Dynamic Resource Exchange with CoinOR-CBC in Cyclus, a Nuclear Fuel Cycle Simulator

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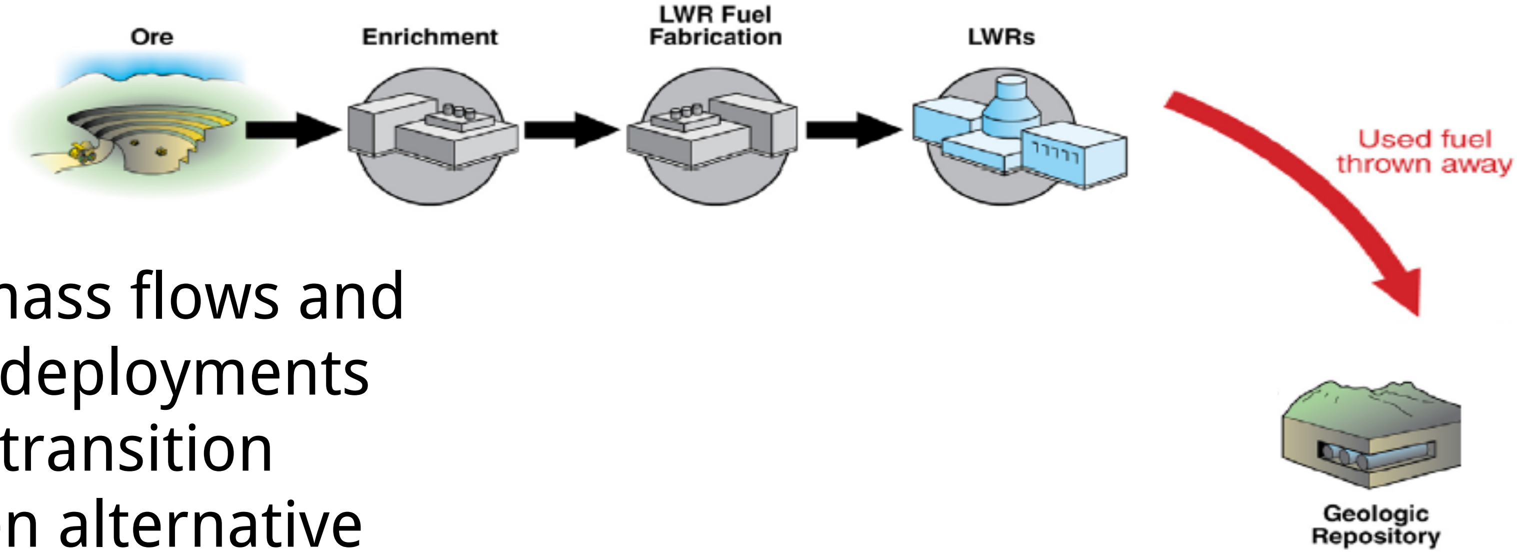
Overview

- What is a nuclear fuel cycle?
- How do we simulate it?
- What is a Dynamic Resource Exchange (DRE) and how does it work?
- How does the DRE perform in practice?

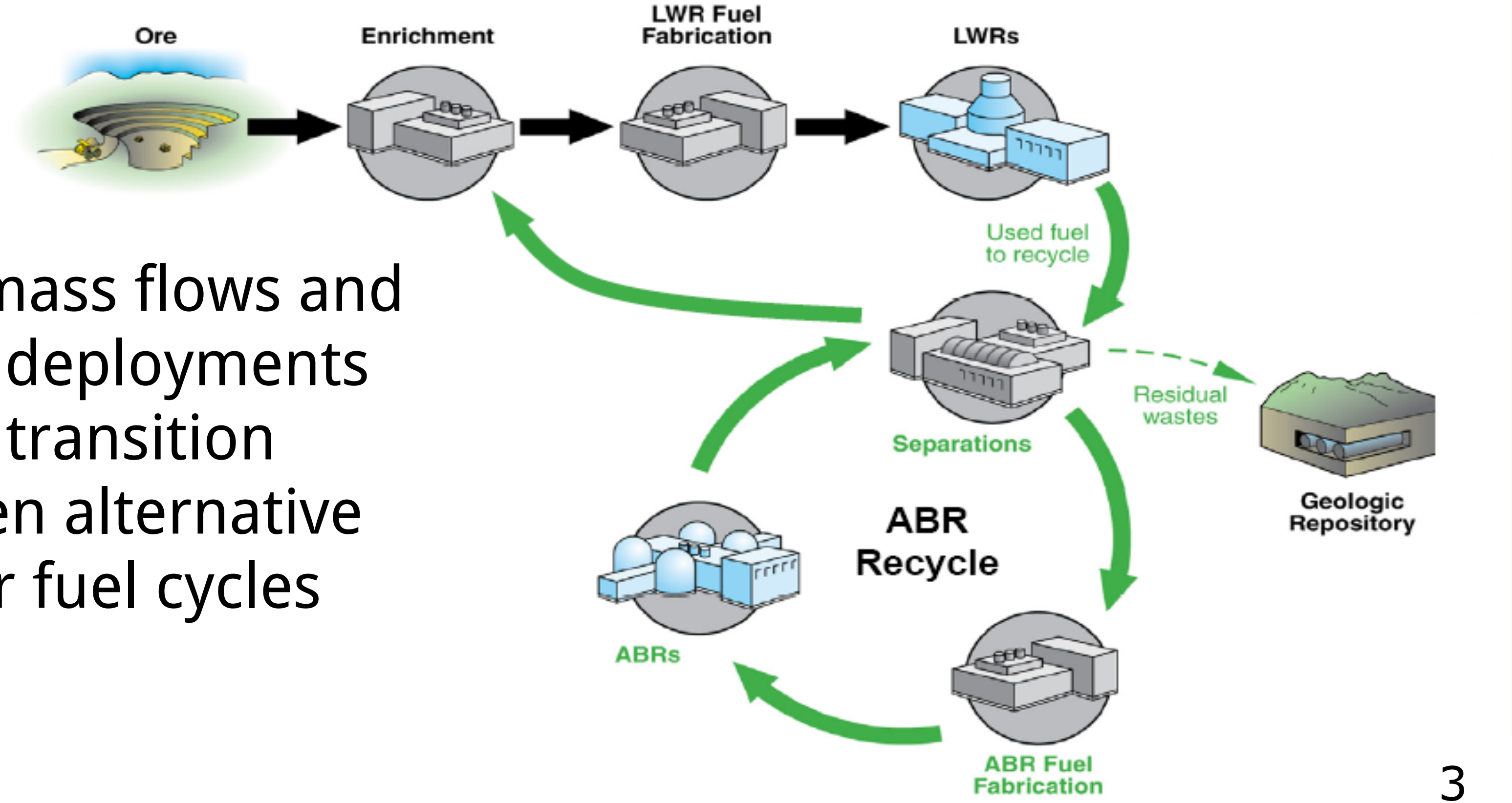
Fuel Cycle Simulator - Purpose



- Track mass flows and facility deployments during transition between alternative nuclear fuel cycles

Fuel Cycle Simulator - Purpose

- Track mass flows and facility deployments during transition between alternative nuclear fuel cycles



Difficulties

- Reactor performance (e.g., cycle length, safety margins) depend on fuel <u>isotopics</u>
- Commodities (i.e., elements, isotopes) are <u>fungible</u>
- Supply chain with <u>recycling</u>
- Reactors use fuel <u>assemblies</u>

