Autonomous Trading in Modern Electricity Markets

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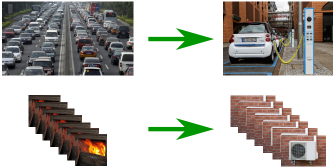
Learning Agents Research Group
The University of Texas at Austin

Modern Electricity Markets?

Transition into Low Carbon Economies

Consumption



$\Longrightarrow$ Increased demand

Transition into Low Carbon Economies

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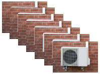

Production

$\Longrightarrow$ Intermittent supply

Transition into Low Carbon Economies

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 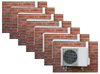

Production

 

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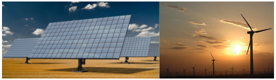
Challenges the current electricity infrastructure

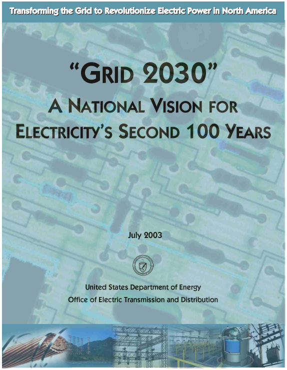
The Smart Grid Vision

- "Grid 2030" - vision for a smart-grid
  - Smart-grid will enable sustainable, clean, efficient, reliable, secure energy supply.



- AI: a main building block
- Smart-grid: new challenges for AI

[Ramchurn et. al 2012]



Proposed and Actual Applications Domains

- Two of the “Grid 2030” milestones:
  - “Intelligent homes and appliances linked to the grid”
    Application domain 1: Smart-thermostat control
    [ECML-13, AAMAS-13]
  - “Customer participation in power markets through demand-side management and distributed generation”
    Application domain 2: Autonomous electricity trading

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New Power Markets

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New Power Markets

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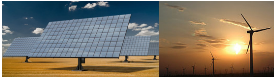
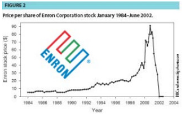
- Power markets will financially incentivize sustainable behaviors
- Demand-side management will adapt demand to supply conditions
- Distributed generation can add efficient, clean, robust supply



- California energy crisis (2001), east-coast blackout (2003)



Potential Risks

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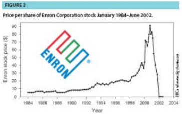

- Needed: low-risk platform for testing
  - Retail power market designs
  - Related automation technologies

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- Power TAC (Power Trading Agent Competition)

The Power Trading Agent Competition (Power TAC)

- Grid 2030 milestone:

  > "Customer participation in power markets through demand-side management and distributed generation"

- Power TAC (Power Trading Agent Competition)
  - Uses a rich smart grid simulation platform
  - Focuses on retail power markets structure and operation
  - Competitors: autonomous broker agents

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  - Do that in real-time

Application domain: Autonomous Electricity Trading

Challenges

Application domain: Autonomous Electricity Trading

- Sequential decision making in a complex domain

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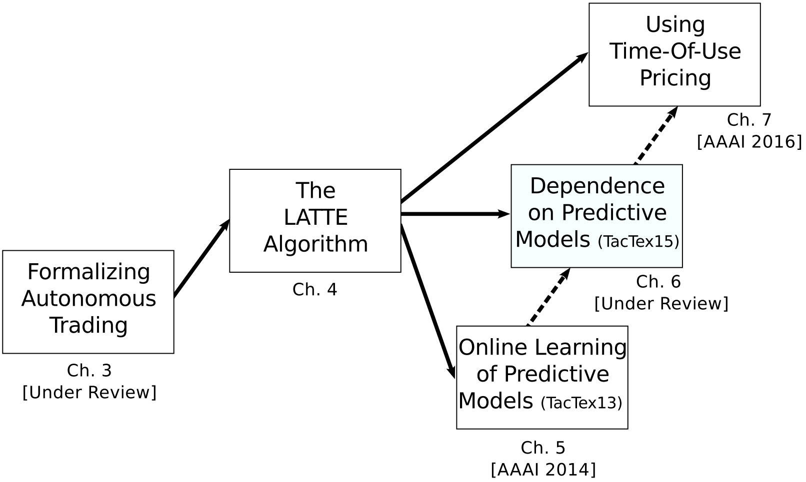
- Sequential decision making in a complex domain
- Specifically [Russell and Norvig, 2009]
  - high-dimensional
  - partially-observable
  - multiagent
  - competitive
  - stochastic
  - sequential
  - dynamic
  - continuous
  - initially-unknown

Dissertation Research Question

Research Question:

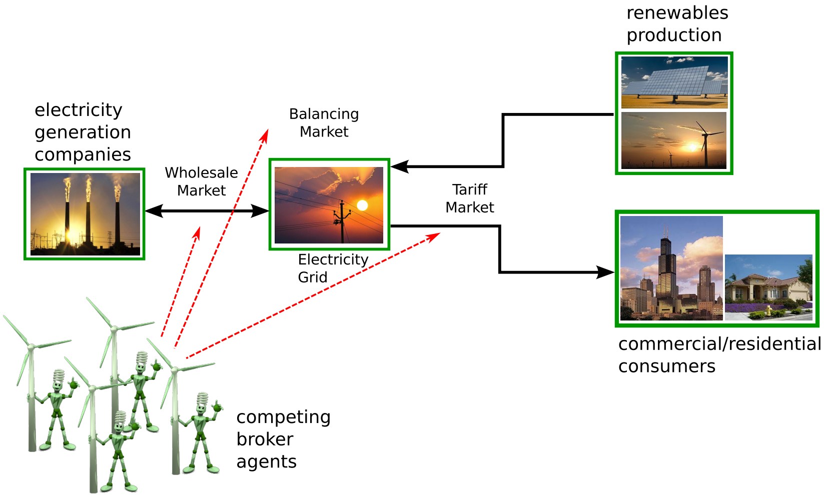
How should an autonomous broker agent act to maximize its utility by trading in time-constrained, modern electricity markets?

