Full Life-cycle Deployment of Distributed Control in Large-scale Infrastructures

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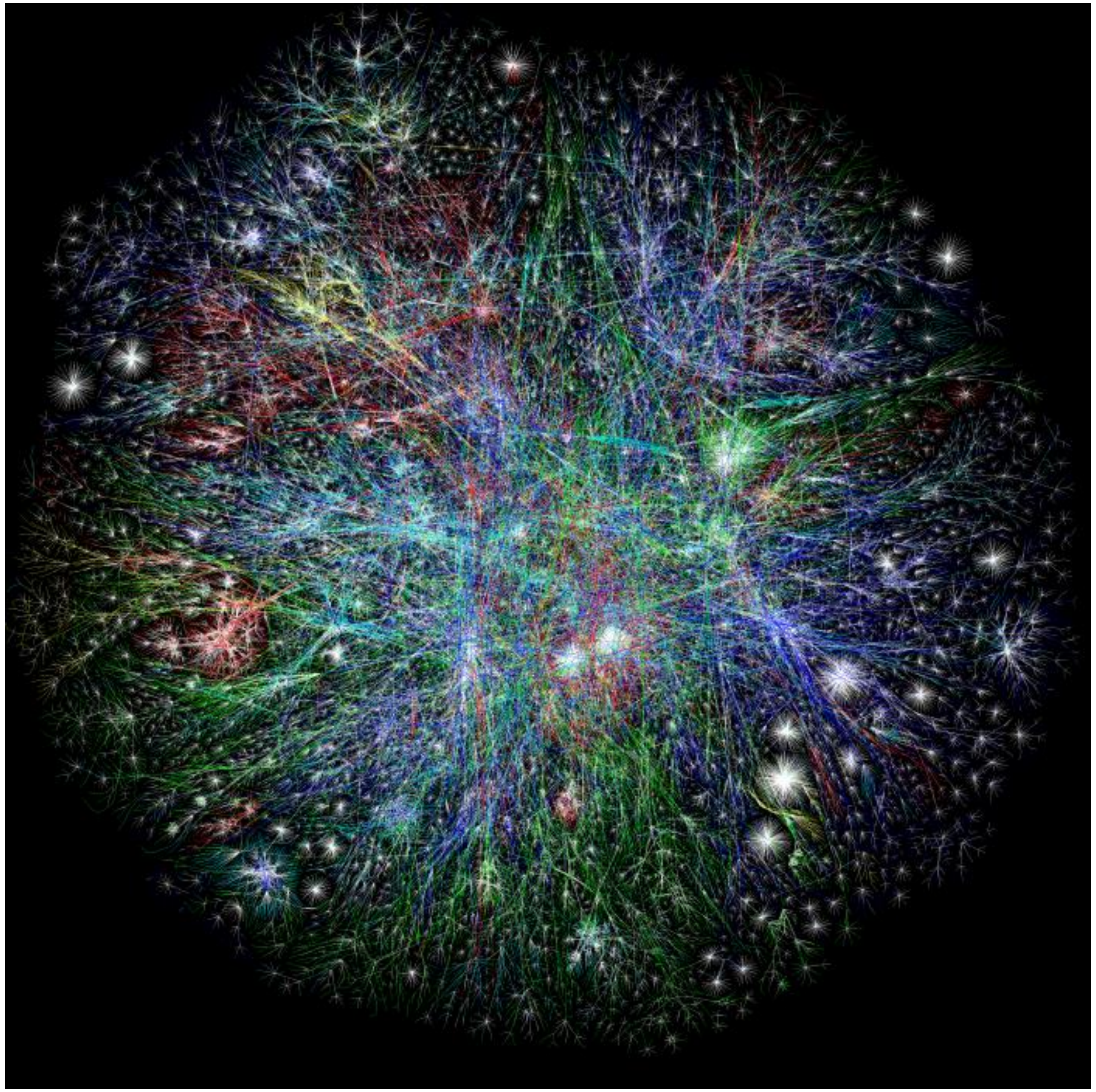
Contents

Our world is more complex and growing faster than our control methods can handle

Complex Systems

- Highly interconnected
- Heterogeneous device-human participation
- Extreme data
- Pervasive intelligence
- Increasing autonomy



Global energy goals cannot be met without changes in how we control complex systems

Energy System

- Potential for substantial efficiencies in end-user systems with new controls
- More data and devices available
- New assets difficult to coordinate
- Existing controls antiquated

Cyber-physical System

- Growing “edge” computing resources
- Cloud computing becoming paradigm
- Existing security models challenged

Traditional centralized control approaches are generally unable to resolve those issues

