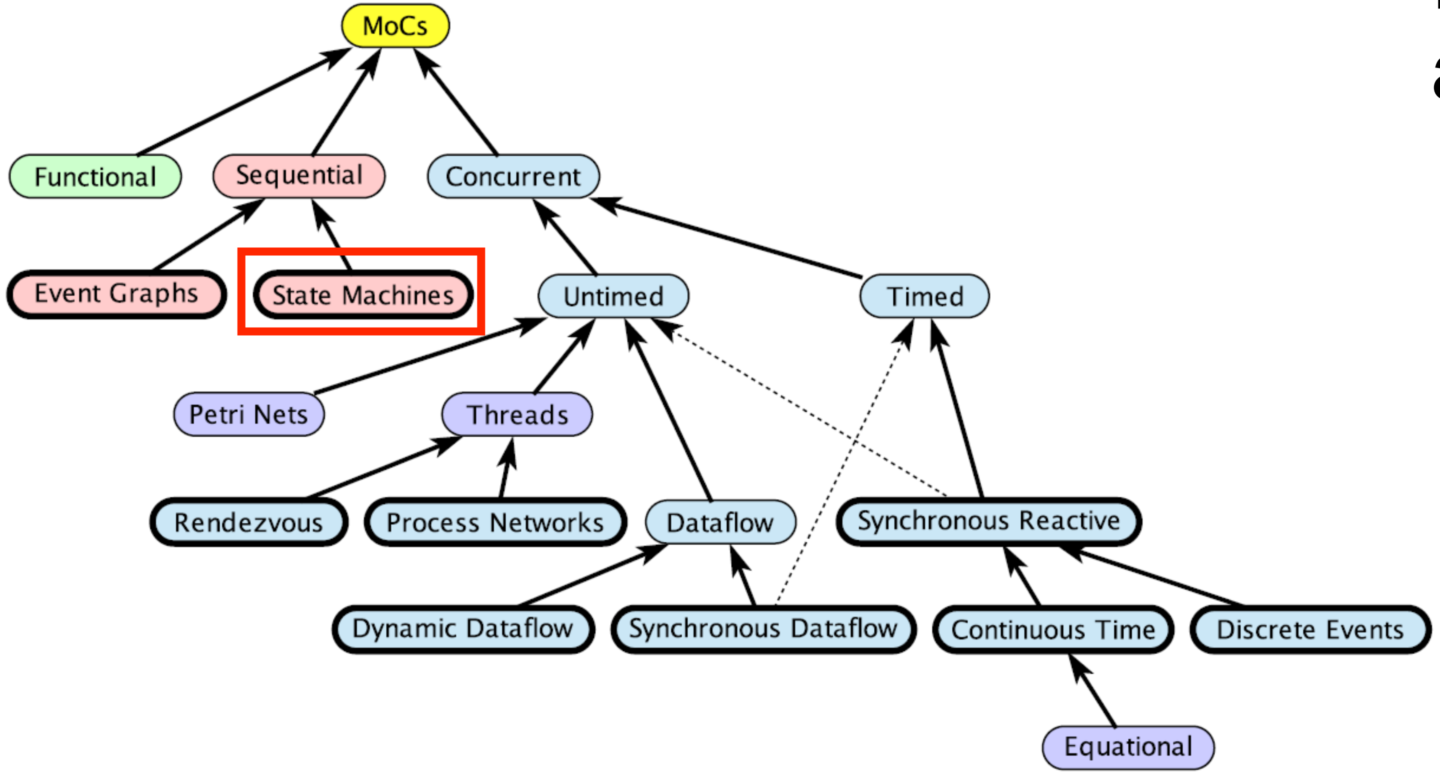
Models of Computation (MoCs) in Ptolemy II



- **Model of Computation**
  - A set of rules orchestrating behavior of actors
    - E.g. When to execute actors, How actors react to inputs

Background

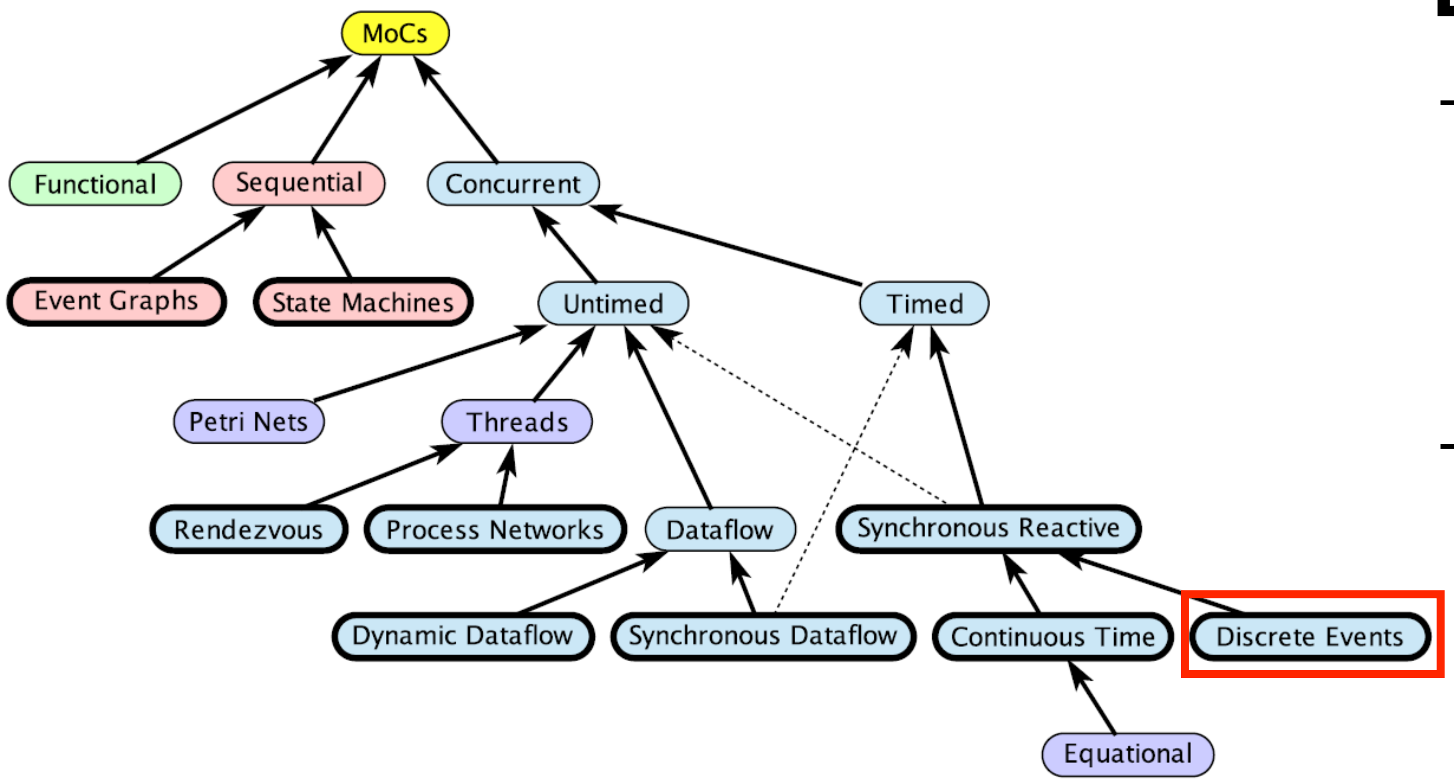
Models of Computation (MoCs) in Ptolemy II