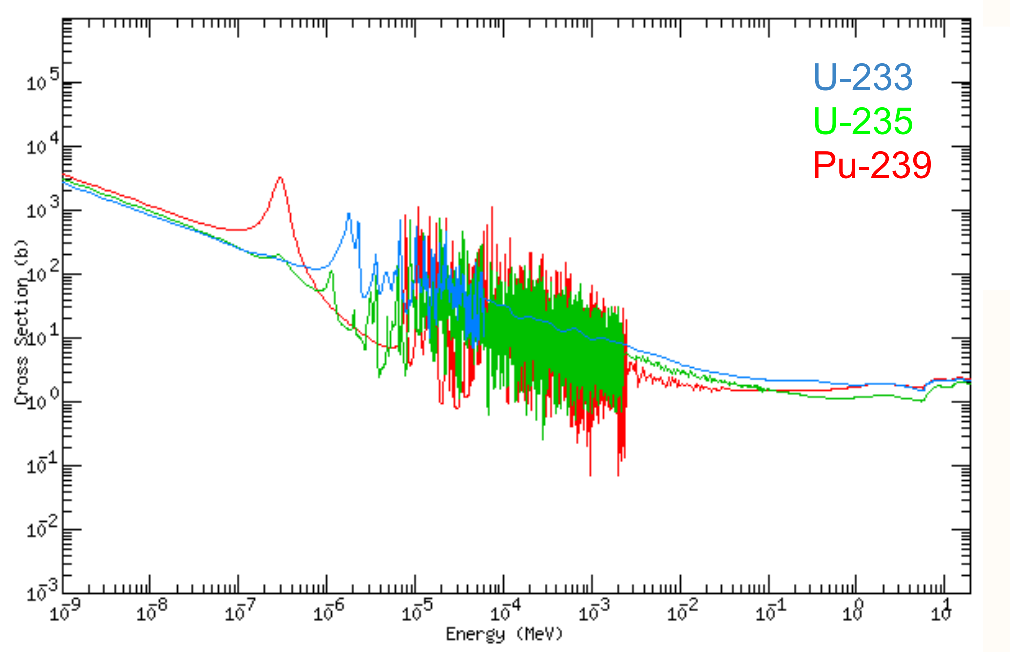


Fig: Fission Cross Section [1]

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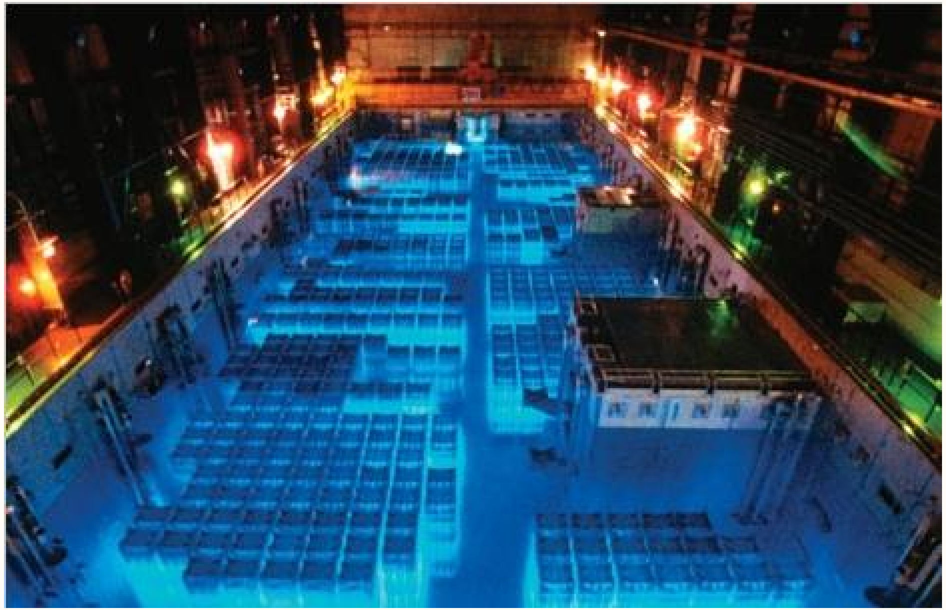


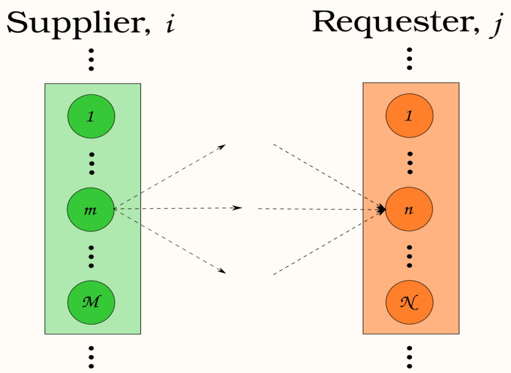
Fig: Used Fuel Assemblies [2]

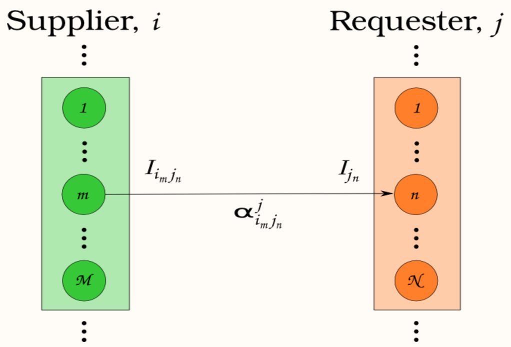
Dynamic Analysis

- Properties
  - Number, type of reactors is function of time
  - Fuel inventories is a function of simulation history
  - “endless number” of possible fuel cycles
  - Regional/Institutional effects
- Cyclus Approach
  - Discrete time
  - Agent-based modeling (individual facilities)
  - Resources have a quality (isotopics)
  - Discrete resource flow
  - Resource flow determined dynamically
  - http://fuelcycle.org/

Dynamic Resource Exchange

- DRE: Core algorithm for fuel cycle simulation
- Recomputed at each time step
- Solves economic problem dynamically; no hard-coded supply-demand behavior
- Treats arbitrarily complicated fuel cycles





DRE Phases

Request for Bids

Queries each requesting Agent in the simulation that ***demands*** a resource

Response to Request for Bids

Queries each responding Agent in the simulation that ***supplies*** a resource

Preference Adjustment

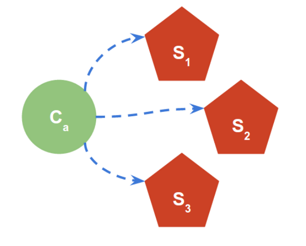
Agent ***reviews*** all matches; opportunity for preference adjustment

Solution

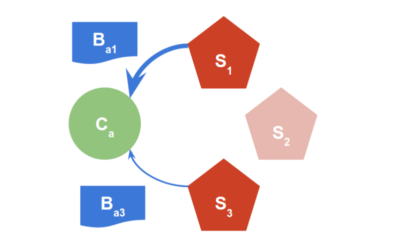
Matches ***selected*** for satisfiable requests

Trade Execution

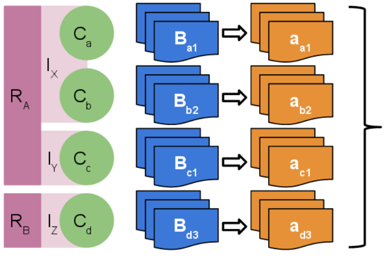
Material ***transaction*** takes place



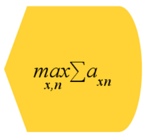
Phase 1: Request for bids



Phase 2: Response to request for bids



Phase 3: Preference Adjustment



Phase 4: Market Resolution

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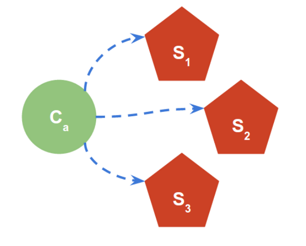