Dissertation Structure



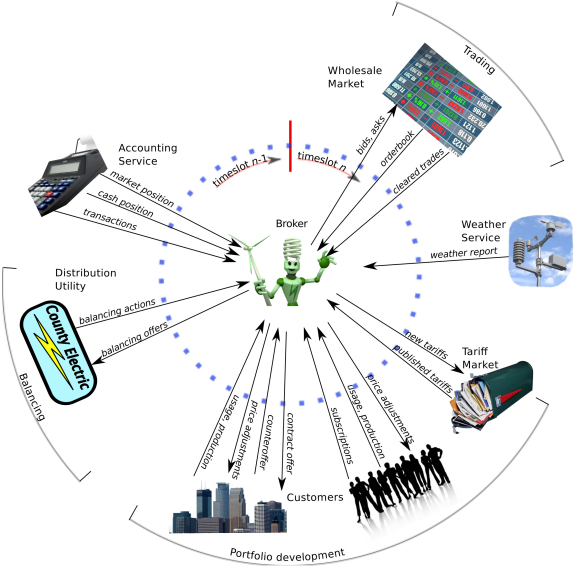
Substrate Domain

Power TAC: Rich Energy Markets Simulation



General Agent Sensing and Acting

Broker Sensing and Acting



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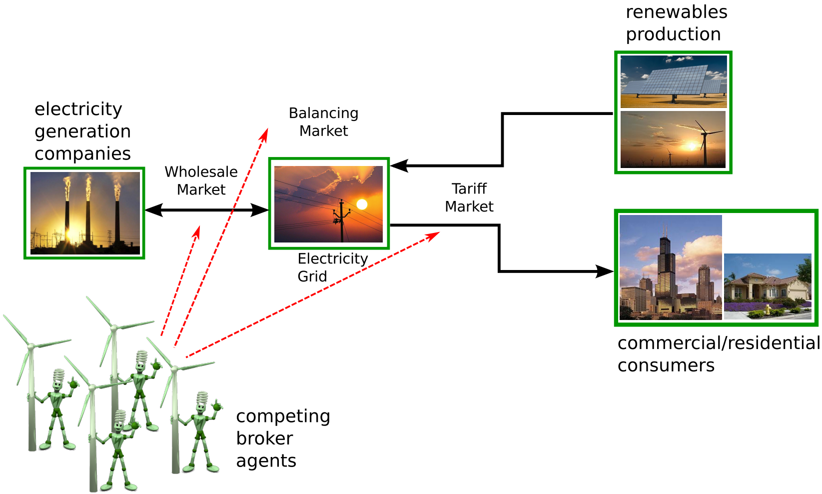
renewables
production
electricity
generation
companies
Balancing
Market
Wholesale
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consumers
competing
broker
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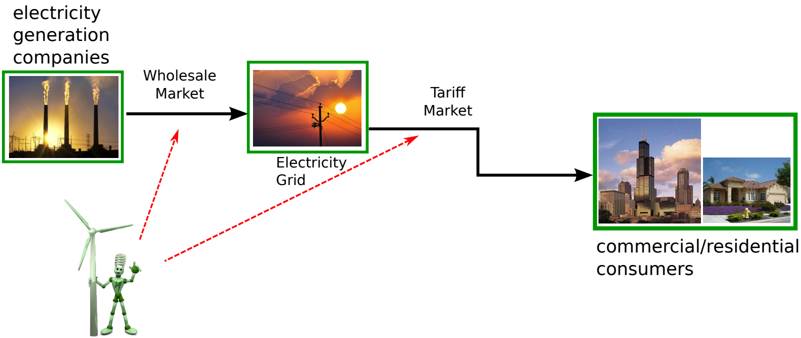
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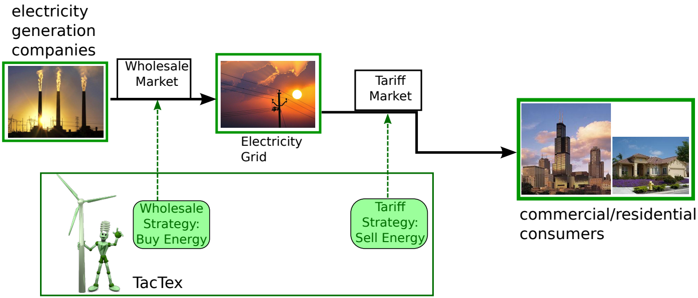
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TacTex

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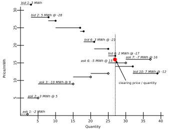

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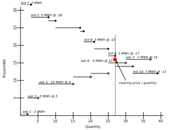

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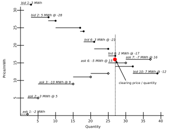

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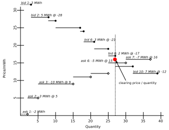

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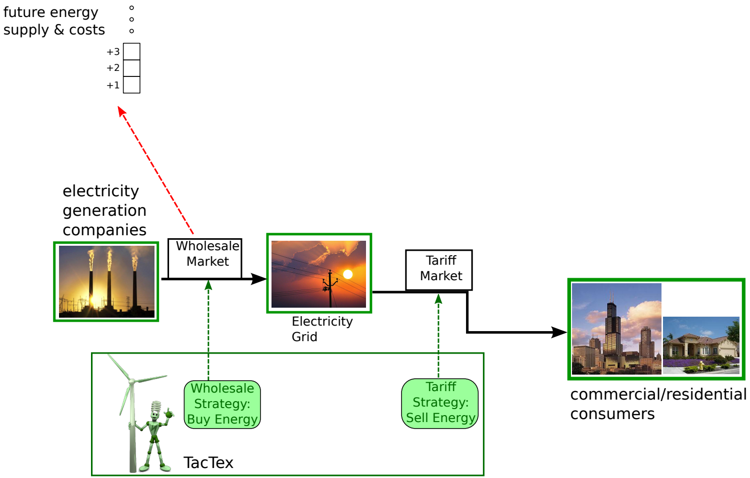
Challenge: what bidding strategy to use?

Power TAC


future energy
supply & costs
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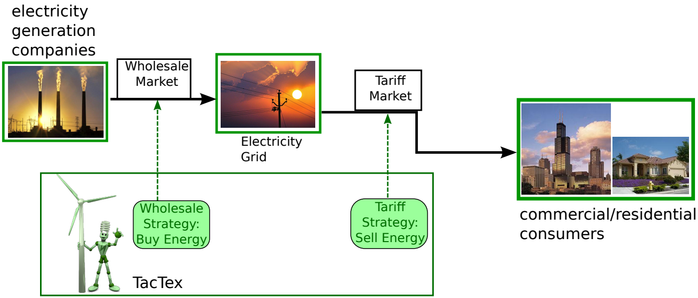
Challenge: what tariffs should a broker publish?

Power TAC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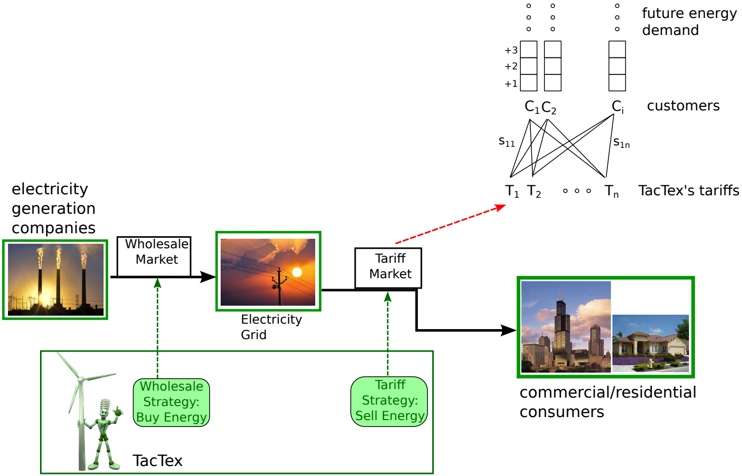

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C_1 C_2
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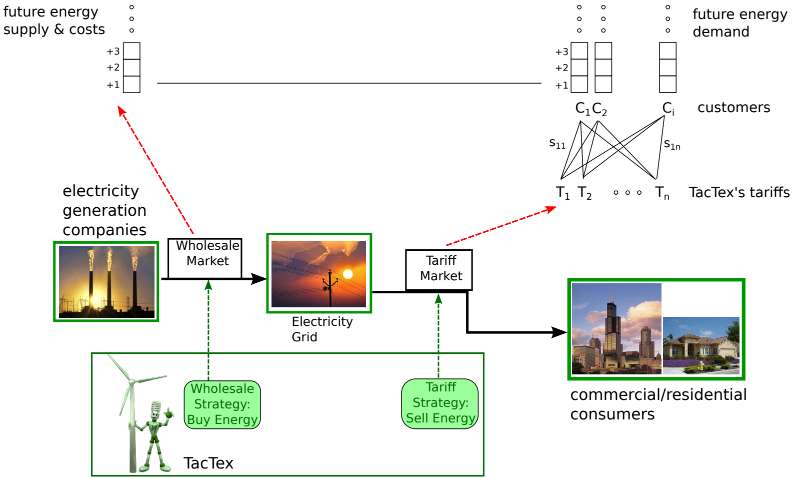

future energy supply & costs
+3
+2
+1
future energy demand
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C_1 C_2
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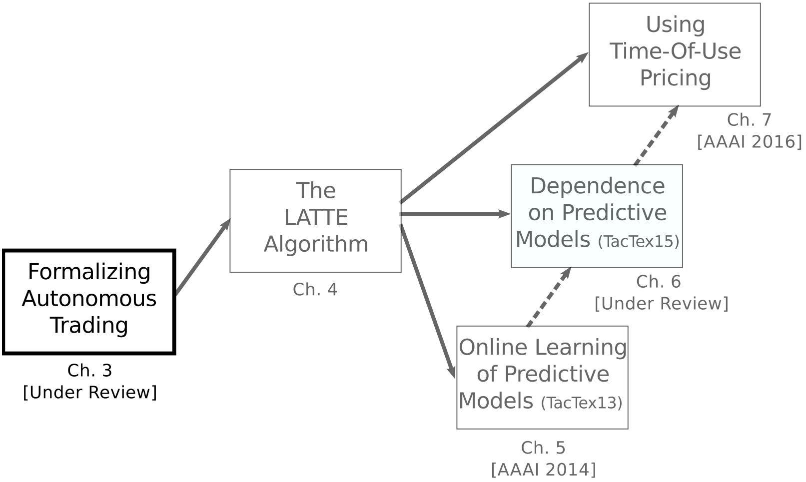

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- We model it as a (large) MDP
  - Treating hidden state as environment stochasticity

Power TAC Game State

$$\langle t, \mathcal{B}, \mathcal{C}, \mathcal{P}, \mathcal{T}, \mathcal{S}_{B_0}, \mathcal{Q}_{B_0}, \mathcal{A}_{B_0}, I_{B_0}, \mathcal{W}, \$_{B_0}, \mathcal{R} \rangle$$