- **Finite State Machines** and **Modal Models**
  - States and state transitions are used to describe behavior
  - Each state can represent different modes of operation (modal models)

Background

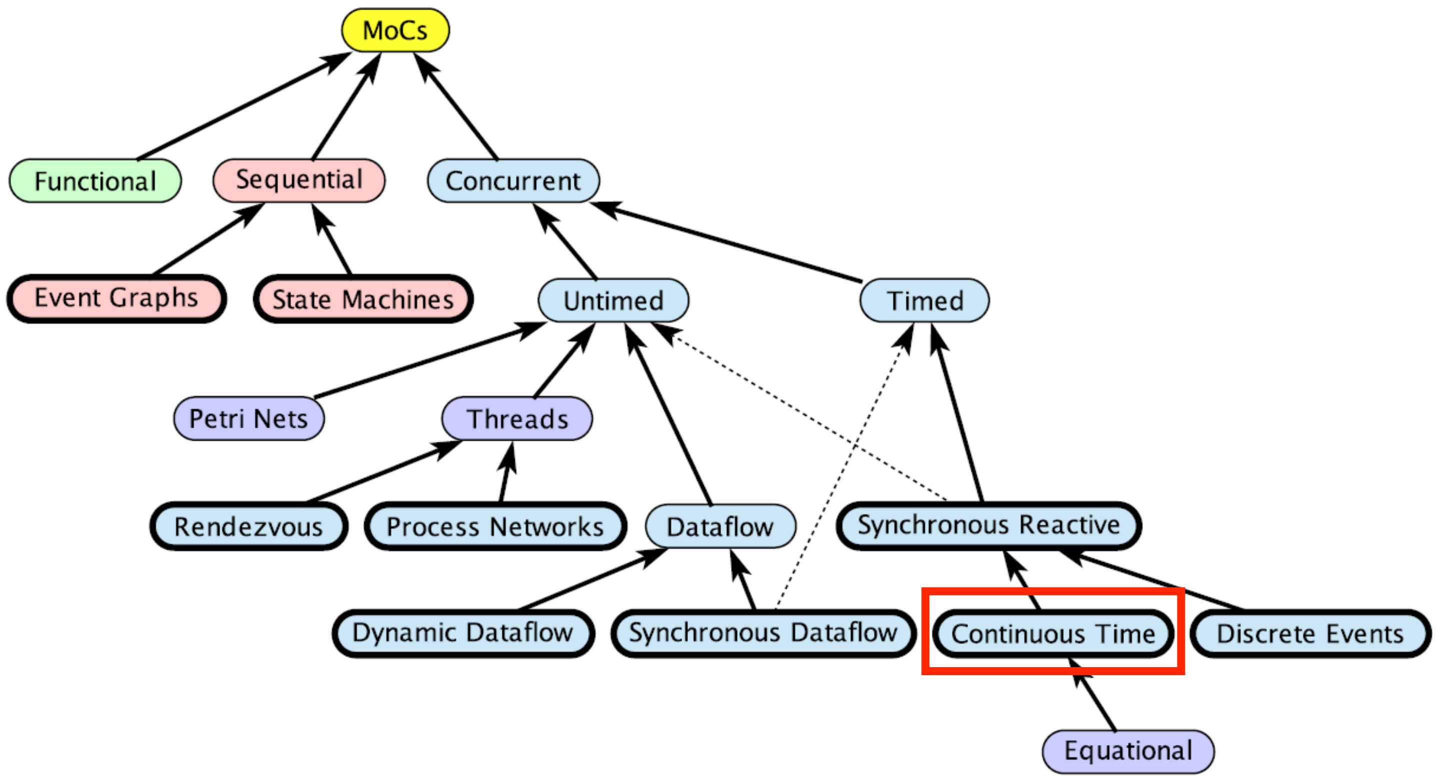
Models of Computation (MoCs) in Ptolemy II



- **Discrete Events (DE)**
  - Time-stamped events (e.g. timer event, arrival of messages) trigger execution of actors
  - Good for modeling computation and communication

Background

Models of Computation (MoCs) in Ptolemy II



- **Continuous Time**
  - Continuous behavior of actors is simulated by sampling and advancing time steps
  - Includes ODE solvers for physical processes modeled in ODEs (similar to Mathworks Simulink)
  - Proper for modeling physical processes (e.g. temperature, thermal transfer)