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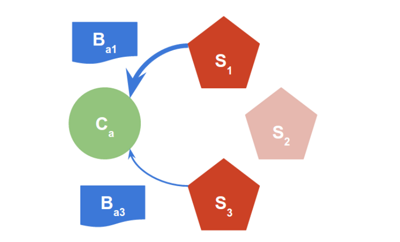
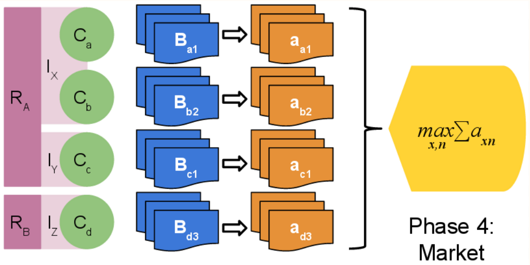


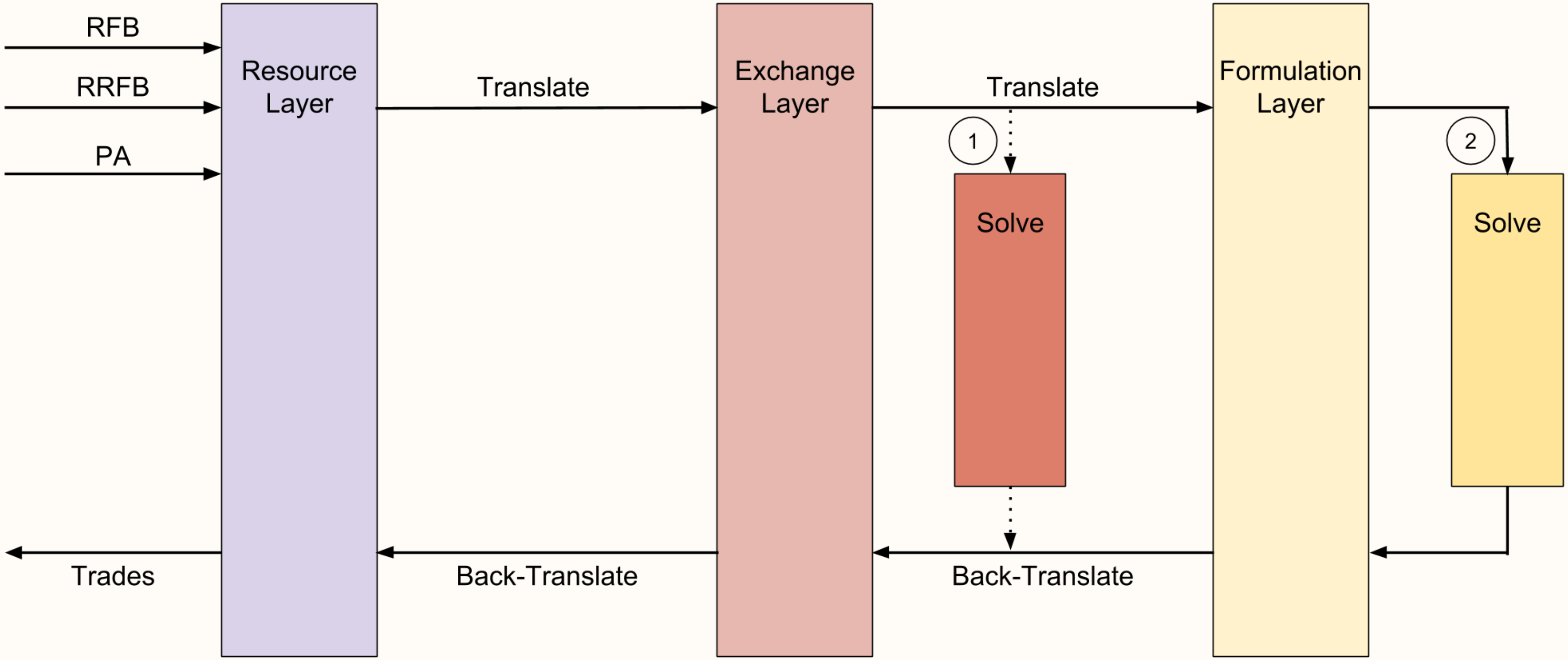
Phase 2: Response to request for bids



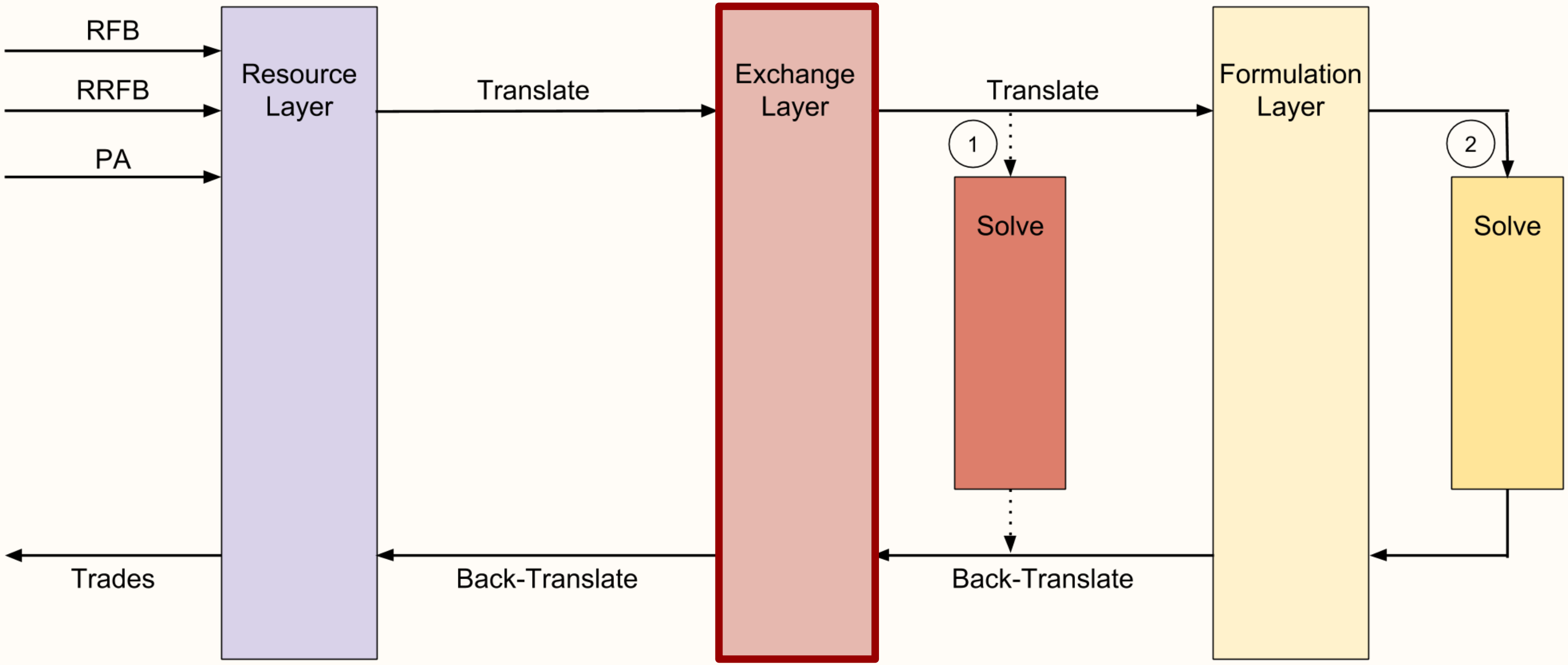
Phase 3: Preference Adjustment

Phase 4: Market Resolution

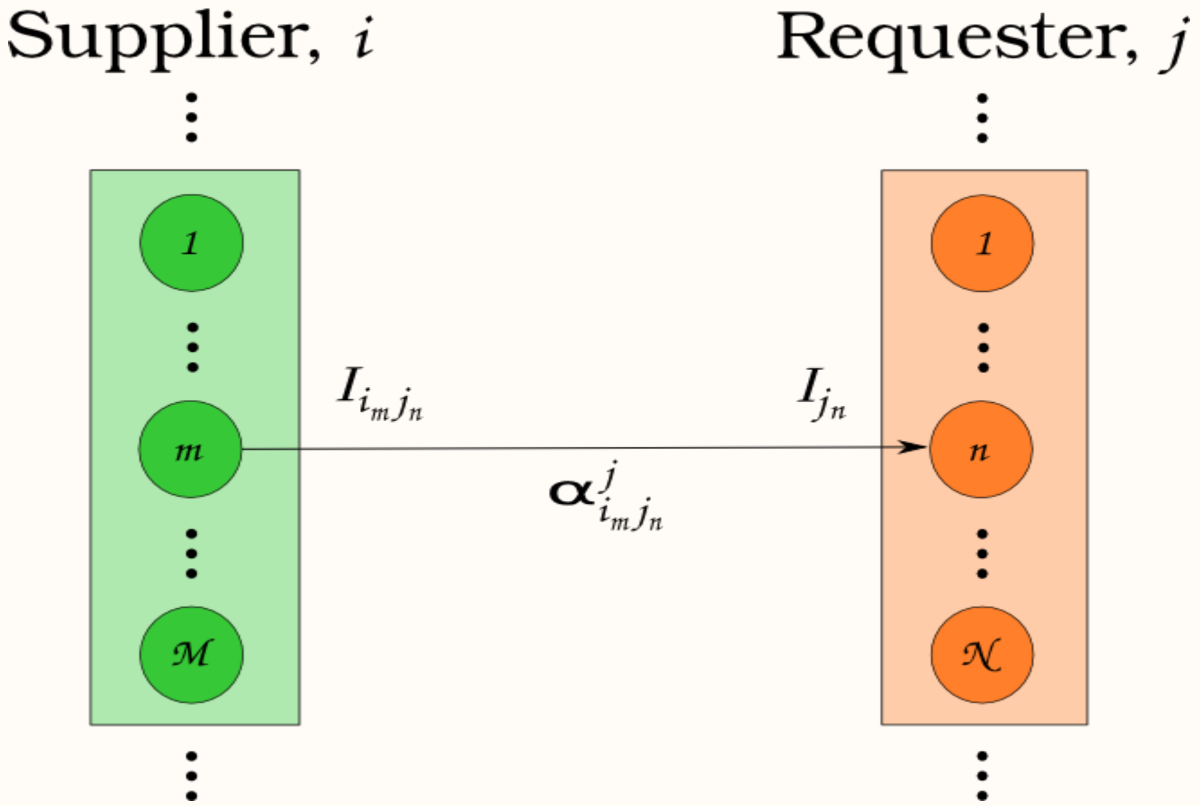
DRE Framework



DRE Framework



DRE Bipartite Graph



DRE Constraints

- Agents define conversion functions for constraint coefficients
  - input: proposed resource quality
  - output: unit capacity coefficient
- Allows arbitrary physics/chemistry fidelity

$$\sum_{j \in J} f_{SWU}(\varepsilon_j) x_{i,j}^{EU} \leq s_{i,SWU}$$

