Agent-Based Modeling of Material Diversion in Nuclear Fuel Cycles

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October 16-17, 2014
NNSA CVT Kick-off Meeting

Overview

- History of Cyclus
- Fundamental Concepts
  - Platform
  - Ecosystem
  - User interface
- Adaptation for nuclear security

Fuel Cycle Simulators

- Long history of different fuel cycle simulation tools
  - Increased in last decade, prompted by GNEP
- Focus on understanding mass flows and facility deployments under alternative civilian nuclear fuel cycles
  - Particularly during transitions between fuel cycles
- Many socio-economic impacts are derived from these primary quantities
- Inform decision-making about fuel cycle technologies

Fuel Cycle Simulator Origin Stories

Fuel cycle simulators have 2 primary motivations

- Immediate commercial interest in managing nuclear fuel
  - Very technical approach built around high-fidelity in-reactor simulation
  - Flexibility for novel systems is constrained
- Long term policy direction
  - Often begin with simple low-fidelity approach accessible to broad audience
  - Complexity increases with desire for detail
  - Encounter limitations of software infrastructure and/or accessibility to original audiences

Why Cyclus?

- Previous efforts
  - Too simple for credibility with technical audiences
  - Too complex for use by non-technical audiences (and some technical audiences)
  - Too rigid for exploring novel technologies
  - Thwarted collaboration with selection of unwieldy software infrastructure
  - Difficult to compare beyond their simplest features (and experimental benchmarks impractical)

Cyclus Development Team

- **University of Wisconsin-Madison (Nuclear)**
  - Robert Carlsen, Matthew Gidden, Michael Gionet, Dr. Kathryn Huff, Dr. Meghan McGarry, Arrielle Opotowsky, Olzhas Rakhimov, Dr. Anthony Scopatz (Project Lead), Zach Welch, Dr. Paul Wilson
- **University of Wisconsin-Madison (Communications)**
  - Dr. Dominique Brossard, Nan Li, Dr. Dietram Scheufele
- **University of Texas-Austin**
  - Dr. Erich Schneider, Robert Flanagan
- **University of Utah**
  - Dr. Yarden Livnat, Dr. Haya Agur
- **University of Idaho**
  - Dr. Robert Hiromoto, Teva Velupillai

Key Feature of Cyclus

- Agent-based approach
- Dynamic resource exchange
- Discrete material tracking
- Run-time plugin architecture
- Open source kernel supporting different licensing choices for plugins
- Separate user interface for building and analyzing simulations

Agent-Based Framework

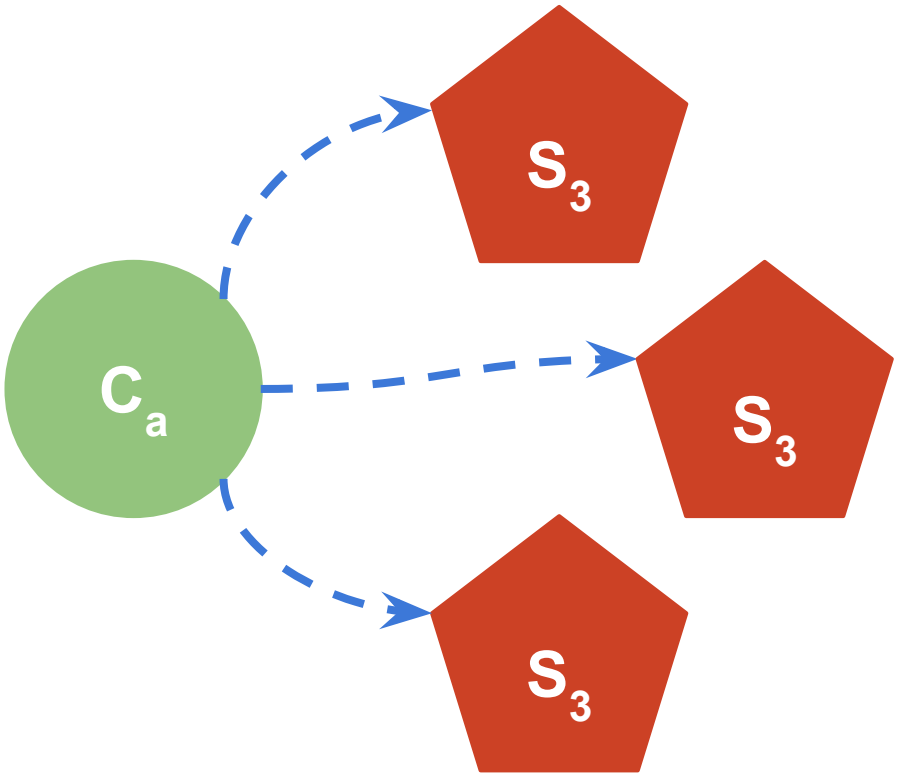
- Every ***Facility*** is an independent agent
  - Physics models govern the fidelity of tracking the isotopic content of materials
  - Behavioral models govern the interactions with other agents