Modeling and Simulation Techniques

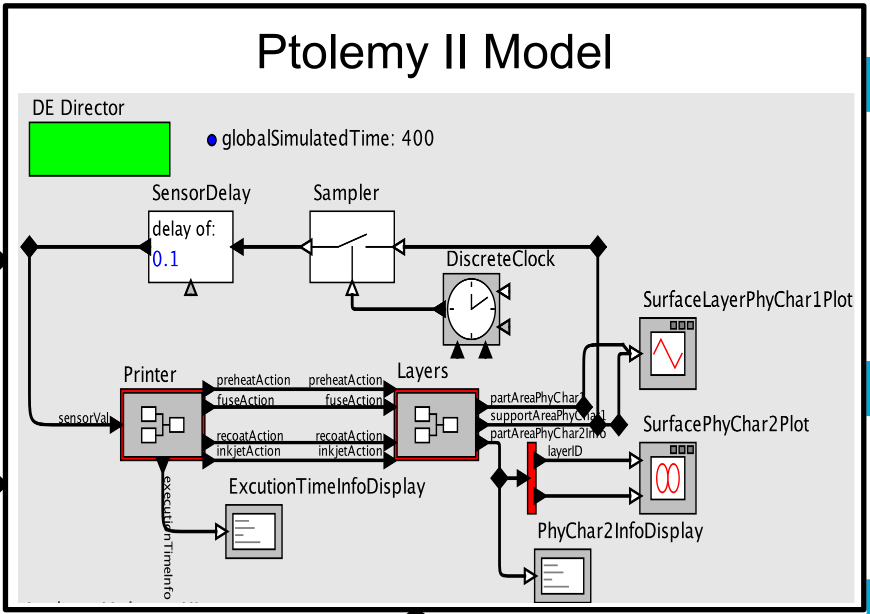
Inputs and Outputs of Ptolemy II Model

Config File

Configuration parameters for printer control & processes

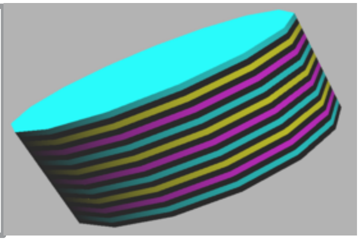
Env File

Parameters for physical environment & material characteristics

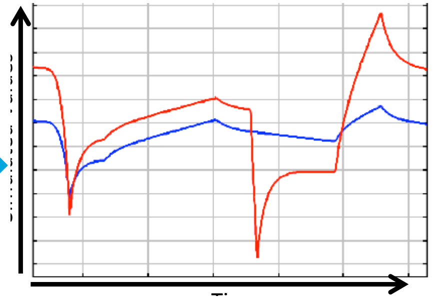


3D Image File

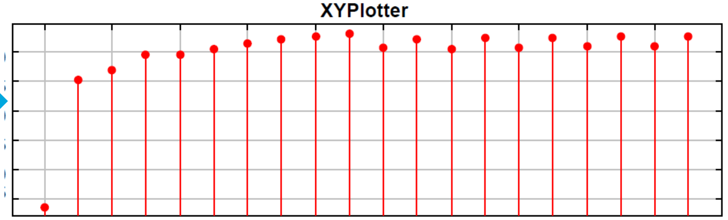
Image Information of each layer



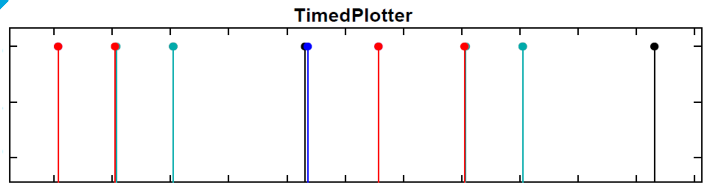
Surface Layer Physical Characteristic 1



Physical Characteristic 2 of each layer