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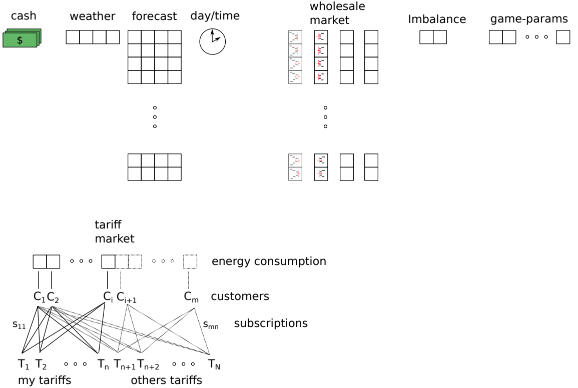

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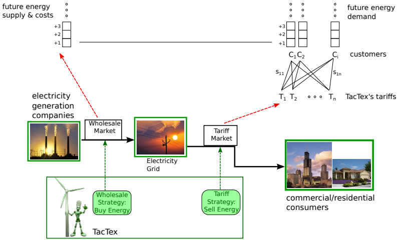
- Wholesale actions: continuous, high-dimensional
  - 2 parameters per action, 10s of actions

Transition Function and Reward Function



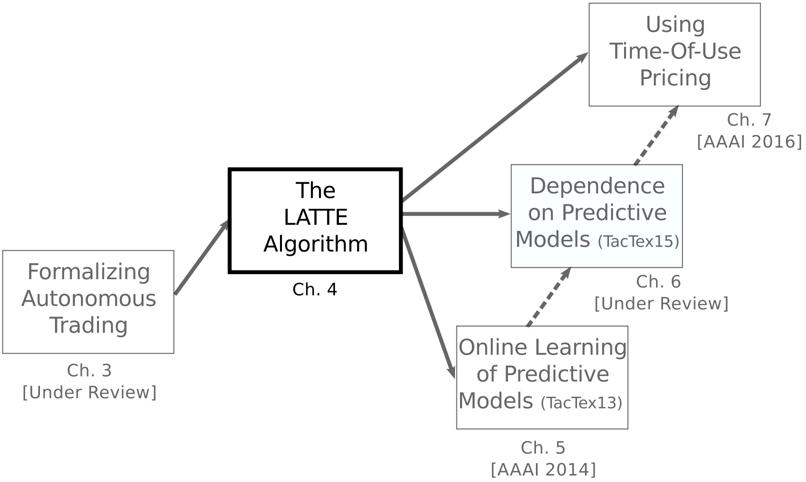
$$r_t(s_{t-1}, t-1, s_t) :=$$

$$\underbrace{Q_t^{cons} p_t^{cons} - Q_t^{prod} p_t^{prod}}_{r^{\tau}(s_t)} + \underbrace{Q_t^{ask} p_t^{ask} - Q_t^{bid} p_t^{bid}}_{r^{\omega}(s_t)} \underbrace{\pm bal(I_{B_0,t})}_{r^{\beta}(s_t)}$$

$$\underbrace{-max(Q_t^{cons}, Q_t^{prod}) \times distFee}_{dist(s_t)} \underbrace{-pub(t-1) - rev(t-1) \pm psw(\mathcal{S}_{B_0,t-1}, \mathcal{S}_{B_0,t})}_{fees(s_{t-1},t-1,s_t)} \quad (1)$$

- Power TAC 2013: 1st place
- Power TAC 2015: Best-Agent*
- Power TAC 2015 post-finals demo: 1st place

Dissertation Structure



TacTex: Approach

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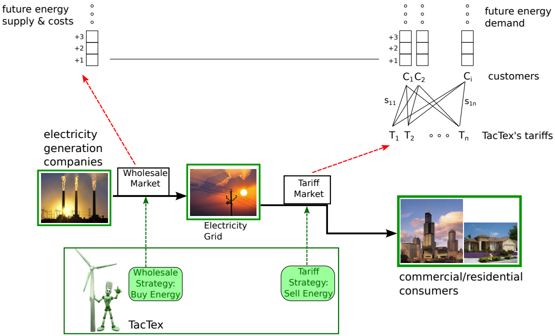
  - Domain non-stationary
  - Unclear relationship between state $\rightarrow$ action
  - Hard to approximate a value function
- Addresses large state spaces, but not large action spaces

Lookahead Policy: Large Action Spaces

- How to optimize action combinations?
  - How to sample actions efficiently?
  - How to combine actions efficiently?



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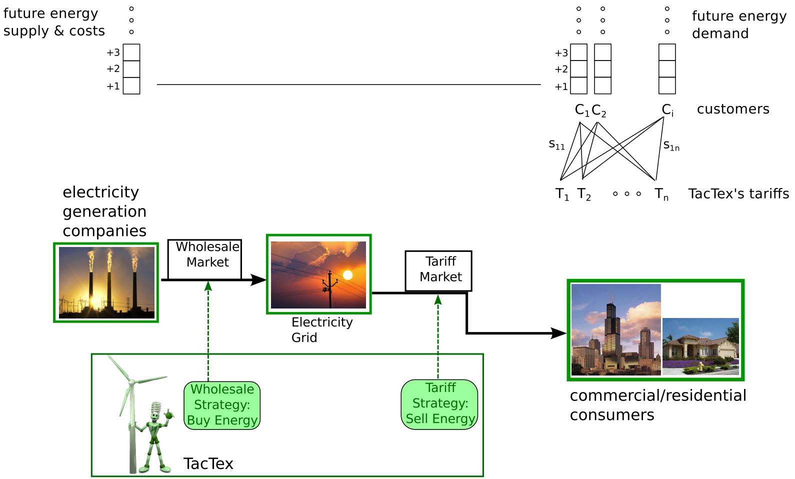
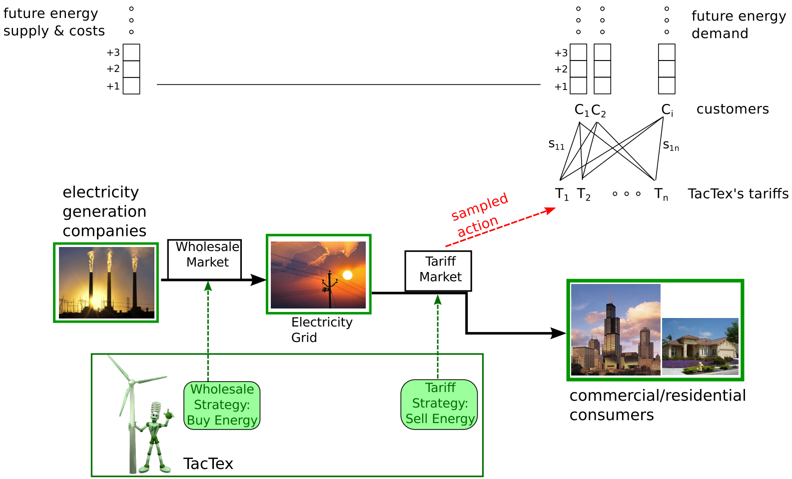
- A general algorithm for autonomous electricity trading
- Can be instantiated in different ways
- LATTE is the main algorithm used by TacTex