$$\sum_{j \in J} f_{NU}(\varepsilon_j) x_{i,j}^{EU} \leq s_{i,NU}$$

$$\sum_{j \in J} \beta_{i,k}(q_j^h) x_{i,j}^h \leq s_{i,k}$$

$$\sum_{j \in J} a_{i,j}^k x_{i,j} \leq b_i^k$$

DRE Constraints

- Requests and bids can be *mutually exclusive*
- Given set of possible connections, only one allowed

$$\sum_{(i,j)\in M_s} y_{i,j} \leq 1$$

$$\sum_{(i,j)\in M_r} y_{i,j} \leq 1$$

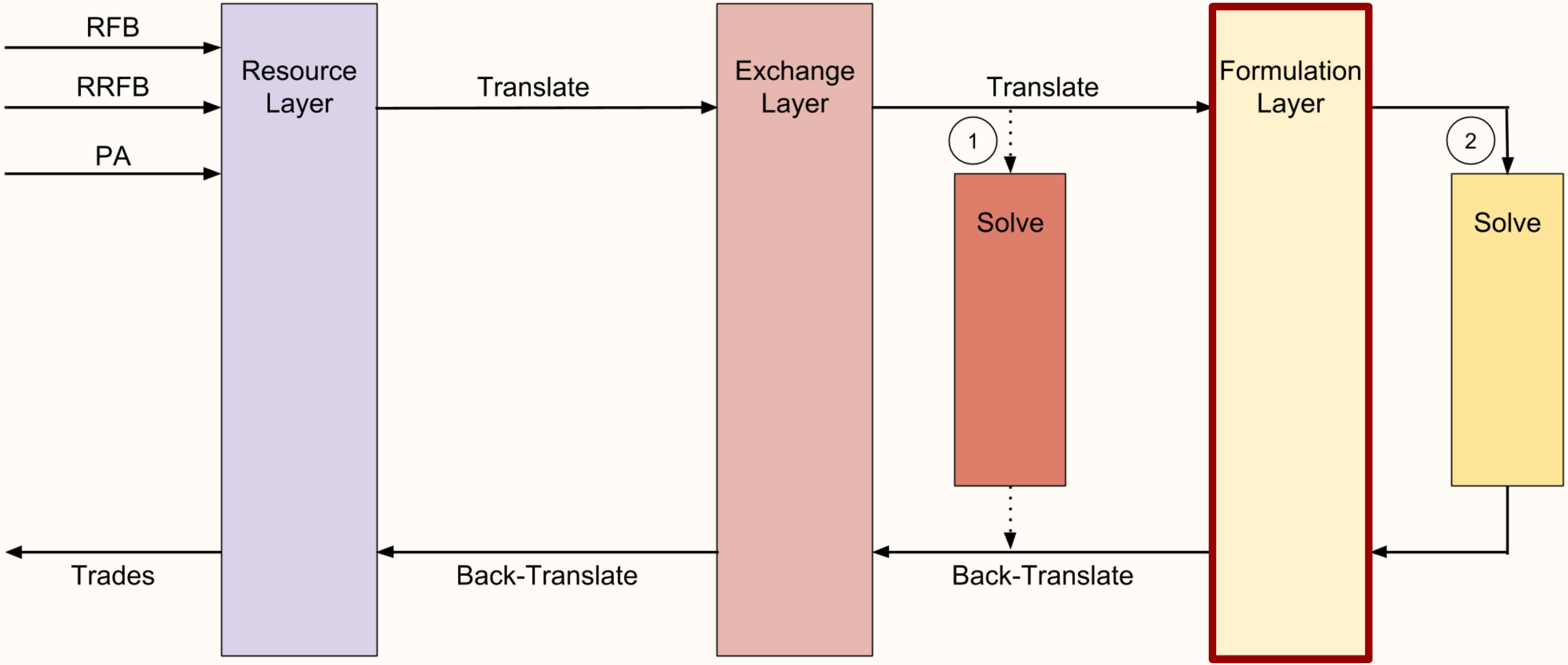
DRE Solution

- Using Heuristics
  - Match arcs subject to supply constraints
  - Allows for exclusive trades
- Formulated as Multicommodity Transportation Problem (MTP) Variant
  - Use false arcs to guarantee feasible solution
  - Translate preferences to costs
  - LP or MILP
  - MILP allows for exclusive trades