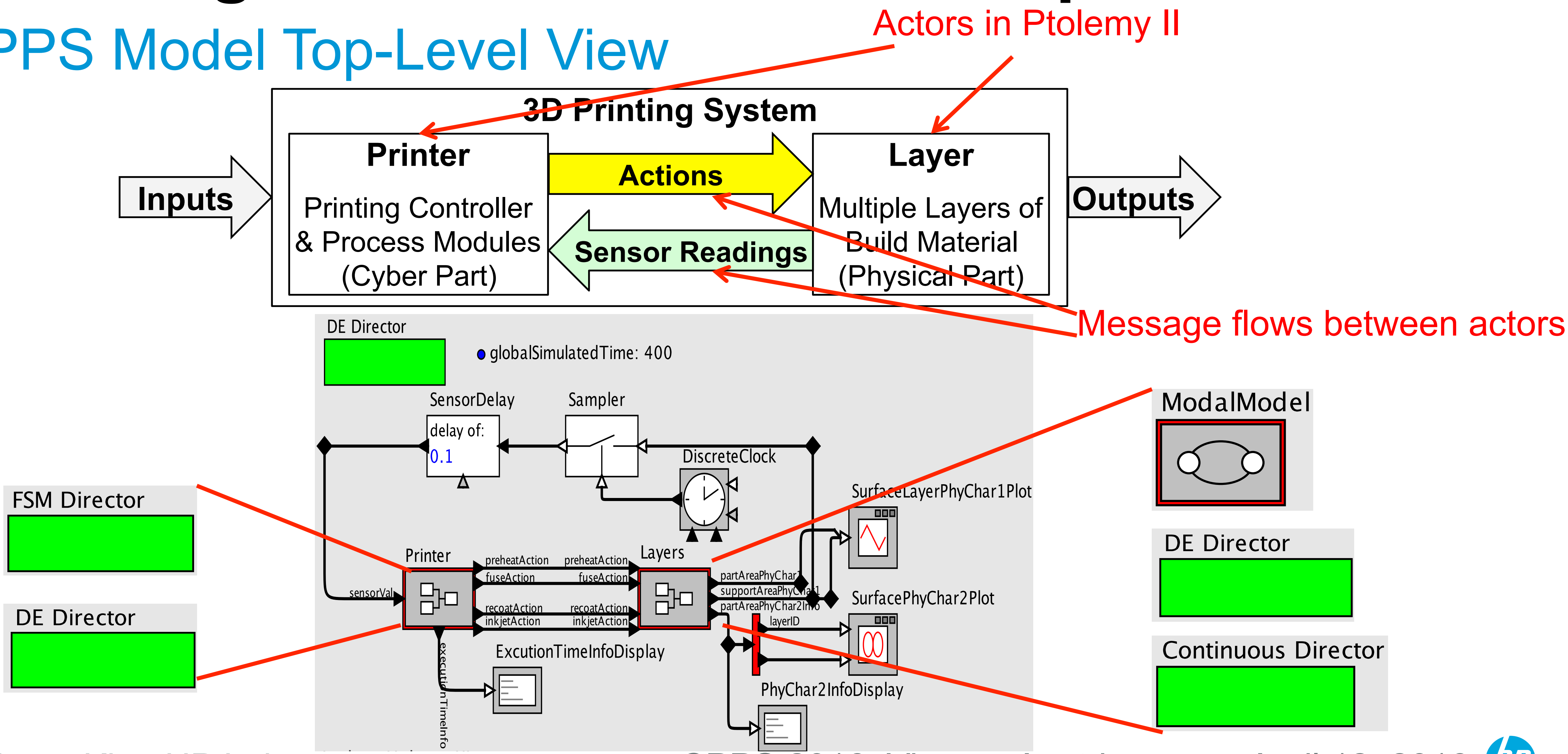


Layer Processing Time



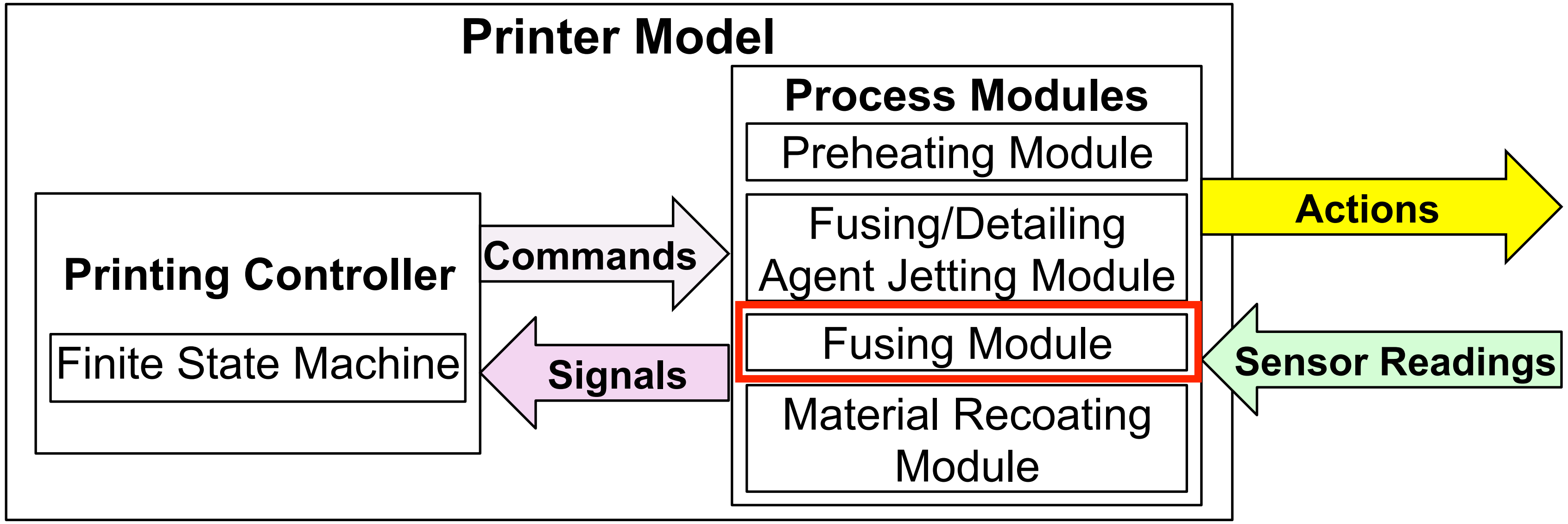
Modeling and Simulation Techniques

CPPS Model Top-Level View



Modeling and Simulation Techniques

Cyber Part of CPPS Model

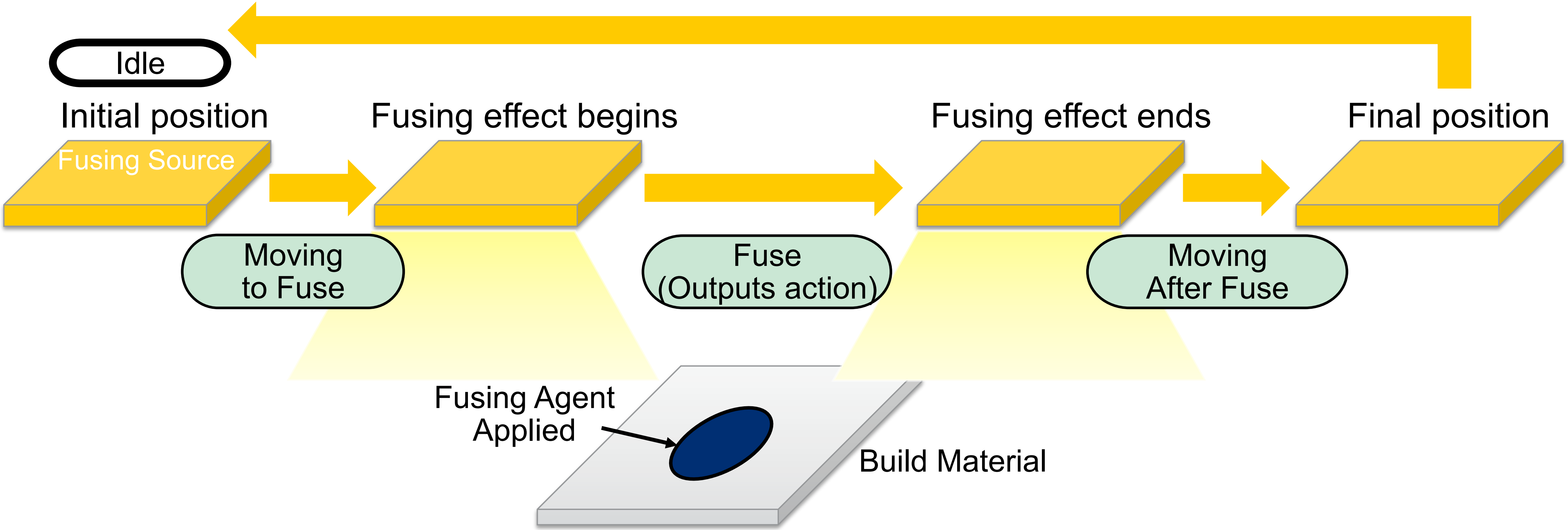


- Controller
  - Sends commands to operate process modules
- Process modules
  - Take actions on build material, and sense physical characteristics of the surface of build material

Modeling and Simulation Techniques

Example of Printing Process Modeling

- Fusing Process Model with a Finite State Machine (FSM)