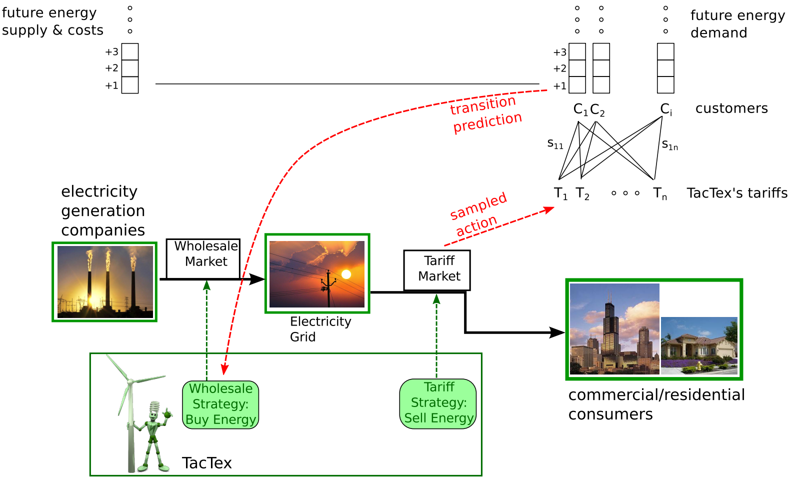
LATTE: Sampling and Combining Actions



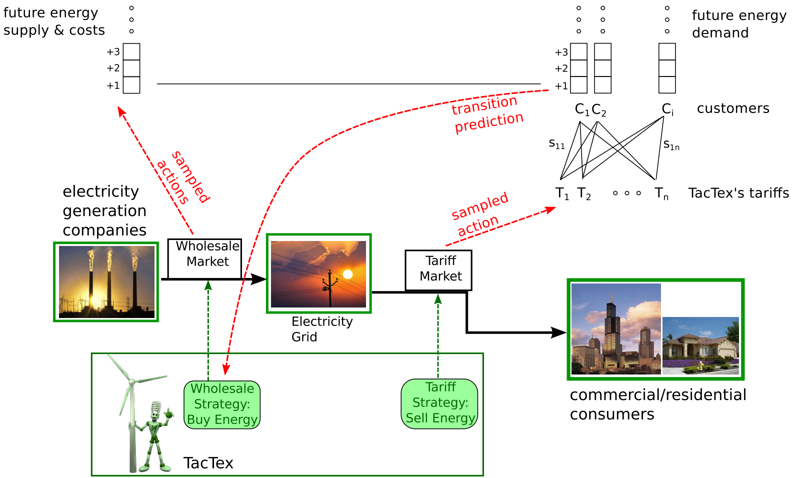
LATTE: Sampling and Combining Actions



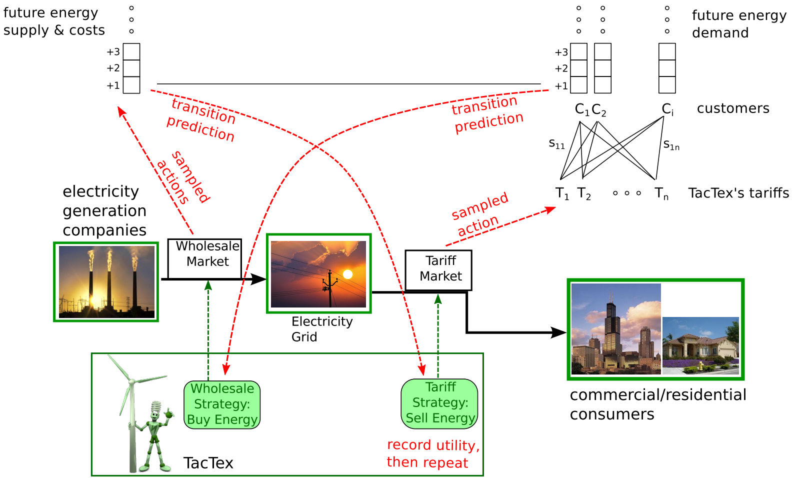
LATTE: Sampling and Combining Actions



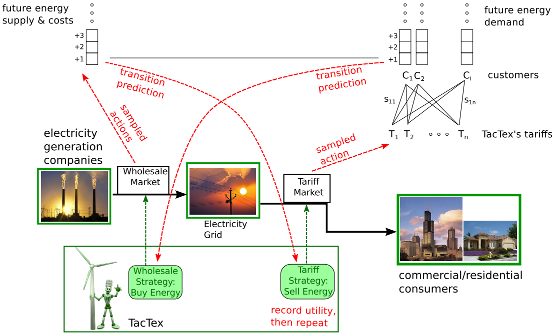
LATTE: Sampling and Combining Actions



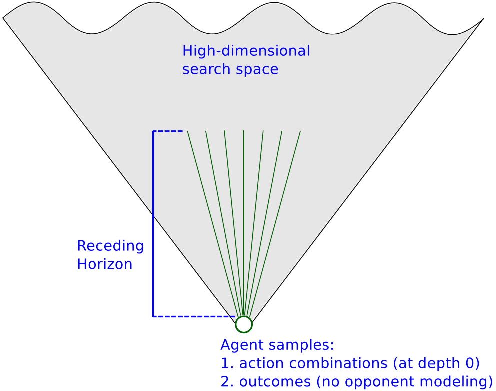
LATTE: Sampling and Combining Actions



- How to optimize action combinations?
  - How to sample actions efficiently?
  - How to combine actions efficiently?



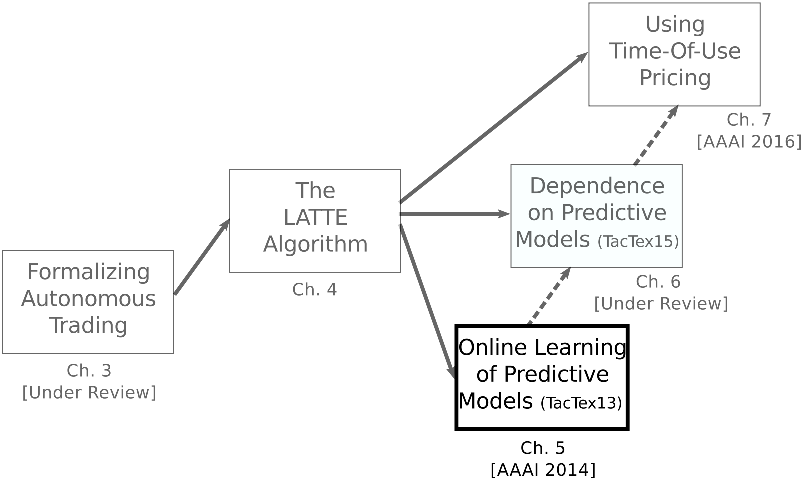
LATTE: Monte-Carlo, Receding Horizon Policy



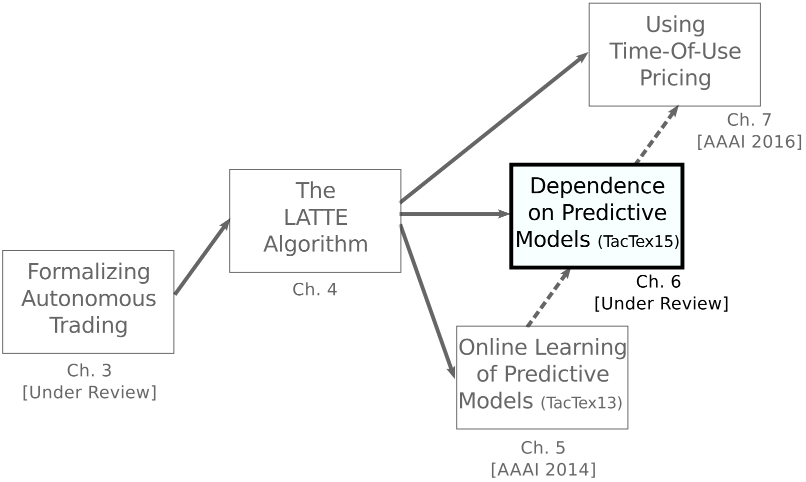
LATTE as a Monte-Carlo, receding horizon policy:

- Action sampling: only at depth 0
- Outcome sampling: any, but we use "expected" transitions
- Horizon length: fixed ("receding horizon")

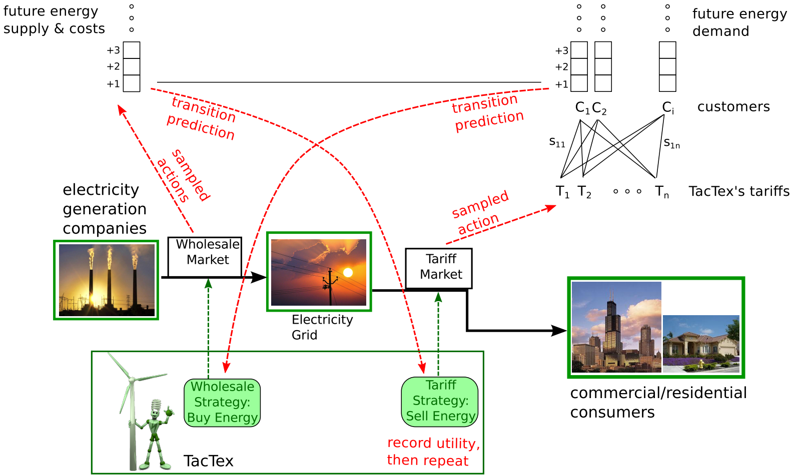
Dissertation Structure



Dissertation Structure



TacTex'15


future energy supply & costs
+3
+2
+1
future energy demand
customers
C_1 C_2 C_i
s_{11}
s_{1n}
T_1 T_2 T_n
TacTex's tariffs
transition prediction
transition prediction
sampled actions
sampled action
electricity generation companies
Wholesale Market
Electricity Grid
Tariff Market
commercial/residential consumers
Wholesale Strategy: Buy Energy
Tariff Strategy: Sell Energy
TacTex
record utility, then repeat

TacTex'15: Competition Results

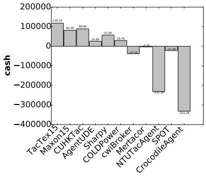
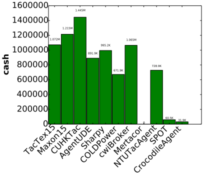
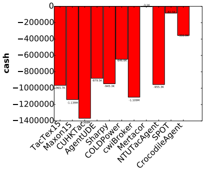
- Power TAC 2015: Best-Agent*