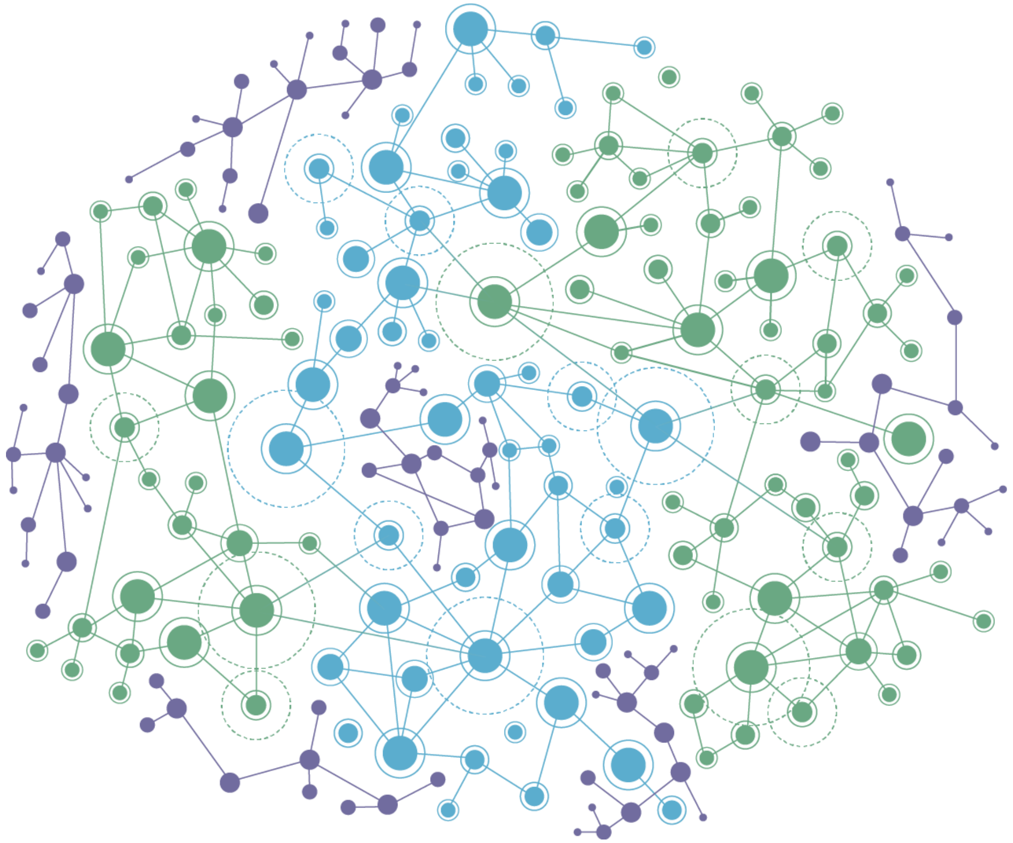





From Big Data to Distributed Control

The move from Big Data to Distributed Control involves addressing:

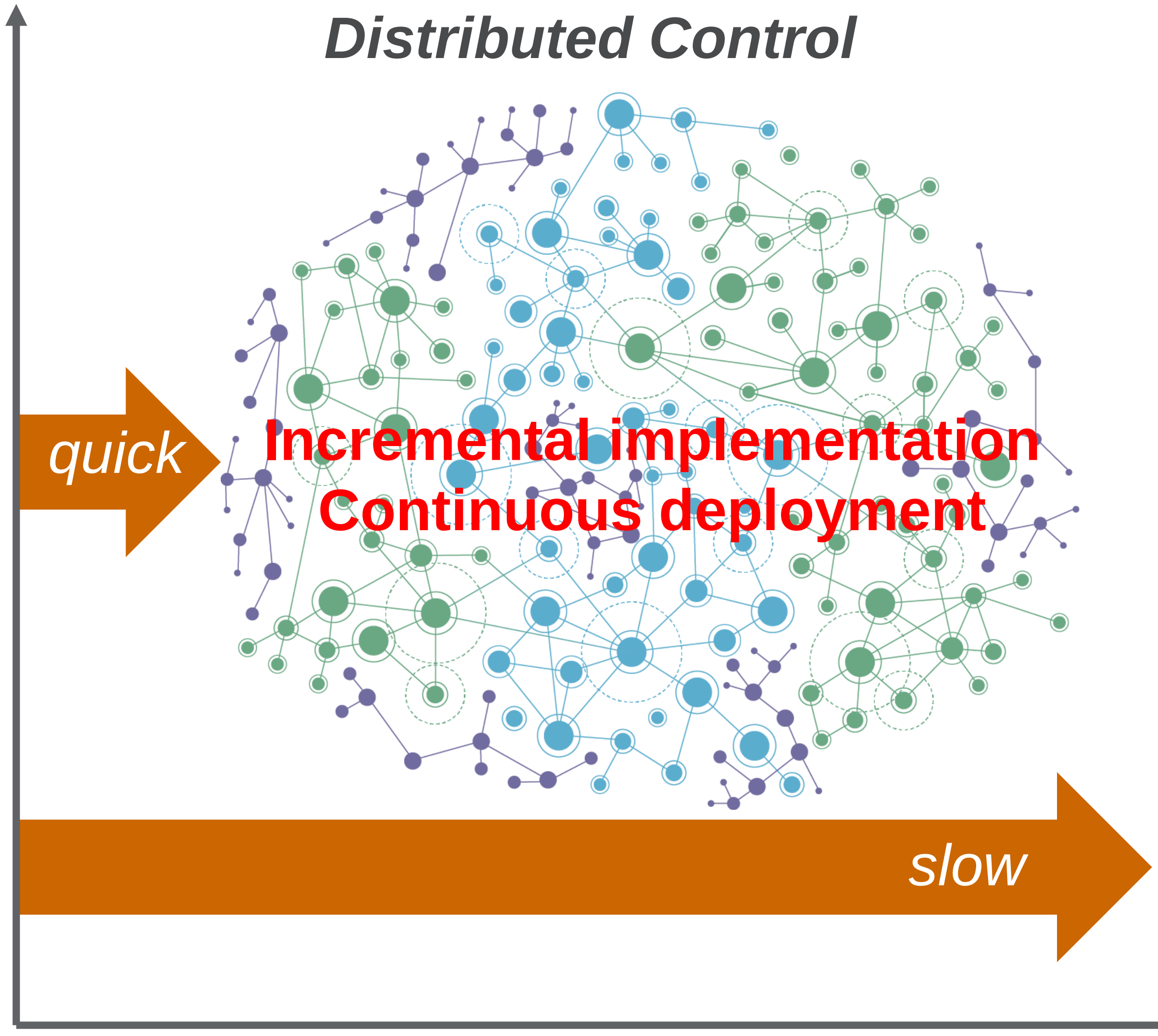
- Large numbers of sensing and/or control end points
- High complexity
- Node heterogeneity
- Multiple scales of operation
- Pervasive computing/ autonomous nodes
- Wide geographical scope