Modeling and Simulation Techniques

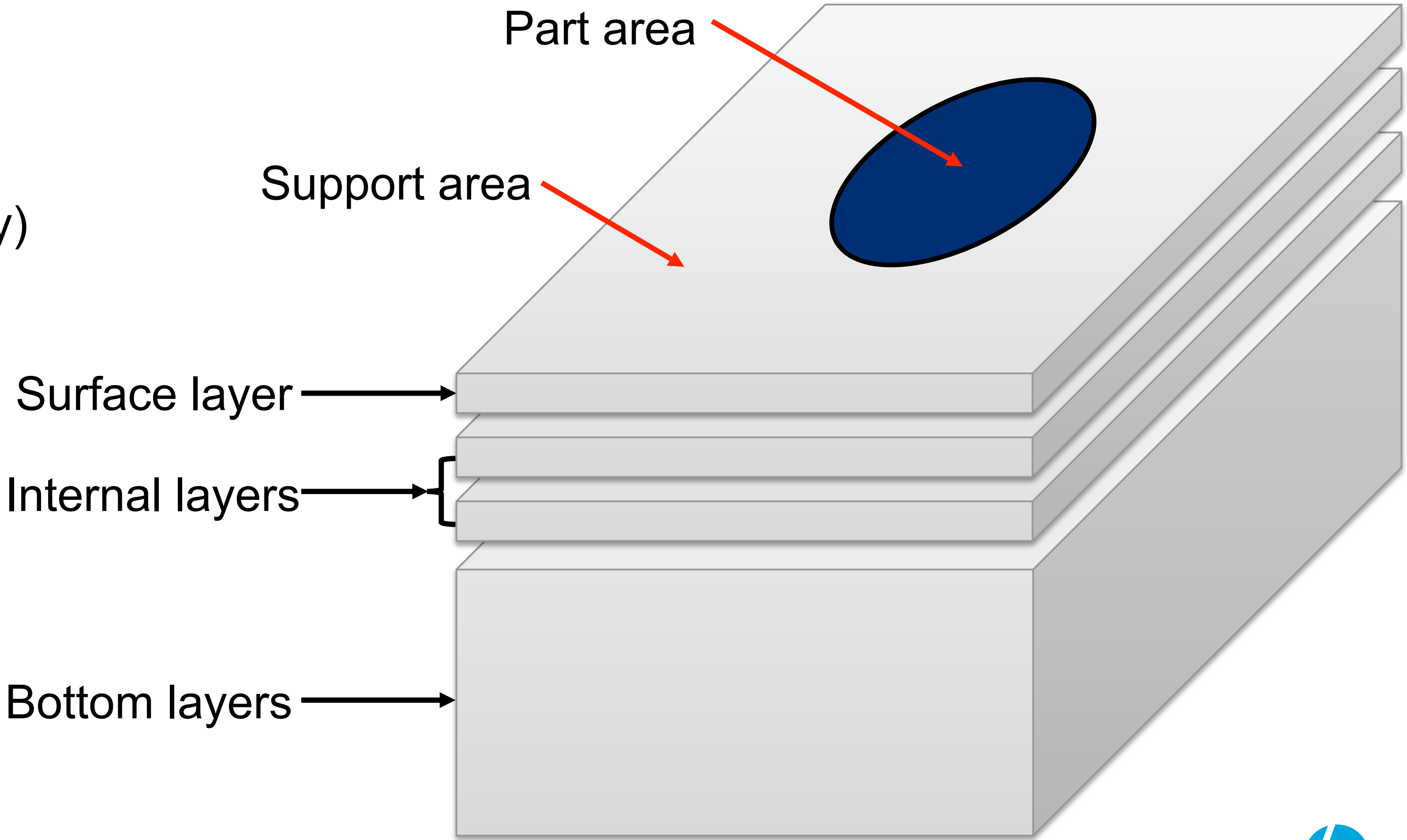
Basic Ideas for Modeling Physical part

- Unlike FEM, We use approximation to simulate physical characteristics of build material for each layer and each area
- Each layer/area is modeled as <u>a single actor</u>
- However, even modeling each layer, if layer grows to 1,000 layers, we will need 1,000 actors, leading to too much overhead for process-level simulation?
- **How can we deal with additive layers efficiently?**

Modeling and Simulation Techniques

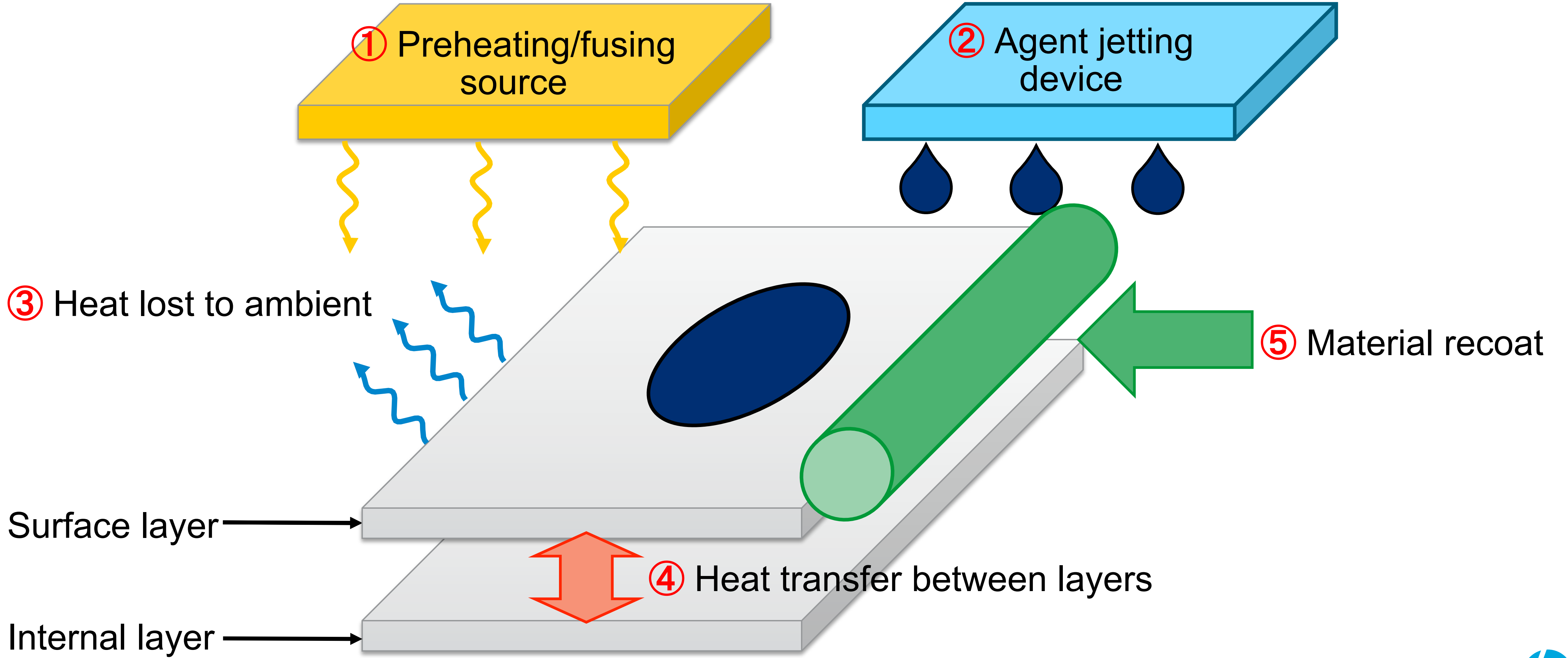
Approximating Physical Part of CPPS Model