Greedy Solver Algorithm

```
order request portfolios by average preference;
forall the request portfolios do
    order requests by average preference;
    matched ← 0;
    while matched ≤ q_J and ∃ a request do
        get next request;
        order arcs by preference;
        while matched ≤ q_J and ∃ an arc do
            get next arc;
            remaining ← q_J - matched;
            to_match ← min{remaining, Capacity(arc)};
            matched ← matched + to_match;
        end
    end
end
```

DRE Framework



LP Formulation

Variable	Description
S, s	Suppliers
I, i	Bids
R, r	Requesters
J, j	Requests
K, k	Capacities
c	Cost of commodity
x	Decision variable
a	Capacity coeff.
b_s	Supply capacity
b_r	Demand capacity

$$\min_x \quad z = \sum_{i \in I} \sum_{j \in J} c_{i,j} x_{i,j}$$

$$\text{s.t.} \quad \sum_{i \in I_s} \sum_{j \in J} a^k_{i,j} x_{i,j} \leq b^k_s \qquad \forall\, k \in K_s, \forall\, s \in S$$

$$\sum_{j \in J_r} \sum_{i \in I} a^k_{i,j} x_{i,j} \geq b^k_r \qquad \forall\, k \in K_r, \forall\, r \in R$$

$$x_{i,j} \in [0, \tilde{x_j}] \qquad \forall\, i \in I, \forall\, j \in J$$

MILP vs. LP

Strict subsets of suppliers and consumers:

1. those that require *exclusive* orders
2. those that allow *partial* orders

$$A = \bigcup_{r \in R} A_{p_r} \cup A_{e_r}$$

Introduce a **binary variable**, $y_{i,j}$:

- 1 if resource is sent by supplier *i* to consumer *j*

MILP Formulation

Variable	Description
A_p	Partial-order arcs
A_e	Exclusive-order arcs
M	Mutually-exclusive arcs
$\tilde{x}$	Exclusive-arc quantity
x, y	Decision variable

$$\min_{x,y} \; z = \sum_{(i,j)\in A_p} c_{i,j} x_{i,j} + \sum_{(i,j)\in A_e} c_{i,j} \tilde{x}_j y_{i,j}$$

$$\text{s.t.} \quad \sum_{(i,j)\in A_{p_s}} a^k_{i,j} x_{i,j} + \sum_{(i,j)\in A_{e_s}} a^k_{i,j} \tilde{x}_j y_{i,j} \le b^k_s \qquad \forall\, k \in K_s, \forall\, s \in S$$

$$\sum_{(i,j)\in M_s} y_{i,j} \le 1 \qquad \forall\, s \in S$$

$$\sum_{(i,j)\in A_{p_r}} a^k_{i,j} x_{i,j} + \sum_{(i,j)\in A_{e_r}} a^k_{i,j} \tilde{x}_j y_{i,j} \ge b^k_r \qquad \forall\, k \in K_r, \forall\, r \in R$$

$$\sum_{(i,j)\in M_r} y_{i,j} \le 1 \qquad \forall\, r \in R$$

$$x_{i,j} \in [0, \tilde{x}_j] \qquad \forall\, (i,j) \in A_p$$

$$y_{i,j} \in \{0, 1\} \qquad \forall\, (i,j) \in A_e$$

Experimental Framework

- Two exchange types: Front-End, Back-End
- Three fuel cycles (f_{fc}: 0, 1, 2)
  - Once through
  - MOX recycle with thermal and fast reactors
  - MOX/THOX recycle with thermal and fast reactors
- Reactors modeled using assemblies or batches (f_{rx}: 0, 1)
- Commodity and location-based (f_{loc}: 0, 1, 2)
- Solve with Greedy Heuristic, Clp, Cbc

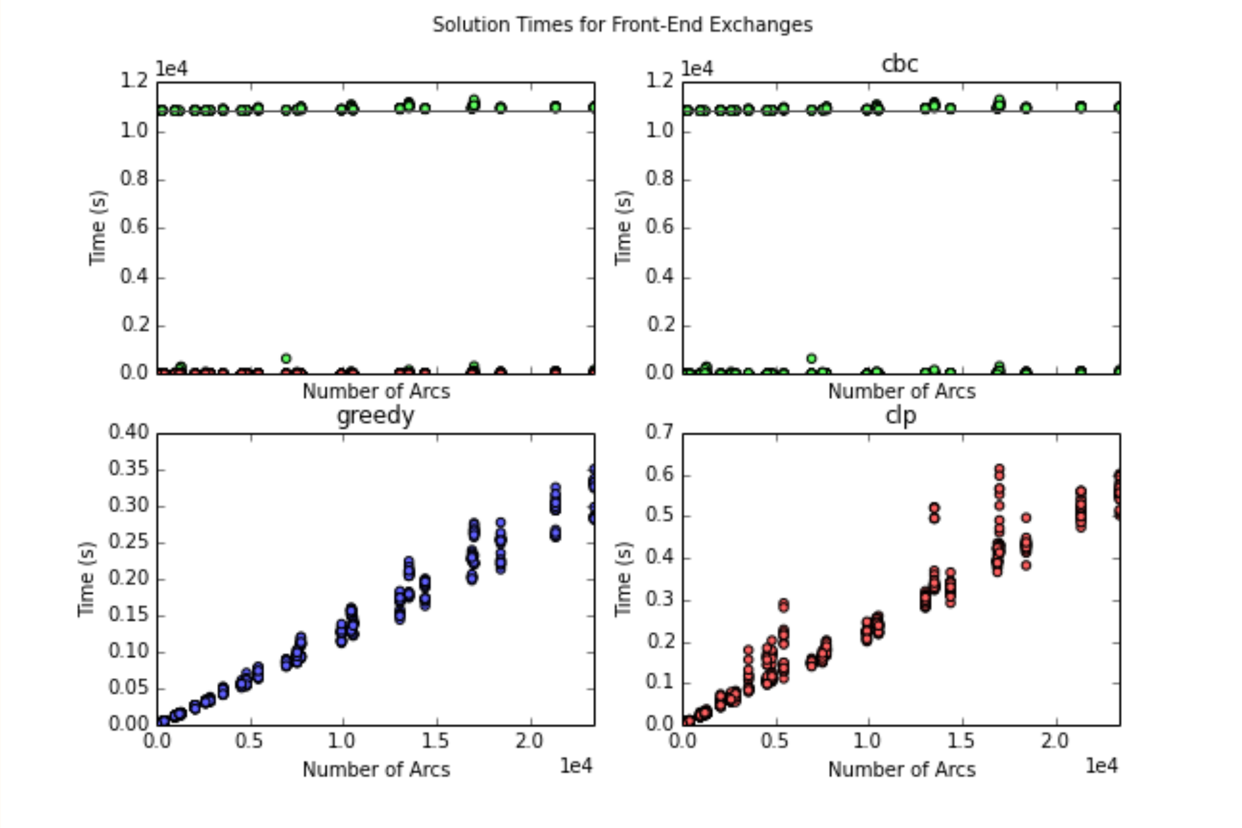
Experimental Framework

- Stochasticity
  - Location assignment
  - Reactor fuel enrichment
- Constraint coefficients function of commodity and enrichment
- Objective coefficients function of commodity and location

$$p(i,j) = p_c(i,j) + r_{l,c} p_l(i,j)$$

$$p_l(i,j) = \delta_{\text{reg}} \frac{\exp(-|\text{reg}_i - \text{reg}_j|) + \delta_{\text{loc}} \exp(-|\text{loc}_i - \text{loc}_j|)}{1 + \delta_{\text{loc}}}$$