The solutions must be:
Deployable, scalable**,** ***robust*****,** ***resilient*****, and** ***adaptable***

Distributed Control Hypothesis

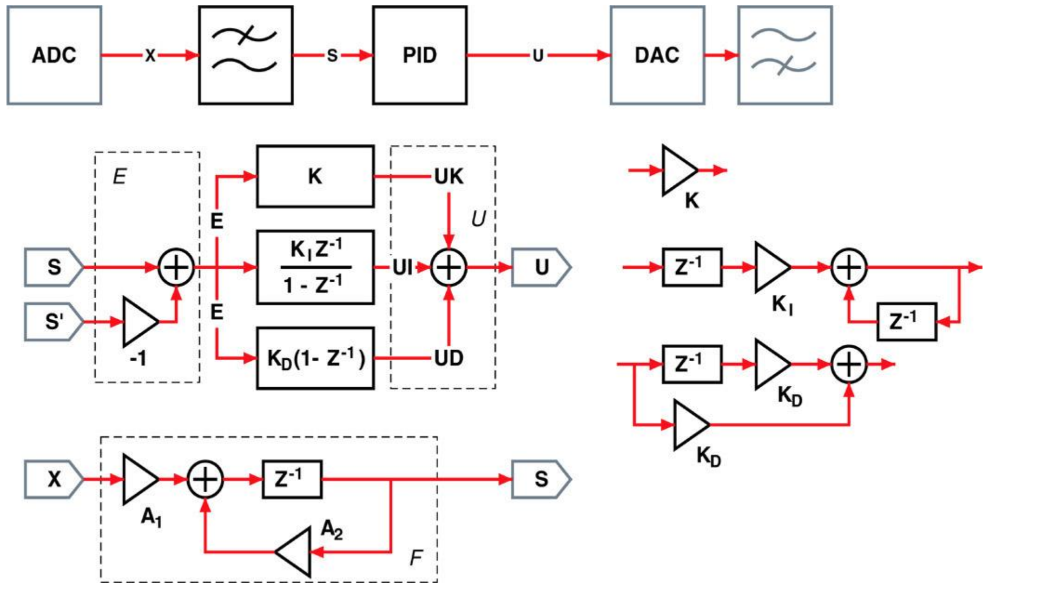
Distributed Control



Hypothesis

Distributed control approach is the fastest way to advance control theory to address the challenges posed by large-scale infrastructure systems