- Dividing build material layers into three categories
  - Surface layer (currently printed)
  - Internal layers (printed previously)
  - Bottom layers
- Dividing each layer into two areas
  - Part area (to be fused)
  - Support area (remains unfused)



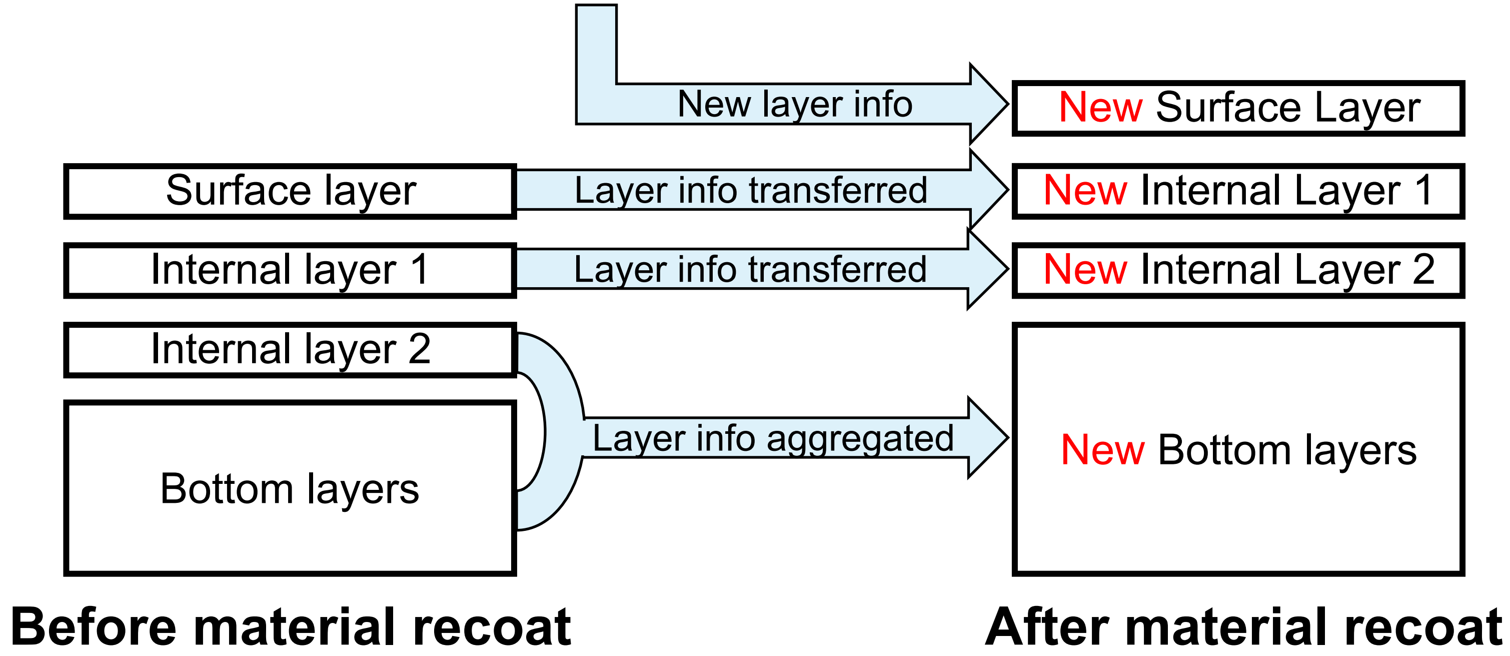
Modeling and Simulation Techniques

Factors Affecting Surface Layer Temperature



Modeling and Simulation Techniques

Modeling Additive Layers with Fixed Number of Actors

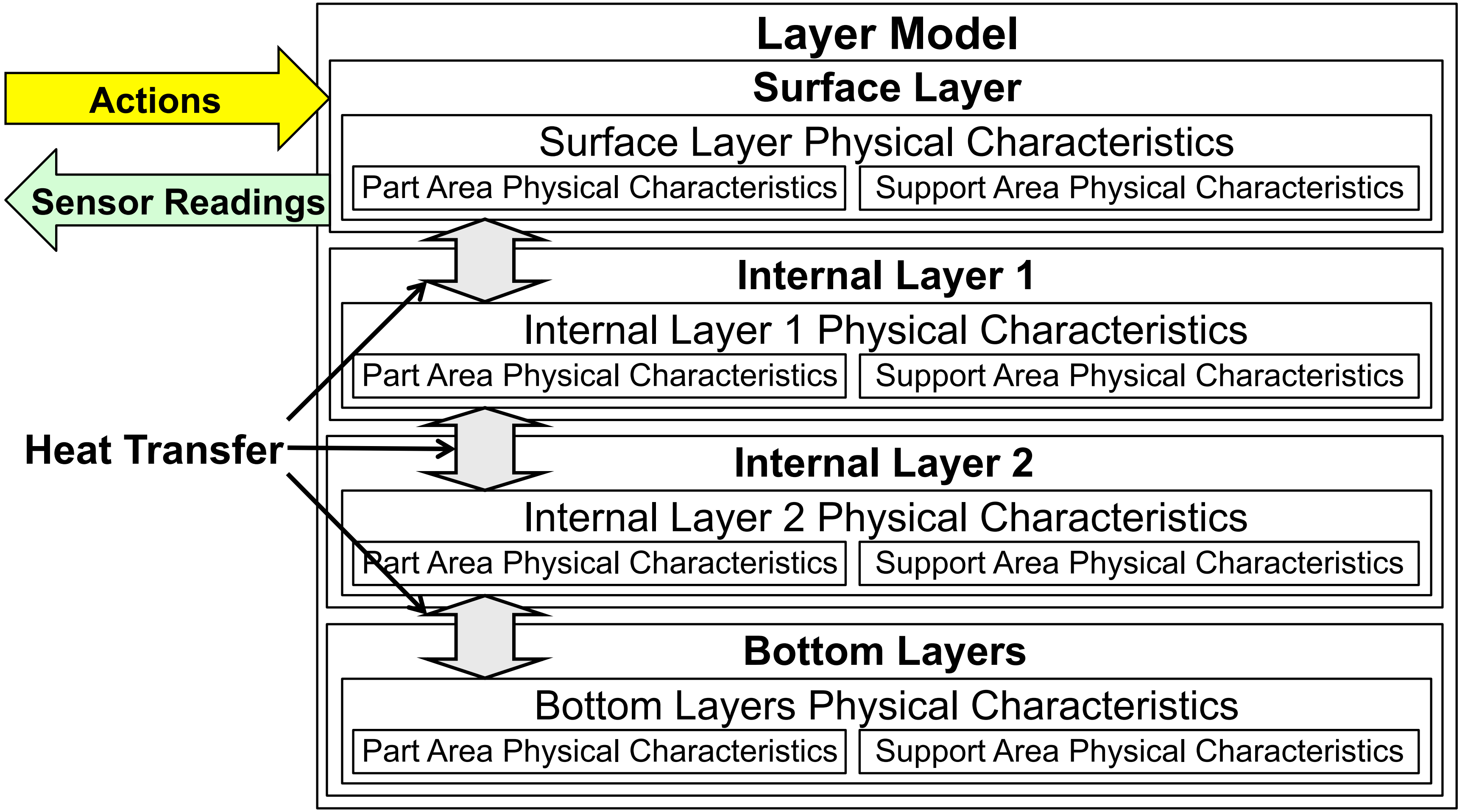