- Each facility is operated by an ***Institution*** in a geopolitical ***Region***
  - These agents can modify interaction behavior in a hierarchical manner

Dynamic Resource Exchange

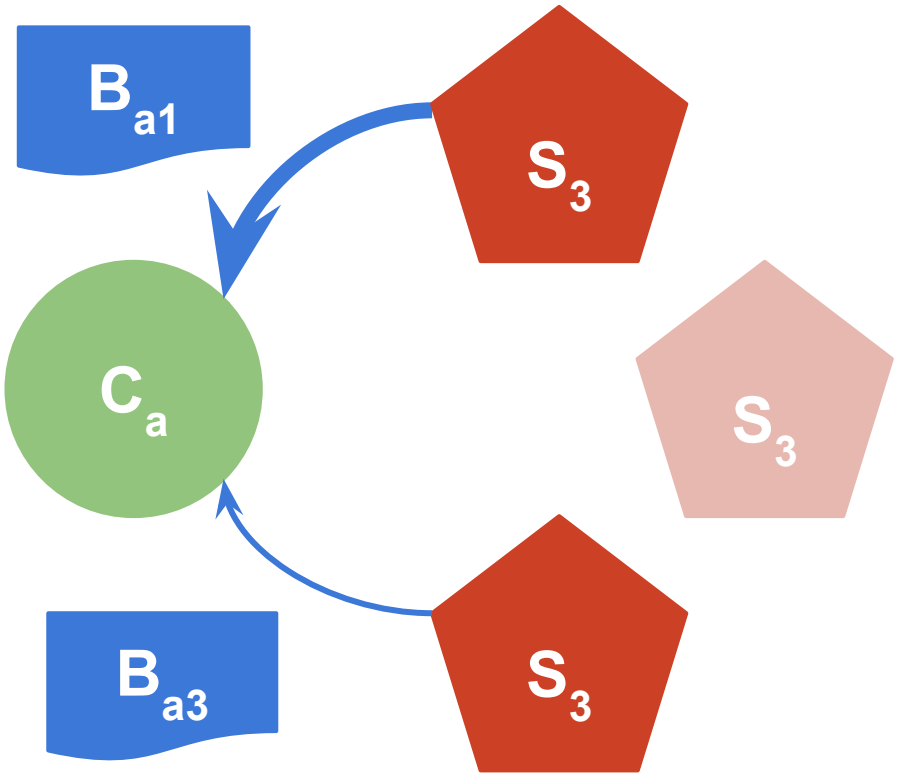
- Flexible deployment of facilities results in changing material flow paths
- Material substitution complicates matching of supply/demand
  - e.g. some reactors may prefer MOX but also accept UOX if there was a supply constraint
- Overcomes facility compatibility constraints of rigid fuel cycle definitions