Conventional Control

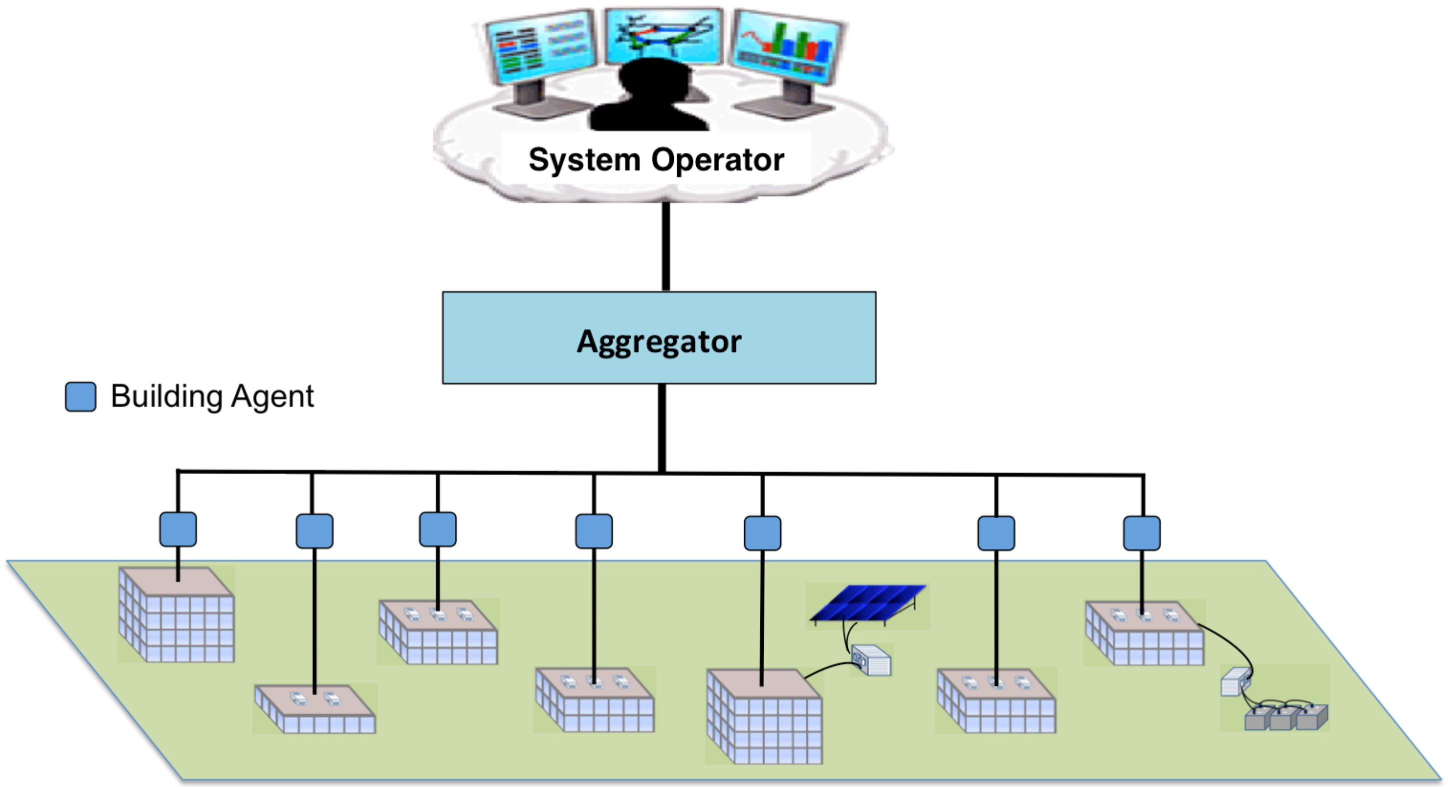


Time to deployment

Electric power system as an example

Building-to-Grid (B2G) Integration

- Two fundamental questions for B2G integration
  - Characterize the capacity flexibility of commercial buildings
  - Control the power consumption to follow dispatched signals