Broker	11-broker	9-broker	3-broker	Total	11-broker (z)	9-broker (z)	3-broker (z)	Total (z)
Maxon15	186K	3.7M	80.7M	84.5M	0.611	0.801	1.990	3.402
TacTex	488K	5.2M	38.8M	44.4M	0.897	1.066	0.258	2.221
CUHKTac	557K	4.0M	35.1M	39.6M	0.962	0.859	0.106	1.927
AgentUDE	-15K	1.2M	52.1M	53.2M	0.421	0.367	0.809	1.597
Sharpy	-6K	2.6M	45.1M	47.7M	0.429	0.614	0.521	1.564
COLDPower	307K	1.3M	14.3M	16.0M	0.726	0.397	-0.751	0.371
cwiBroker	-462K	-1.6M	43.8M	41.7M	-0.002	-0.120	0.465	0.343
Mertacor	-23K	-0.1M	32.2M	-0.1M	0.413	0.142	-1.341	-0.786
NTUTacAgent	-1533K	-10.4M	43.5M	31.5M	-1.017	-1.638	0.453	-2.202
SPOT	-1570K	-2.3M	7.5M	3.6M	-1.052	-0.243	-1.032	-2.327
CrocodileAgent	-2981K	-13.9M	-3.3M	-20.2M	-2.387	-2.244	-1.479	-6.111

- Power TAC 2015 (post-finals demo): 1st place

Broker	4-broker	4-broker (z)
TacTex	15.0M	1.122
Maxon15	10.7M	0.627
CUHKTac	10.0M	0.537
AgentUDE	9.7M	0.509
cwiBroker2015	7.9M	0.297
Sharpy	4.6M	-0.092
COLDPower	-0.8M	-0.724
SPOT	-14.0M	-2.276

TacTex'15: 2015 Competitions

<table>
<tr><th>Game size</th><th>Profit</th><th>Revenue</th><th>Costs</th></tr>
<tr><td>9-broker</td><td>
</td><td>
</td><td>
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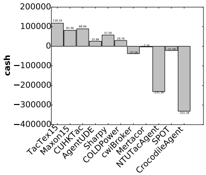
<td>
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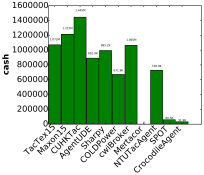
<td>
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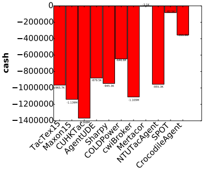
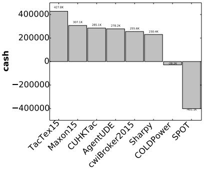
<td>
</td></tr>
<tr><td>4-broker</td>
<td>
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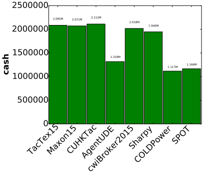
<td>
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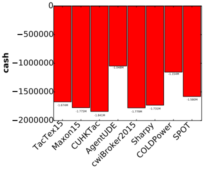
<td>
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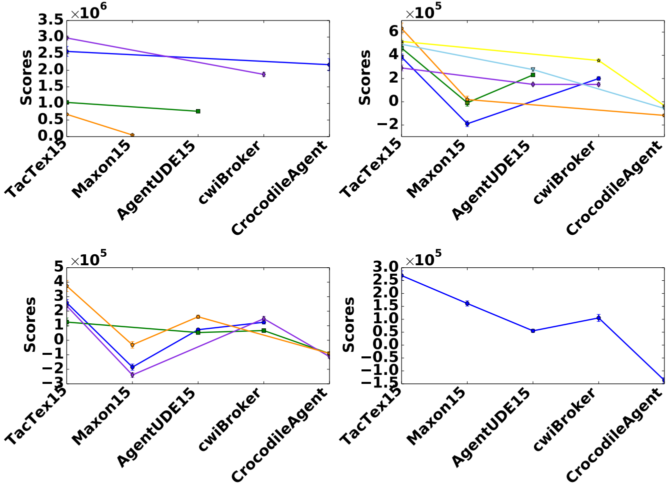
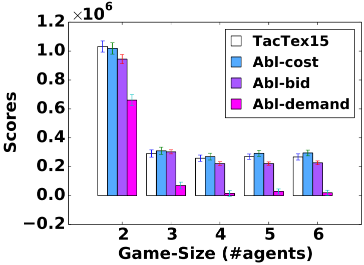


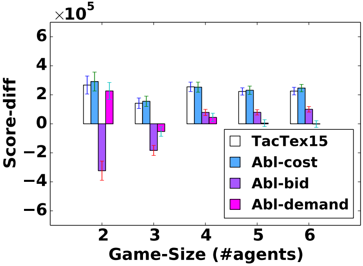
Performance of TacTex'15 against Power TAC 2015 finalists in controlled experiments of game-sizes of 2-5.

TacTex'15: Ablation Analysis

Average scores:

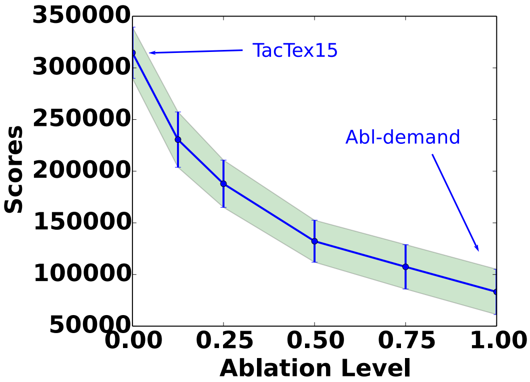


Average score difference:



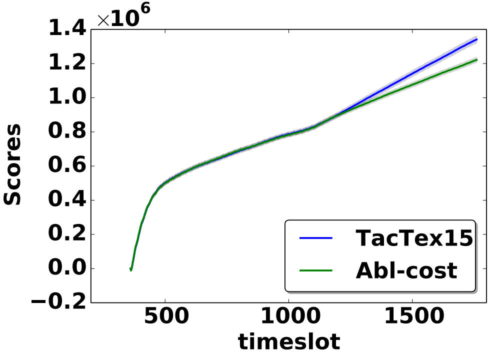
- Ablated agents created from TacTex'15:
  - **Abl-cost**: cost-predictor replaced with TacTex13's
  - **Abl-bid**: bidding-strategy replaced with TacTex13's
  - **Abl-demand**: demand-predictor replaced with TacTex13's

Demand Predictor Ablation

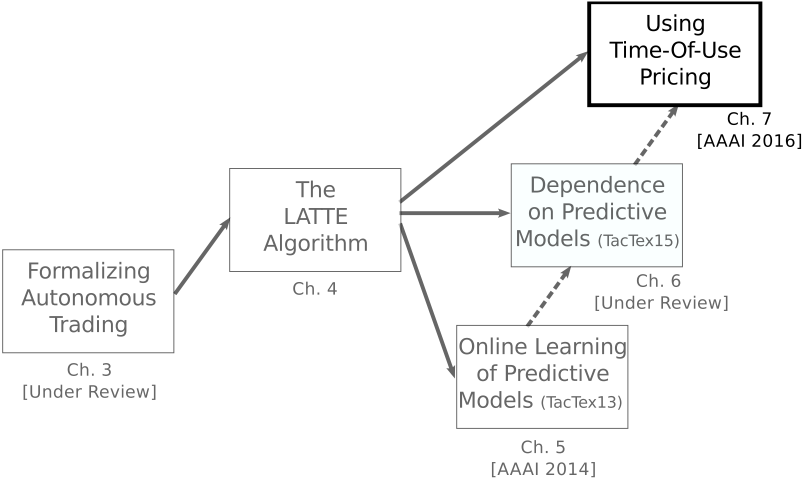


Gradual demand predictor ablation in 3-agent games

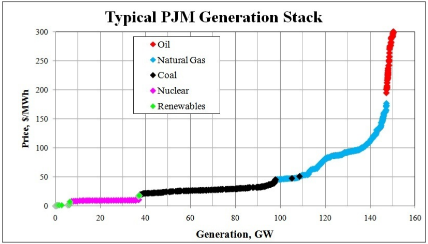
Cost Predictor Ablation



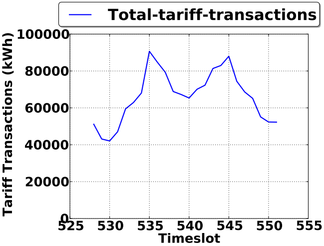
TacTex'15 cost predictor is quicker to adapt to changing costs