Scoping Study, $f_{rxtr} = 0$



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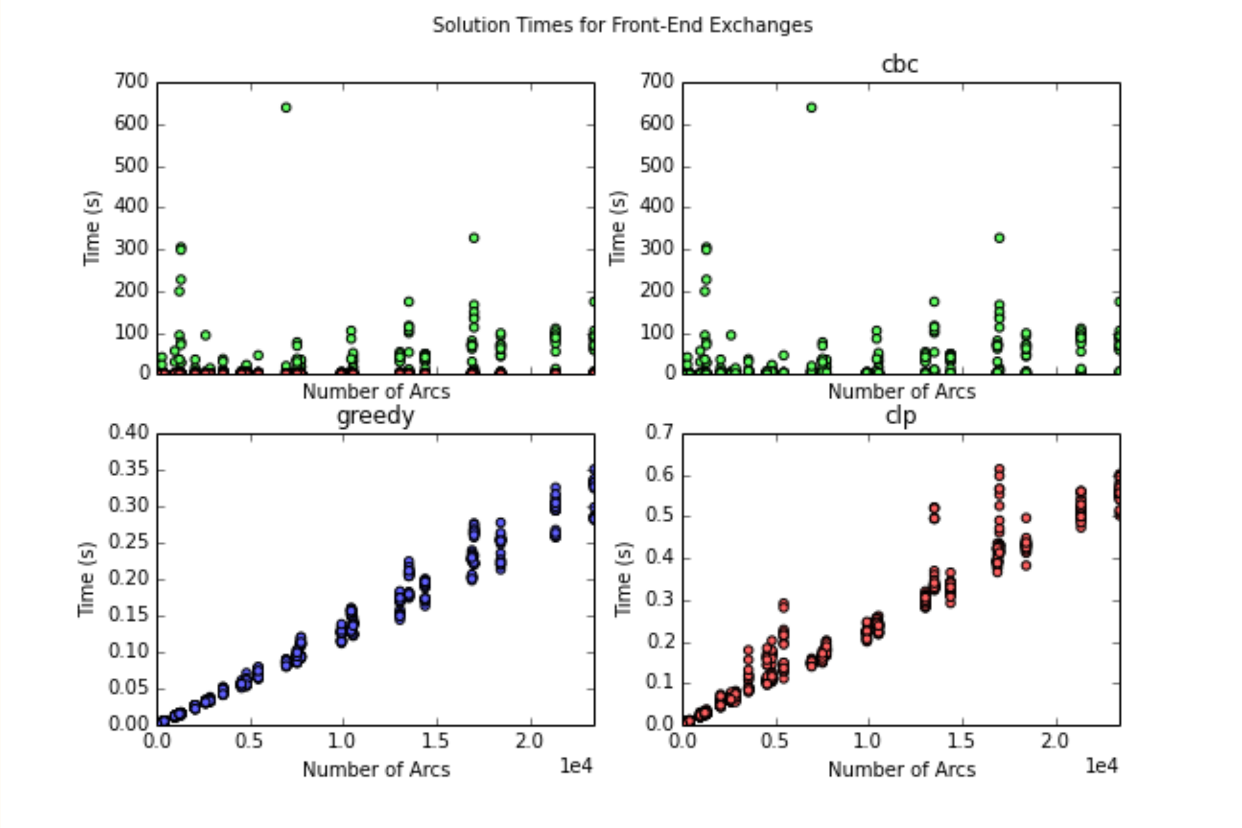

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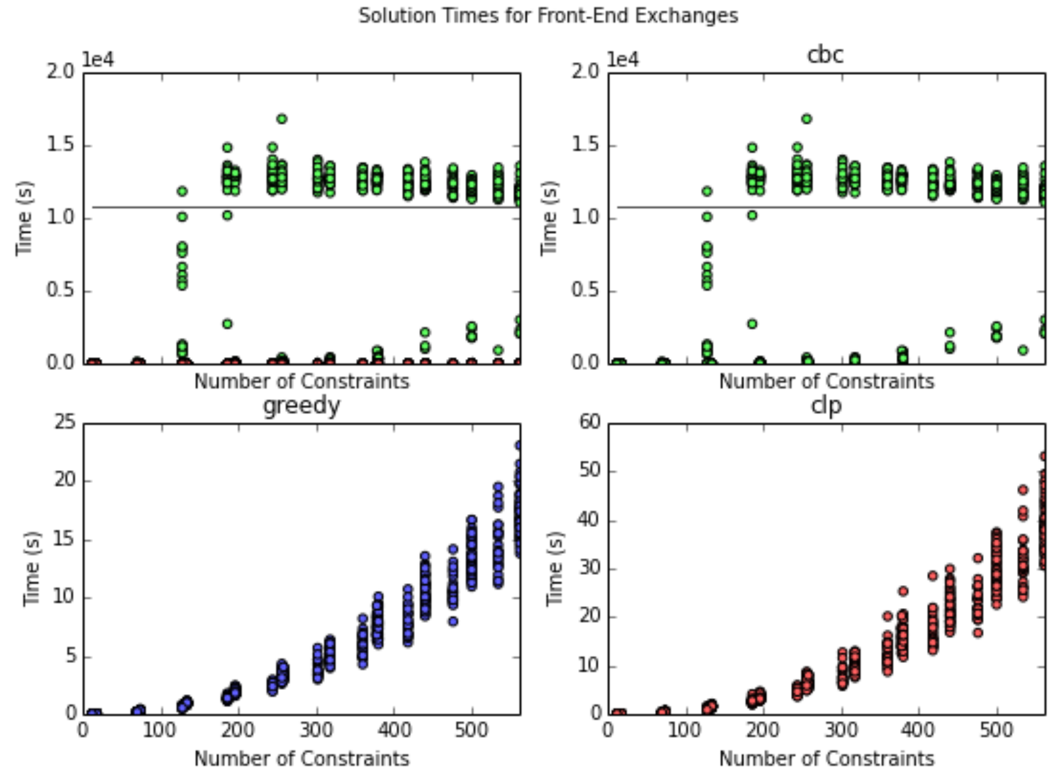