- Information aggregation example for temperature

$$T_{NewBottom} = \frac{N_{Bottom} \times T_{Bottom} + T_{Internal2}}{N_{Bottom} + 1}$$

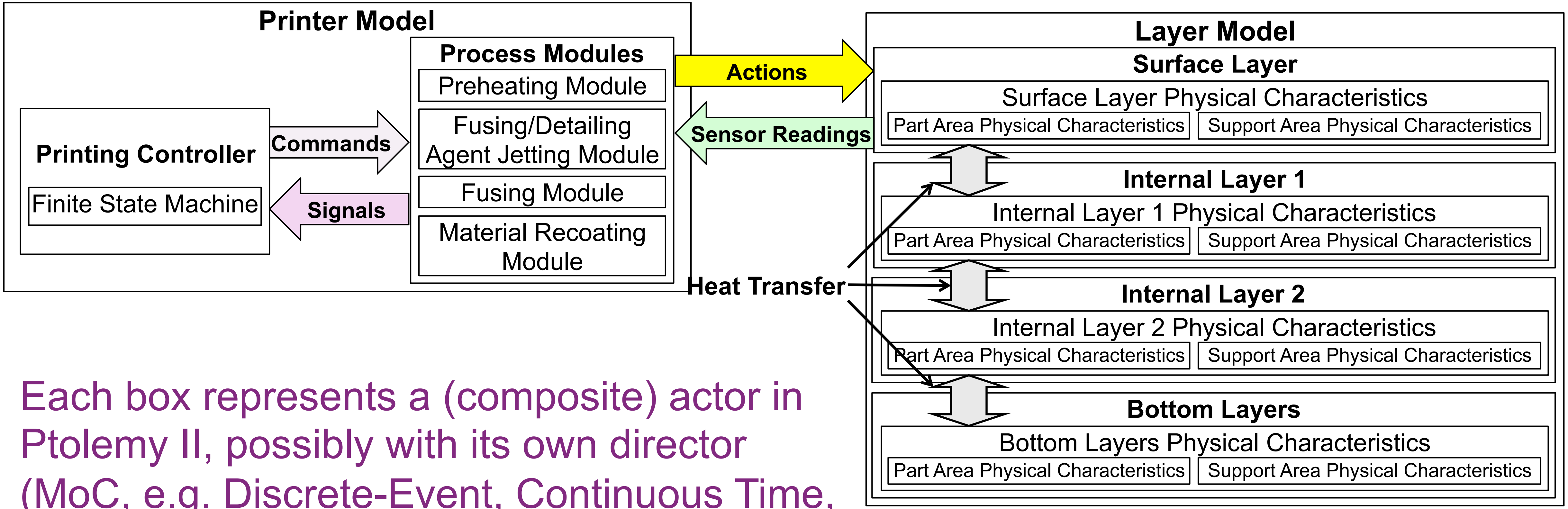
Modeling and Simulation Techniques

Physical Part of CPPS Model



Modeling and Simulation Techniques

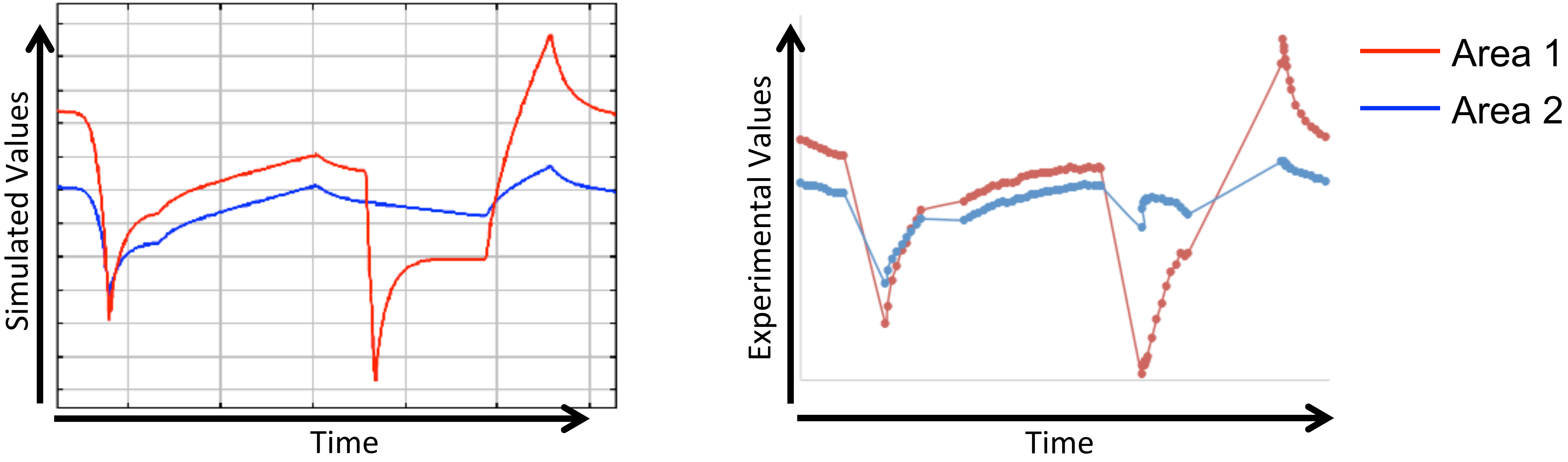
Complete CPPS Model



Each box represents a (composite) actor in Ptolemy II, possibly with its own director (MoC, e.g. Discrete-Event, Continuous Time, or FSM)