Using
Time-Of-Use
Pricing
Ch. 7
[AAAI 2016]
The
LATTE
Algorithm
Ch. 4
Dependence
on Predictive
Models (TacTex15)
Ch. 6
[Under Review]
Formalizing
Autonomous
Trading
Ch. 3
[Under Review]
Online Learning
of Predictive
Models (TacTex13)
Ch. 5
[AAAI 2014]

The Problem with Peaked Demand



Cost as a function of generation



24-hour demand

Autonomous Electricity Trading using Time-Of-Use Tariffs in a Competitive market

- Time-Of-Use (TOU) Pricing Schemes:
  - Goal: adapt demand to energy availability

Autonomous Electricity Trading using Time-Of-Use Tariffs in a Competitive market

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    [Desert Sun, May 2015]

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  - In monopoly market: saves costs

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    [Desert Sun, May 2015]
  - In monopoly market: saves costs
  - In competitive market: less attractive for customers

TOU vs. Fixed-Rate Tariffs

For TOU to be competitive with fixed-rate tariffs, we need:

$$\underbrace{cost\left(T_{tou}, e_H^*\right) + w \times d\left(e_H, e_H^*\right)}_{TOU} \overset{?}{<} \underbrace{cost\left(T_{fixed}, e_H\right)}_{Fixed-Rate}$$

TOU vs. Fixed-Rate Tariffs

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Where

- $cost\left(T, e_H\right)$: cost of 24-hour consumption e_H under tariff τ
- e_H^*: optimally shifted energy profile
- w: weight representing cost-convenience trade-off
- $d\left(e_H, e_H^*\right)$: distance between desired and optimally-shifted profiles

TOU vs. Fixed-Rate Tariffs

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Questions:

- Can TOU tariffs benefit the broker?

TOU vs. Fixed-Rate Tariffs

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Questions:

- Can TOU tariffs benefit the broker?
- If TOU tariffs benefit broker, would they benefit the economy in competitive markets?

TOU vs. Fixed-Rate Tariffs

For TOU to be competitive with fixed-rate tariffs, we need:

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Questions:

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- If TOU tariffs benefit broker, would they benefit the economy in competitive markets?
- How should an autonomous agent design TOU tariffs?

TOU vs. Fixed-Rate Tariffs

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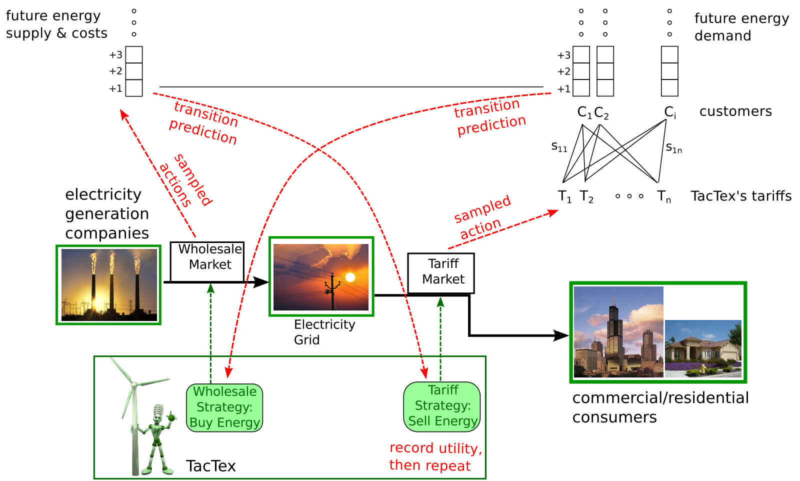
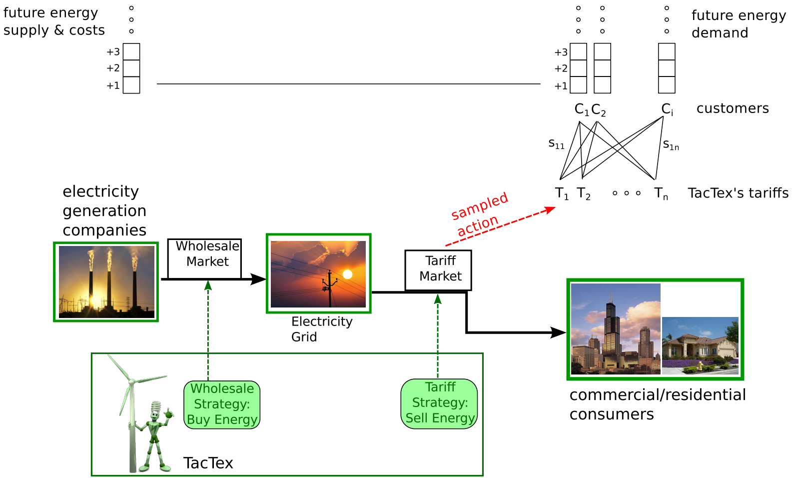
Questions:

- Can TOU tariffs benefit the broker?
- If TOU tariffs benefit broker, would they benefit the economy in competitive markets?
- How should an autonomous agent design TOU tariffs?
- Can we extend LATTE with TOU tariffs?

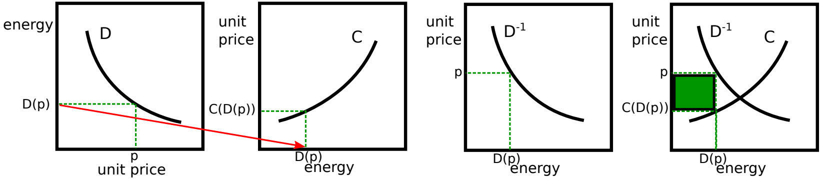
LATTE-TOU: Extending LATTE with Tariffs



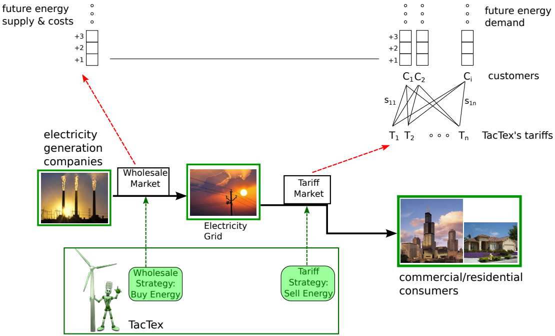
LATTE-TOU: Extending LATTE with Tariffs



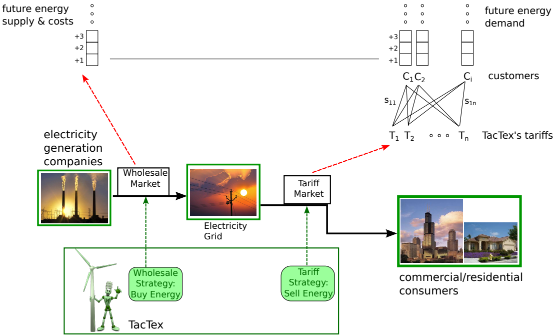
Demand and Unit-Cost Curves



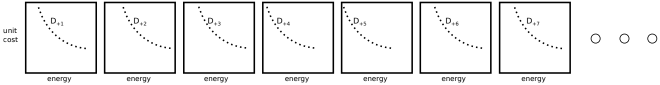
Utility Estimation - TOU Tariffs



- Fixed-rate tariffs
- TOU tariffs



- Fixed-rate tariffs



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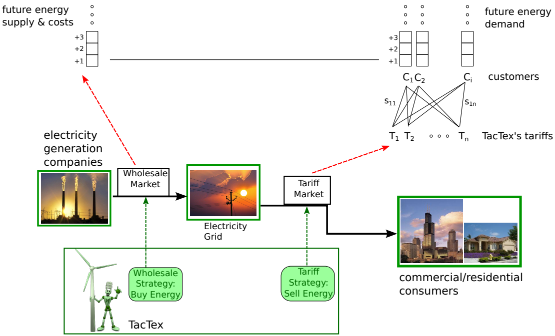

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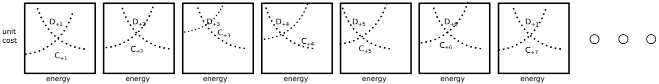

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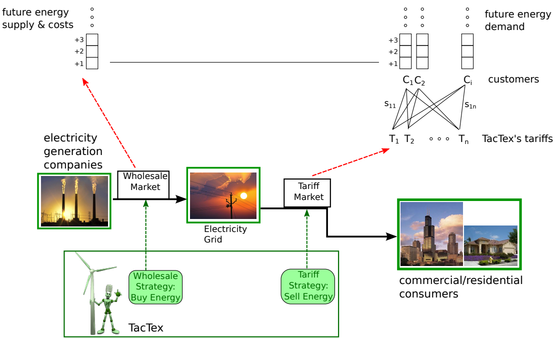