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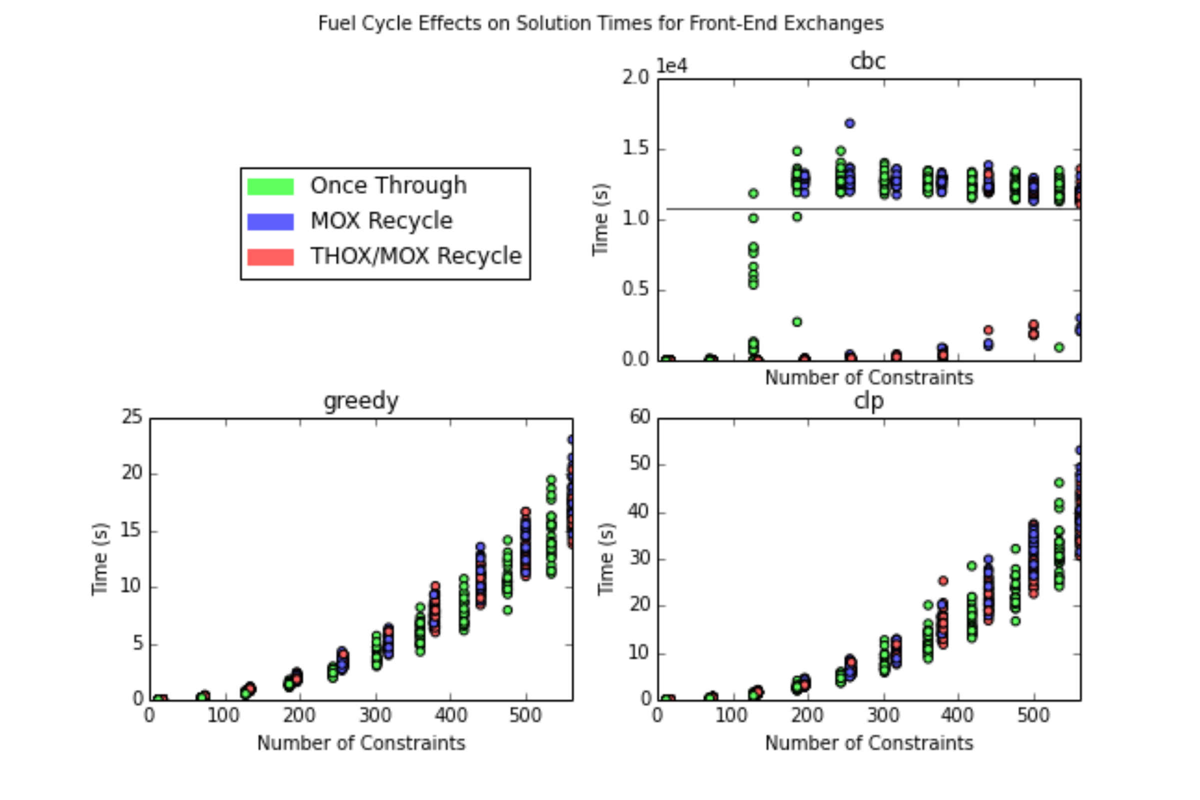

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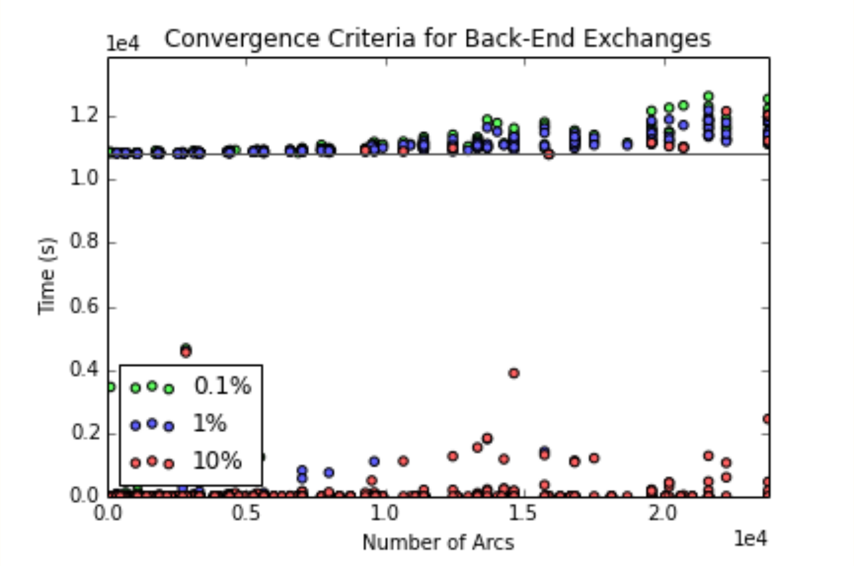