Preliminary Results

Simulated Values vs Experimented Values



(a) Simulation results **(b) Experimental results**

❖Details are excluded for HP's confidential information

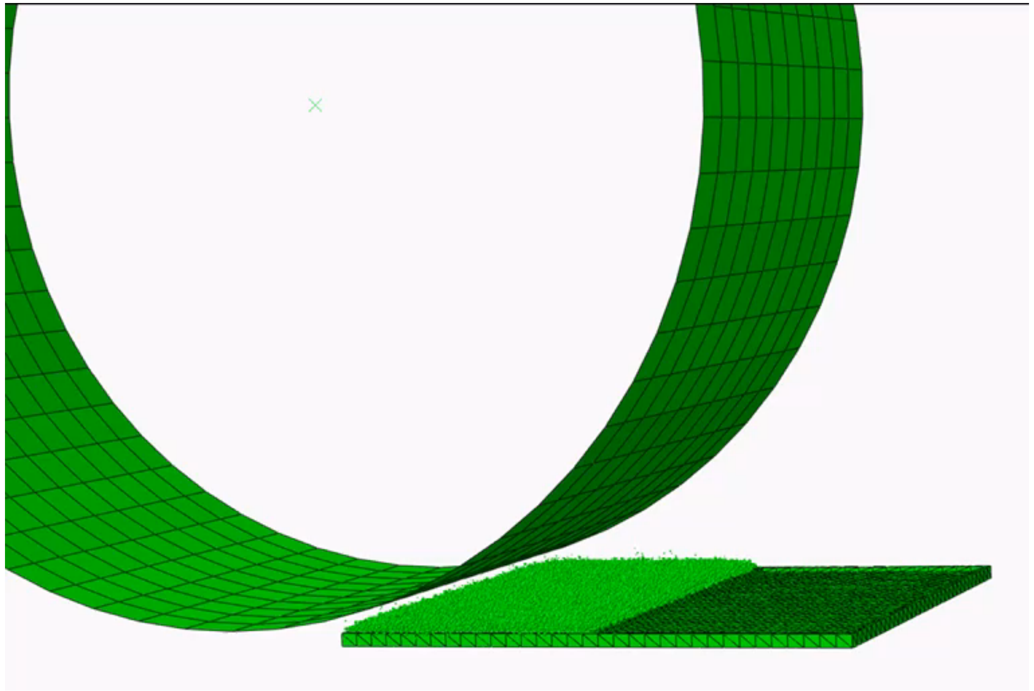
- Reasonable accuracy for each area

Preliminary Results

Simulation Time – Proposed vs Finite Element Method

- Material recoat process simulation using finite element method (FEM)

❖ **Visualization of FEM simulation for material recoat process**



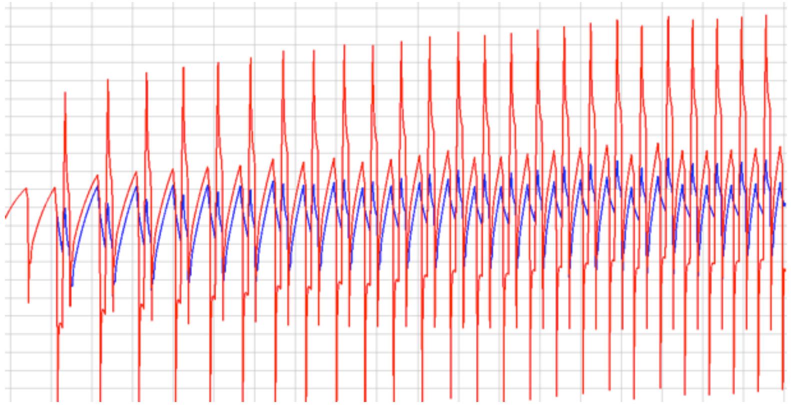
Simulation Platform (Workstation)	two Intel Xeon E5 @2.60 GHz (6 cores each, total 12 cores) and 64 GB RAM
Simulation time for one layer of 1cm × 1cm area (reduced scale)	**127 minutes**
Expected simulation time for one layer of 10cm × 10cm area (normal scale)	100 × 100 × 127 minutes = **7.62 × 10^7 seconds**

- Simulation time of FEM is at least quadratic to the number of particles (≈ area)
- 100 times area ➔ 100 × 100 times simulation time

Preliminary Results

Simulation Time – Proposed vs Finite Element Method

- Proposed approach – simulation time for process-level simulation for all processes including material recoat



Simulation Platform (Laptop, HP Z-book)	Intel Core i7 2.8 GHz (4 cores) and 16 GB RAM
Simulation time for 100 layers for all processes	**592 seconds**
Simulation time for 1 layer for all processes	**5.92 seconds**

- FEM for material recoat process: 7.62×10^7 seconds / layer
- Proposed approach for all processes: 5.92 seconds / layer

Indication: proposed approach is faster than FEM by approximately 7 orders of magnitude!

Conclusion

- Proposed modeling and simulation techniques of HP's Multi Jet Fusion 3D printing technology as a CPPS using Ptolemy II
- Significantly faster speed than FEM, with reasonable accuracy
  - By approximation of layers of build material
  - Information aggregation for additive layers
- Flexible design in configuration, can be easily extended and improved
- Future Work
  - Supporting more complex geometry (Currently we assume printed shapes are identical for all layers)
  - Improving accuracy with equations extracted from experimental data

Thank you!

- **Q&A**

- **Contact Info**
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- **Acknowledgement**
  - Prof. Edward A. Lee and Ptolemy Project group at UC Berkeley