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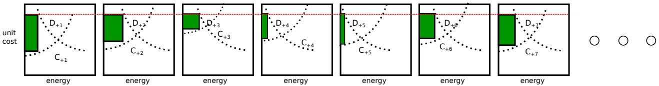

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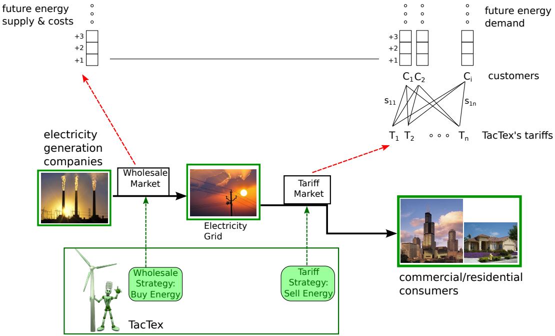

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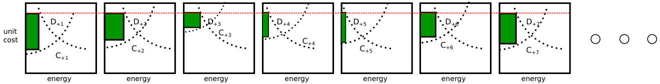

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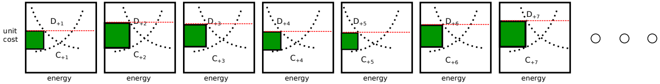
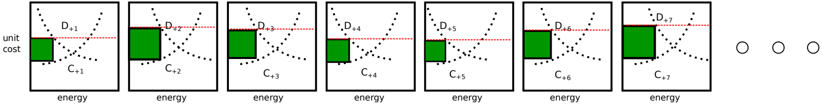


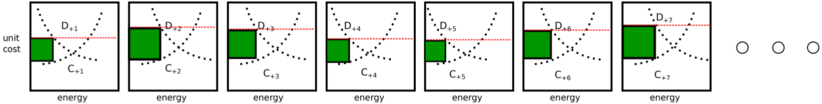
LATTE-TOU: Gradient-Based Optimization



LATTE-TOU:

- Find best fixed-rate tariff

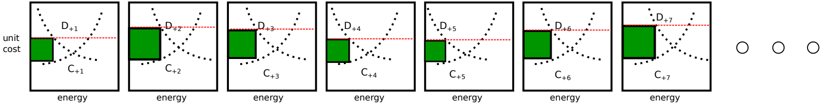
LATTE-TOU: Gradient-Based Optimization



LATTE-TOU:

- Find best fixed-rate tariff
- Perturb each of the 24 rates by $\pm\epsilon$ and estimate utility

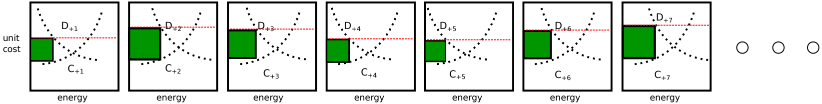
LATTE-TOU: Gradient-Based Optimization



LATTE-TOU:

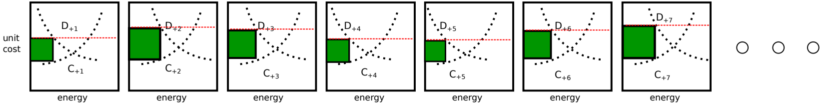
- Find best fixed-rate tariff
- Perturb each of the 24 rates by $\pm\epsilon$ and estimate utility
- Use the 2 x 24 = 48 points to estimate gradient

LATTE-TOU: Gradient-Based Optimization



LATTE-TOU:

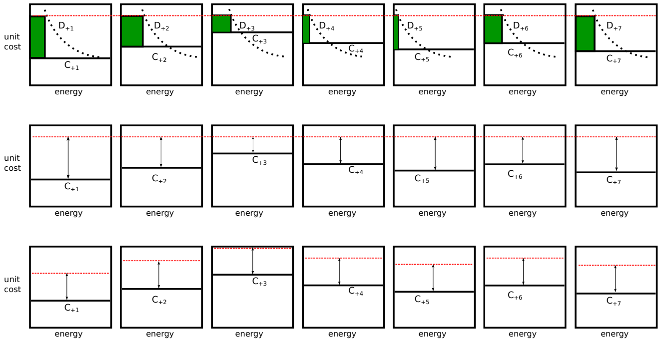
- Find best fixed-rate tariff
- Perturb each of the 24 rates by $\pm\epsilon$ and estimate utility
- Use the 2 x 24 = 48 points to estimate gradient
- Climb gradient until a local maximum



LATTE-TOU:

- Find best fixed-rate tariff
- Perturb each of the 24 rates by $\pm\epsilon$ and estimate utility
- Use the 2 x 24 = 48 points to estimate gradient
- Climb gradient until a local maximum
- Optimization objective is the predictive lookahead model

Baseline TOU Algorithm - TOUNaive



Experimental Setup

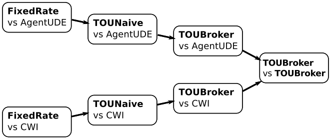
- Compare three brokers:
  - TOUBroker - uses LATTE-TOU
  - TOUNaive - from previous slide
  - FixedRateBroker - uses LATTE with fixed-rate tariffs

Experimental Setup

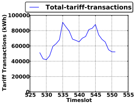
- Compare three brokers:
  - TOUBroker - uses LATTE-TOU
  - TOUNaive - from previous slide
  - FixedRateBroker - uses LATTE with fixed-rate tariffs
- Each broker plays 200 games against:
  - AgentUDE (1st place, 2014)
  - CWIBroker (2nd place, 2014)

Experimental Setup

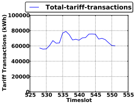
- Compare three brokers:
  - TOUBroker - uses LATTE-TOU
  - TOUNaive - from previous slide
  - FixedRateBroker - uses LATTE with fixed-rate tariffs
- Each broker plays 200 games against:
  - AgentUDE (1st place, 2014)
  - CWIBroker (2nd place, 2014)



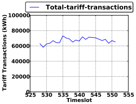
FixedRateBroker



TOUNaive



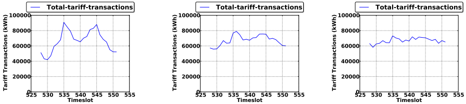
TOUBroker



Total consumption, 24 hours.

TOUBroker: Utility Optimization $\Longrightarrow$ Peak-Flattening

FixedRateBroker | TOUNaive | TOUBroker



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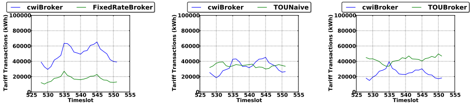

Per-broker consumption, 24 hours.

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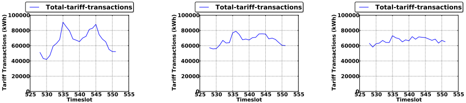

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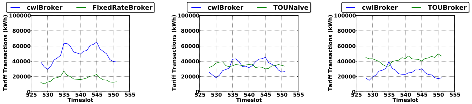

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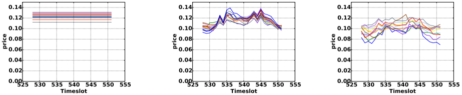
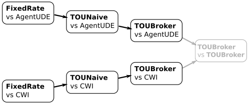


Active tariffs, 24 hours.

Results: TOUBroker vs. AgentUDE, CWI

- vs. AgentUDE

	(a) FixedRate-vs-UDE	(b) TOUNaive-vs-UDE	(c) TOUBroker-vs-UDE	Change (c)/(a)
score: our-agent (M$)	**1.893**	**1.689**	**1.922**	1.016 **(+1.6%)**
score: UDE (M$)	**0.895**	**0.578**	**1.122**	1.253 **(+25.3%)**
market-share: our-agent (%)	64.0	73.3	61.4	0.959 **(-4.1%)**
(our) avg electricity-buy price	0.053	0.051	0.051	0.963 **(-3.7%)**
(our) avg electricity-sell price	0.105	0.098	0.105	1.000 **(-0.0%)**
(all) avg electricity-buy price	0.051	0.049	0.049	0.961 **(-3.9%)**
(all) avg electricity-sell price	0.105	0.099	0.104	0.990 **(-1.0%)**
peak-demand (MW)	**86.771**	**71.882**	**73.519**	0.847 **(-15.3%)**



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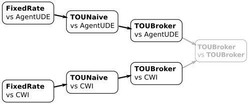
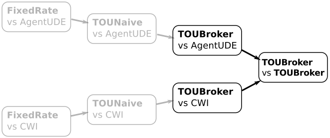