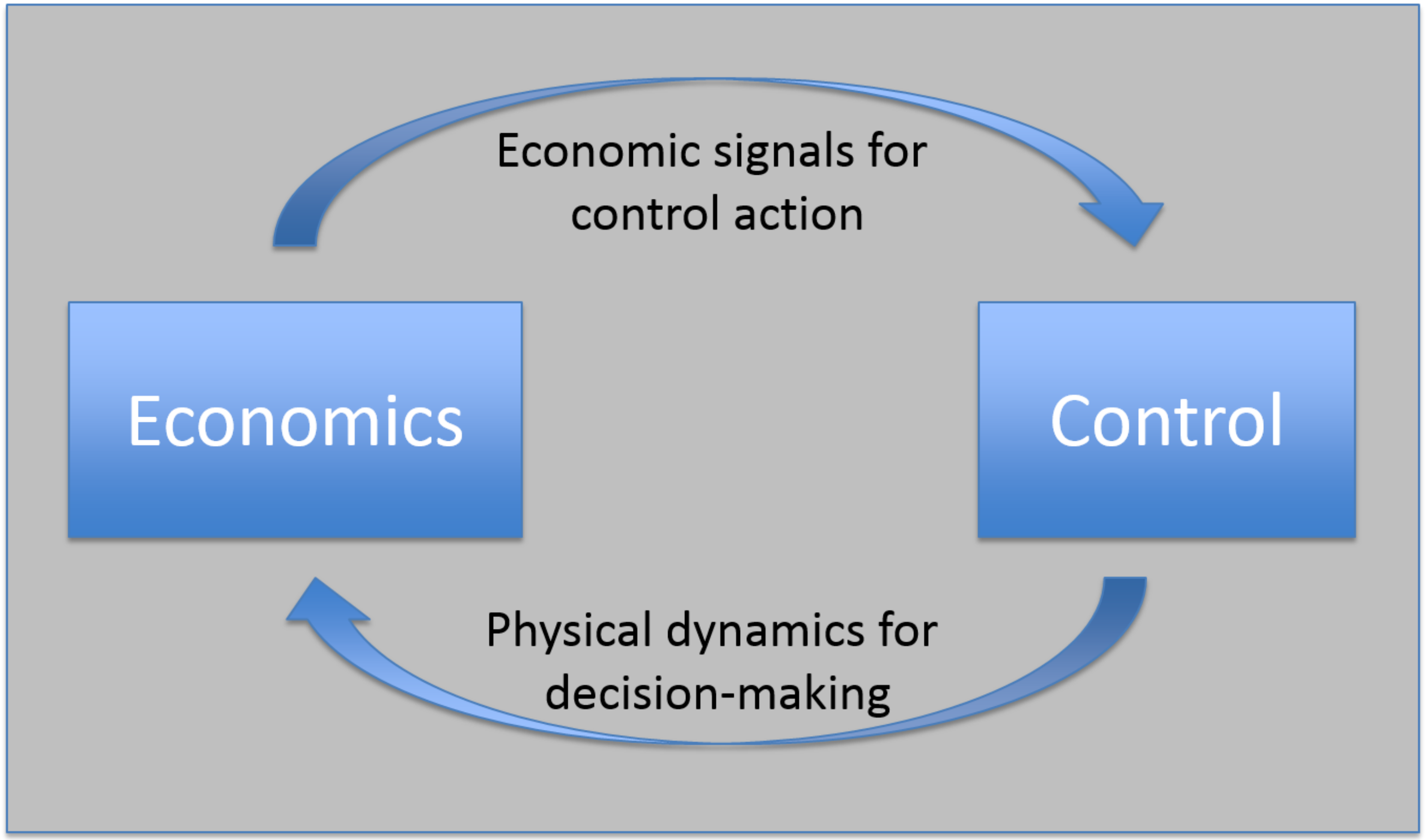


Key: Respect distinct preferences of building occupants

Demand Side Response

- Manage power grid by actively engaging both customer-owned and third-party distributed energy resources (DERs) into system operation through
  - Direct control
    - ✓ Utility companies remotely control operations of residential loads based on prior agreements
    - ✓ Traditionally concerned with peak load reduction
    - ✓ Recent efforts focus on modeling and control of different types of loads to provide various grid services
  - Price control
    - ✓ Price signals directly sent to individual loads to affect local demand
    - ✓ Example: time-of-use (TOU) pricing, critical peak pricing (CPP), real-time pricing (RTP)
  - Transactive control
    - ✓ Automated loads engaged in market interaction
    - ✓ Information exchange includes quantity and price