Dynamic Resource Exchange



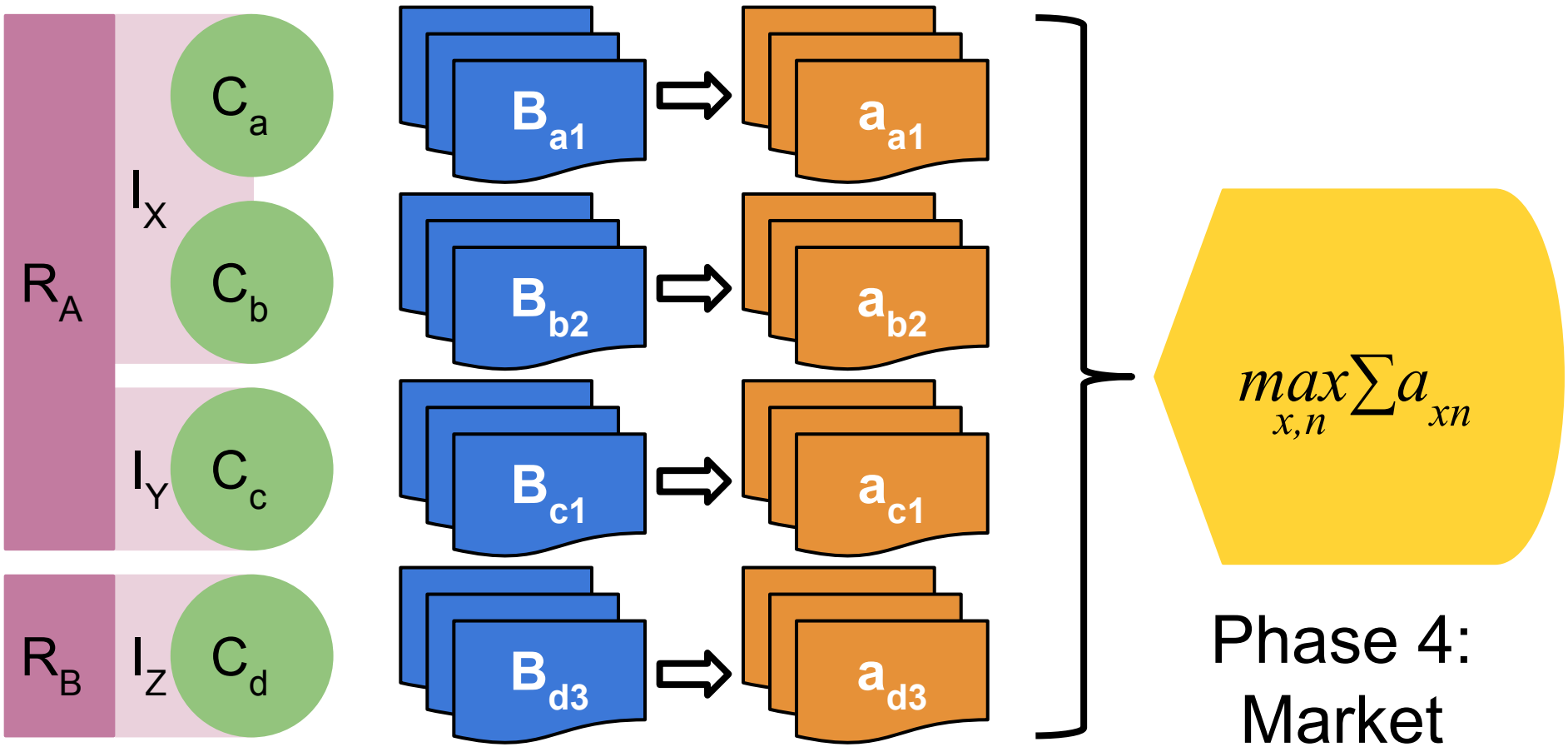
Phase 1: Request for bids

Dynamic Resource Exchange



Phase 2: Response to request for bids

Dynamic Resource Exchange



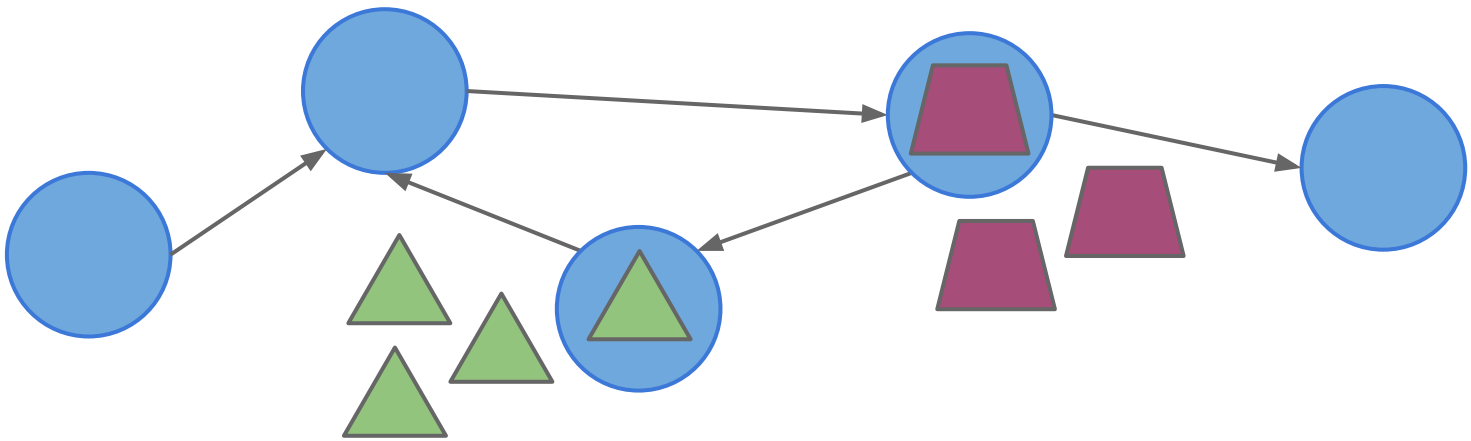
Phase 3: Preference Adjustment

Phase 4: Market Resolution

Discrete Material Tracking

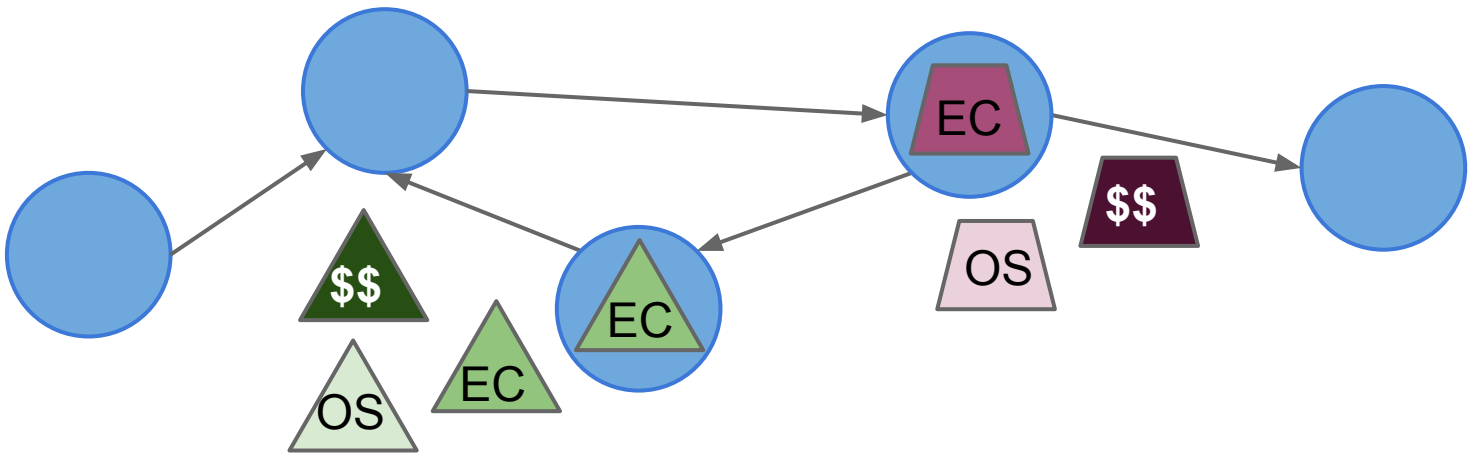
- Follow discrete quanta of materials as they flow around the system
- Log and determine:
  - Facilities, institutions & regions that have “owned” a given material object
  - Locations where material changed composition (burnup & decay)
  - Locations where material changed form (fuel fabrication, separations)
- Arbitrary list of isotopes defined by user

Plug & Play Archetypes



- Facility archetypes can be exchanged without changes to the Cyclus kernel
- Example: increase reactor modeling fidelity
  - Low fidelity: fixed input/output recipes
  - Medium fidelity: lookup tables for output given input
  - High fidelity: burnup calculation based on given input
- Inter-facility dependencies allowed but discouraged

Varied Licensing Options



- Fundamental capabilities distributed as open source kernel
- Individual archetype developers are free to distribute them as the like
  - Open source archetypes
  - Export controlled archetypes
  - Licensed archetypes
  - Commercial archetypes

User Interface Separate from Modeling Platform

- Past efforts selected “user-friendly” modeling platforms (e.g. system dynamics)
  - Ultimate models were so complex that benefit was lost
- Communications research:
  - Understand what information is in demand by different audiences
  - In what form can they most easily digest it
- Drag-and-drop interface for building new fuel cycle ideas
- Dynamic exploration of output

Adaptation for Nuclear Security

- Social/behavior models of agents
  - Easily experiment with different models of diversion/theft of material from declared fuel cycles
  - Identify locations for additional scrutiny
- Physics models of agents
  - Track appropriate isotopes for risk assessment and detector system performance
- Seeking feedback and guidance from consortium partners

Acknowledgements

NEUP Nuclear Energy University Programs

U.S. Department of Energy

Additional student support provided by:

Argonne NATIONAL LABORATORY

NSF

U.S.NRC

U.S. DEPARTMENT OF HOMELAND SECURITY