- vs. CWI

	(a) FixedRate-vs-CWI	(b) TOUNaive-vs-CWI	(c) TOUBroker-vs-CWI	Change: (c)/(a)
score: our-agent (M$)	**0.677**	**0.524**	**0.622**	0.919 **(-8.1%)**
score: CWI (M$)	**0.771**	**0.620**	**0.558**	0.724 **(-27.6%)**
market-share: our-agent (%)	44.2	54.3	54.7	1.238 **(+23.8%)**
(our) avg electricity-buy price	0.057	0.054	0.054	0.947 **(-5.3%)**
(our) avg electricity-sell price	0.095	0.087	0.086	0.905 **(-9.5%)**
(all) avg electricity-buy price	0.057	0.055	0.053	0.930 **(-7.0%)**
(all) avg electricity-sell price	0.094	0.086	0.086	0.915 **(-8.5%)**
peak-demand (MW)	**86.701**	**74.720**	**73.651**	0.849 **(-15.1%)**

TOUBroker: Self-Play

	(d) TOUBroker-vs-TOUBroker	Change (d)/(c) (UDE)	Change (d)/(c) (CWI)
score: our-agent (M$)	**0.493**	0.257 **(-74.3%)**	0.791 **(-20.9%)**
score: agent-copy (M$)	**0.482**	–	–
market-share: our-agent (%)	50.5	0.823 **(-17.7%)**	0.927 **(-7.3%)**
(our) avg electricity-buy price	0.051	1.000 **(-0.0%)**	0.944 **(-5.6%)**
(our) avg electricity-sell price	0.083	0.790 **(-21.0%)**	0.954 **(-4.6%)**
(all) avg electricity-buy price	0.051	1.041 **(+4.1%)**	0.944 **(-5.6%)**
(all) avg electricity-sell price	0.083	0.798 **(-20.2%)**	0.954 **(-4.6%)**
peak-demand (MW)	**70.101**	0.954 **(-4.6%)**	0.947 **(-5.3%)**



Ablation analysis

	TOUBroker	NoShift	FlatCost
score: our-agent (M$)	**0.622**	**0.507**	**-0.007**
score: CWI (M$)	0.558	0.550	0.210
peak-demand (MW)	**73.651**	**83.728**	**82.779**

Ablation analysis: erratic-predictions

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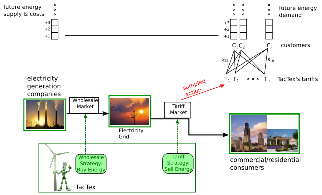
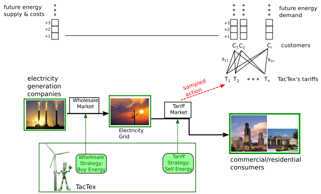
Ablation analysis: erratic-predictions

- Shifting and cost predictions are critical for
  - Profits
  - Peak-flattening

Conclusions 1: LATTE-TOU



- **LATTE-TOU:** LATTE with gradient-ascent action sampling
  - Local optimization of TOU tariff actions



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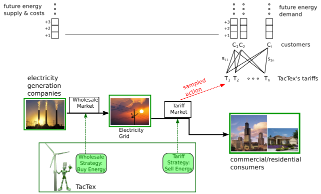

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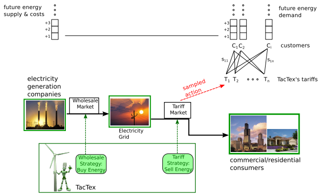

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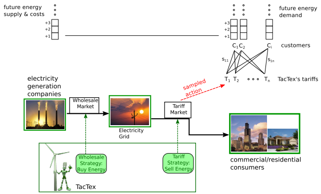

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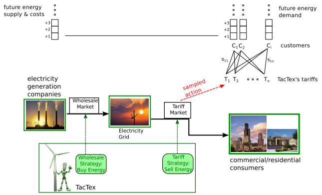

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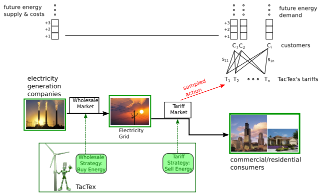

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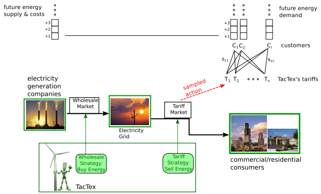

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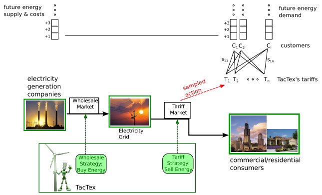

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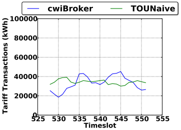
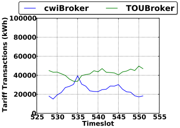
- LATTE-TOU requires accurate demand/cost predictions

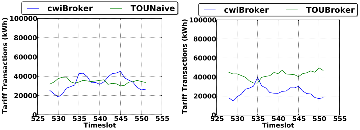
Conclusions 2: Broker Incentives to use TOU





Broker incentives to use TOU?

Conclusions 2: Broker Incentives to use TOU



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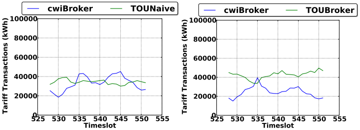

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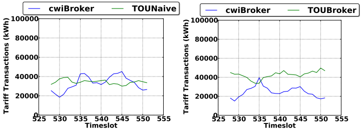

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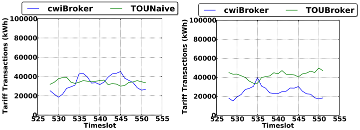

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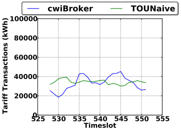

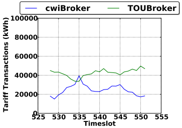

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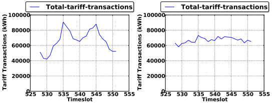
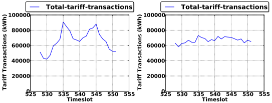
Conclusions 3: TOU Impact in Competitive Markets



TOU Impact on the economy:



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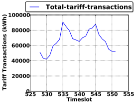

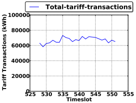

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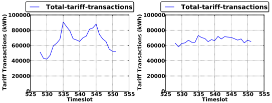

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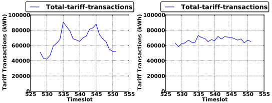

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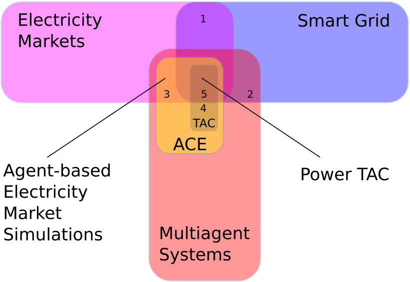
Demonstrates a potential benefit of employing autonomous (TOU) brokers in future power markets

Related Work: Contribution Areas



Future Work 1: Extending LATTE within Power TAC

- Extending Time-Of-Use (TOU) Tariffs

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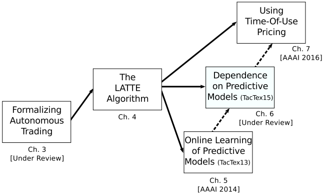
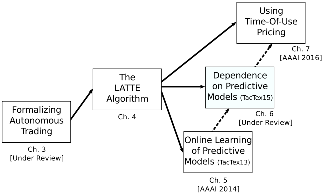


- Research Question:
  - How should an autonomous broker agent act to maximize its utility by trading in time-constrained, modern electricity markets?



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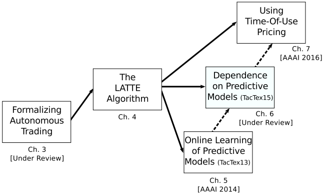

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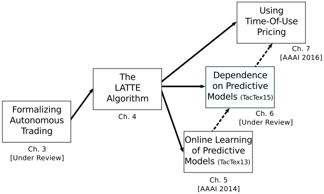

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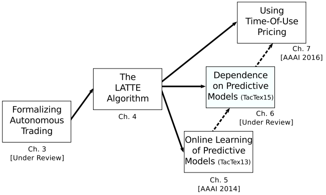

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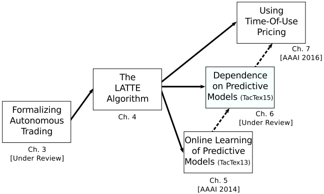

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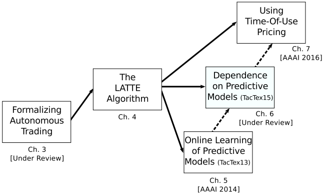

Thanks!

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