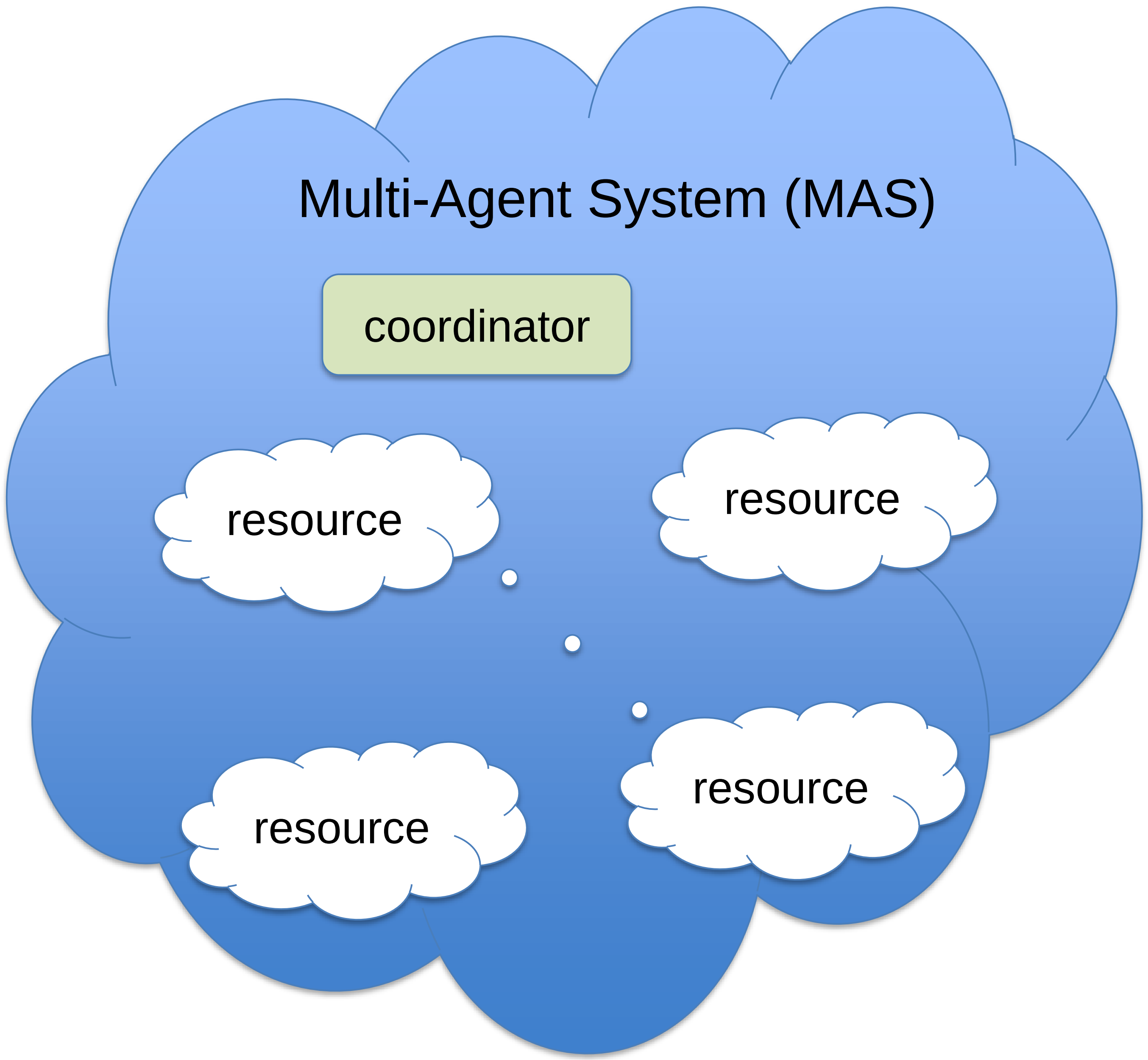
Transactive Control



Transactive Control = Market-based Coordination + Value-driven Control

- Key features
  - Open, flexible and interoperable
- Value proposition
  - Promote voluntary participation by value-based incentives
  - Respect local objectives and choice domains
  - Ensure stability and predictability of system response
  - Simplify coordination through decomposition and localization
  - Engage multiple stakeholders with different preferences