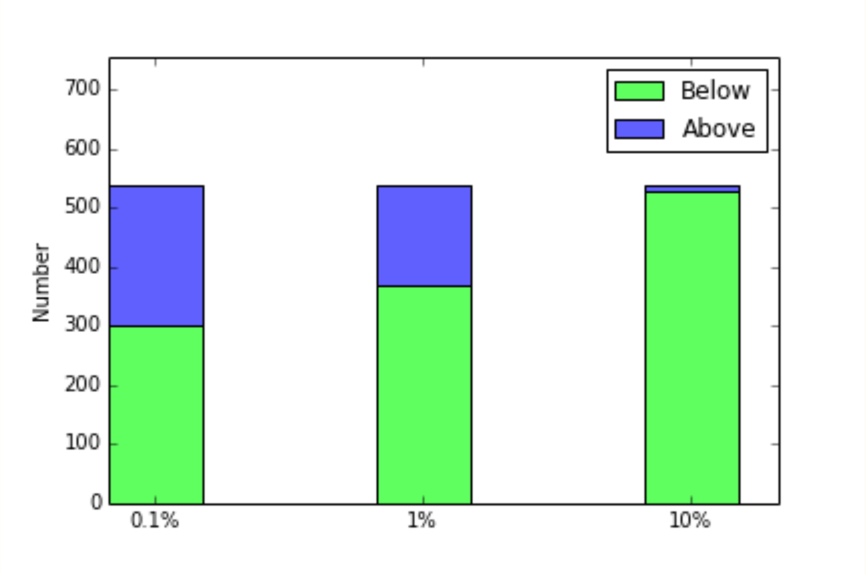

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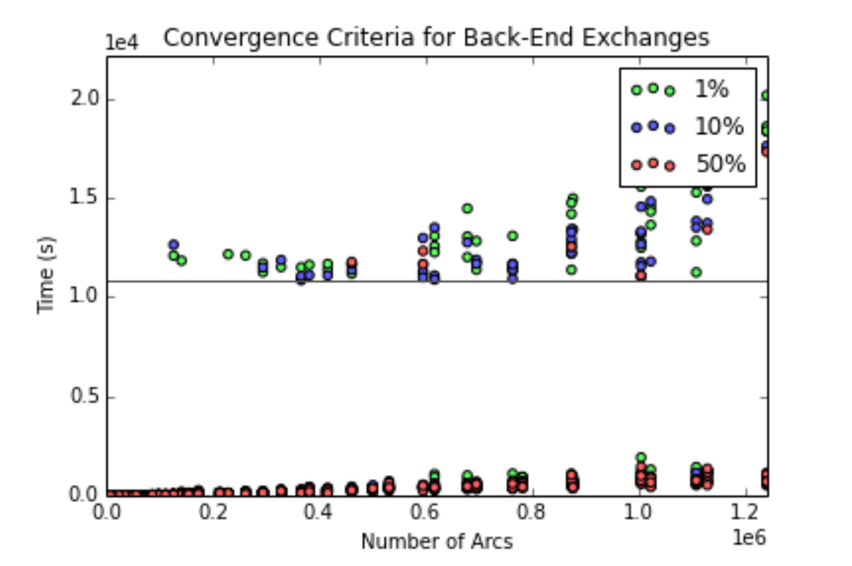
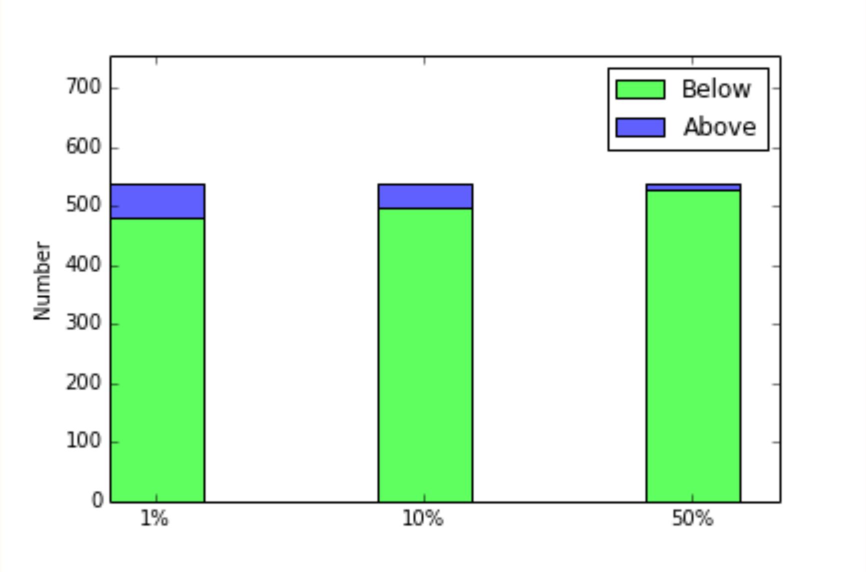
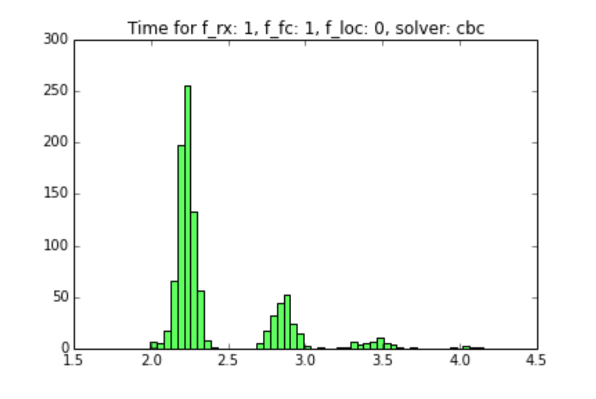
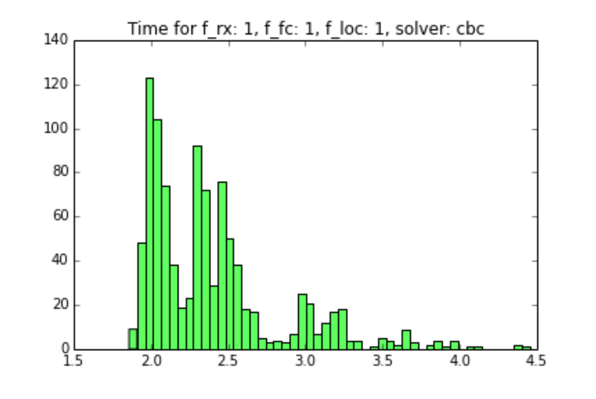
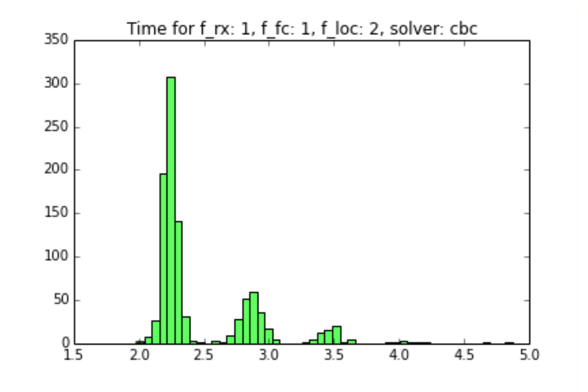




Stochastic Study, Front-End

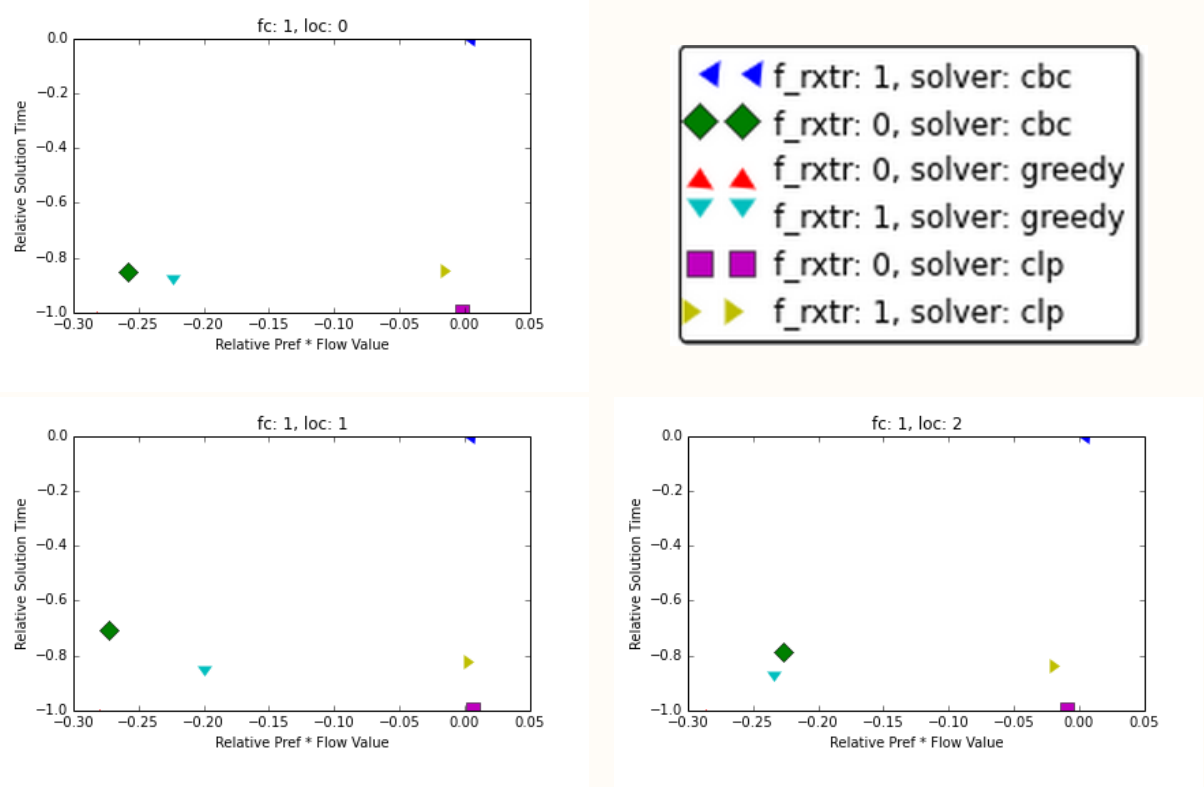






- ~17,500 variables
- ~100 constraints

Stochastic Study, Front-End



Conclusions

- Dynamic, physics-informed supply and demand framework designed and implemented
- Large-scale, high-throughput experimental apparatus designed and implemented
- Characteristics of solutions can vary greatly based on fuel cycle, reactor fidelity, and how preferences are modeled
- Time for some simulation!

Acknowledgements

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Citations

[1] Korea Atomic Energy Institute Table of Nuclides, http://atom.kaeri.re.kr/, accessed 29-10-2014

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[3] Essential Physics for Fuel Cycle Modeling & Analysis. Scopatz, A. Dissertation. Dec., 2011.