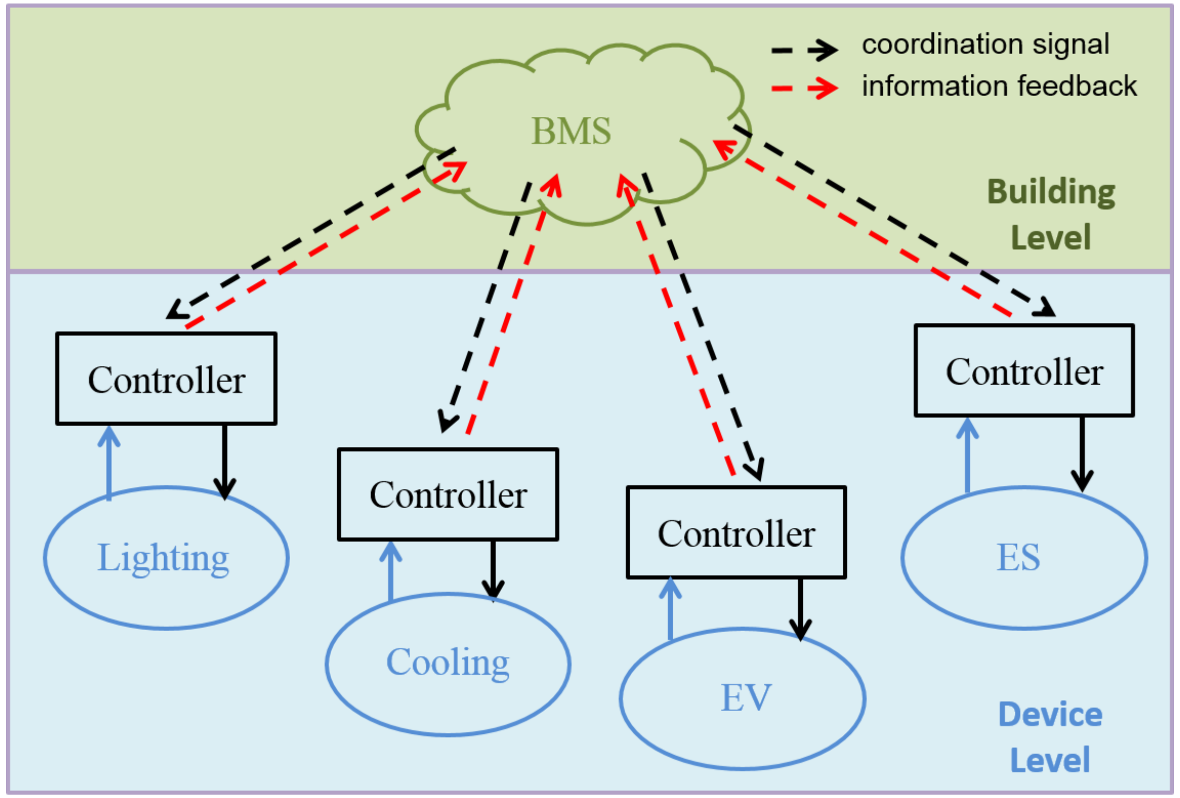
Fundamental Concepts



- Agent types
  - Coordinator (market)
  - Supplier (seller)
  - Customer (buyer)
- Power systems
  - Distributed generator
  - Photovoltaic system
  - Energy storage
  - Residential appliances
  - Building loads (AHU, chiller, etc.)
  - Residential building
  - Commercial building
  - Community
  - Microgrid
  - Distribution system

Transactive Building
(BTO Transactive Campus)

- One commercial building with responsive building loads
- Objective: reduce peak demand during real-time operations



- Customer – RTU, VAV, Lighting

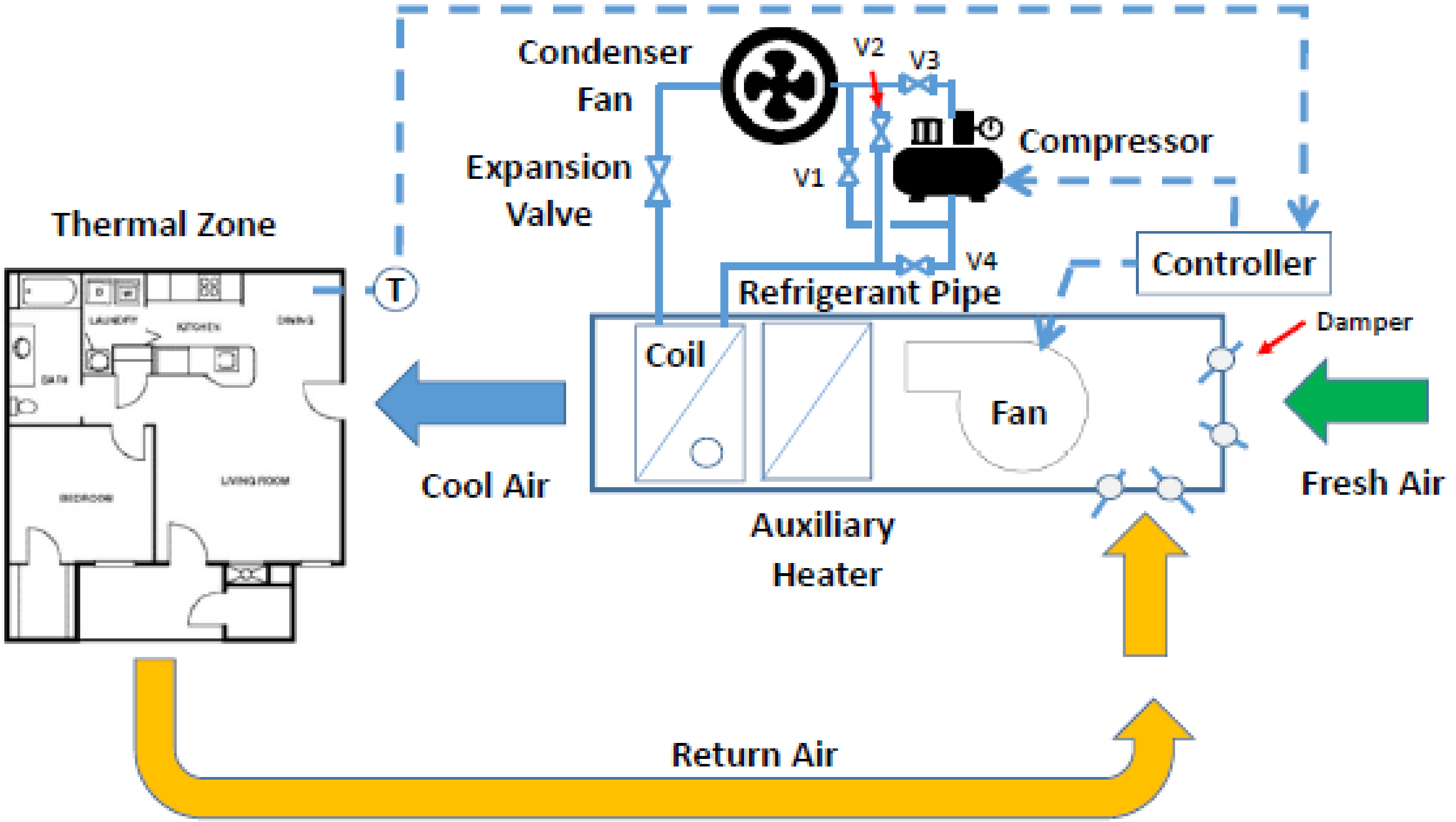
$$\max_{\text{power}_i} \quad \text{utility}_i(\text{power}_i) - \text{payment}_i$$
$$\text{s.t.} \quad i\text{-th load dynamics}$$

- Coordinator – BMS

$$\max_{\text{power}_i} \quad \sum_{i=1}^{N} \text{utility}_i(\text{power}_i) - \text{cost}(\text{power}_g)$$
$$\text{s.t.} \quad \text{power}_g = \sum_{i=1}^{N} \text{power}_i + \text{power}_{uc} \leq \text{limit}$$
$$i\text{-th load dynamics}$$

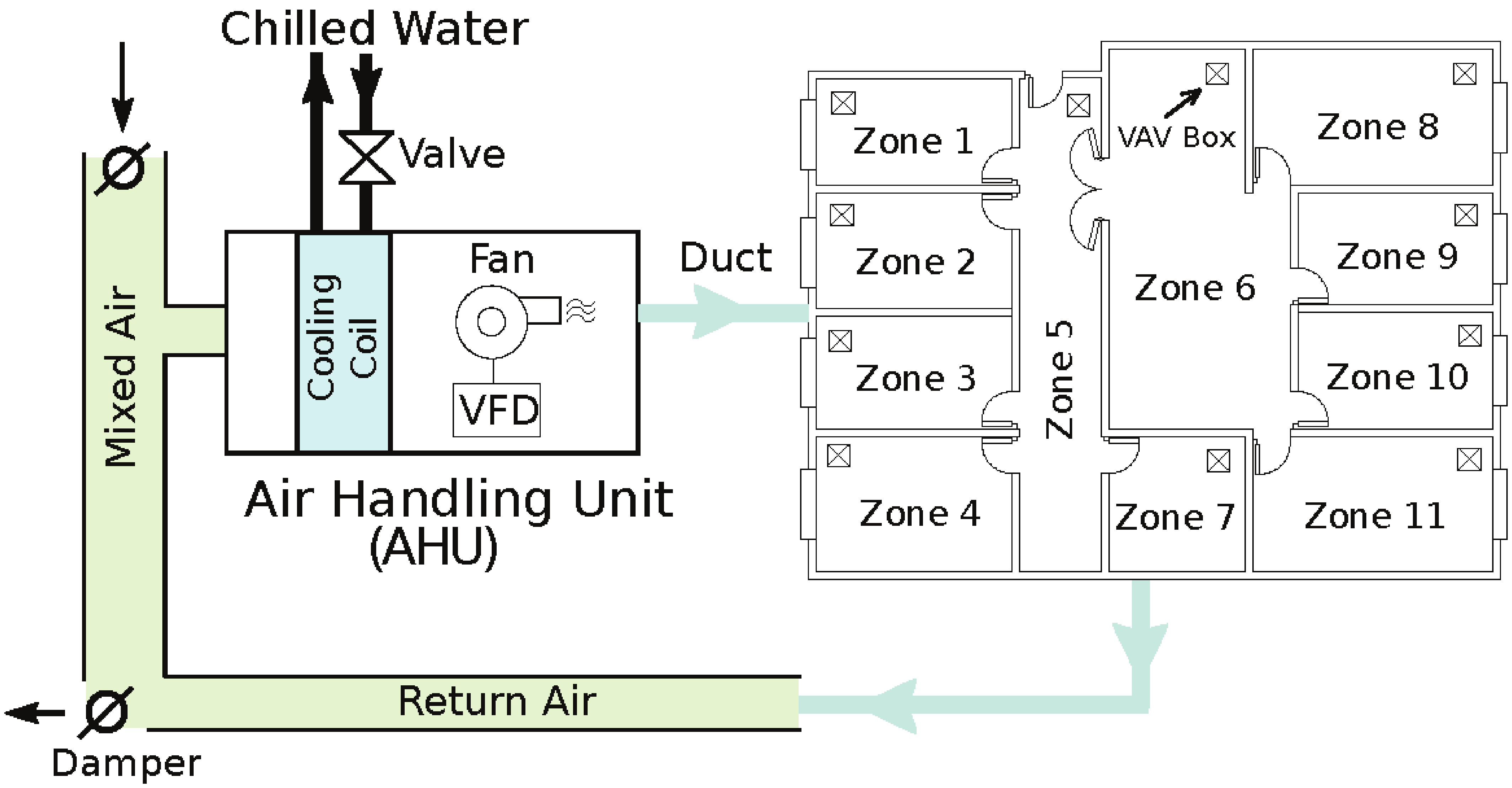
Demand limiting

RTU System



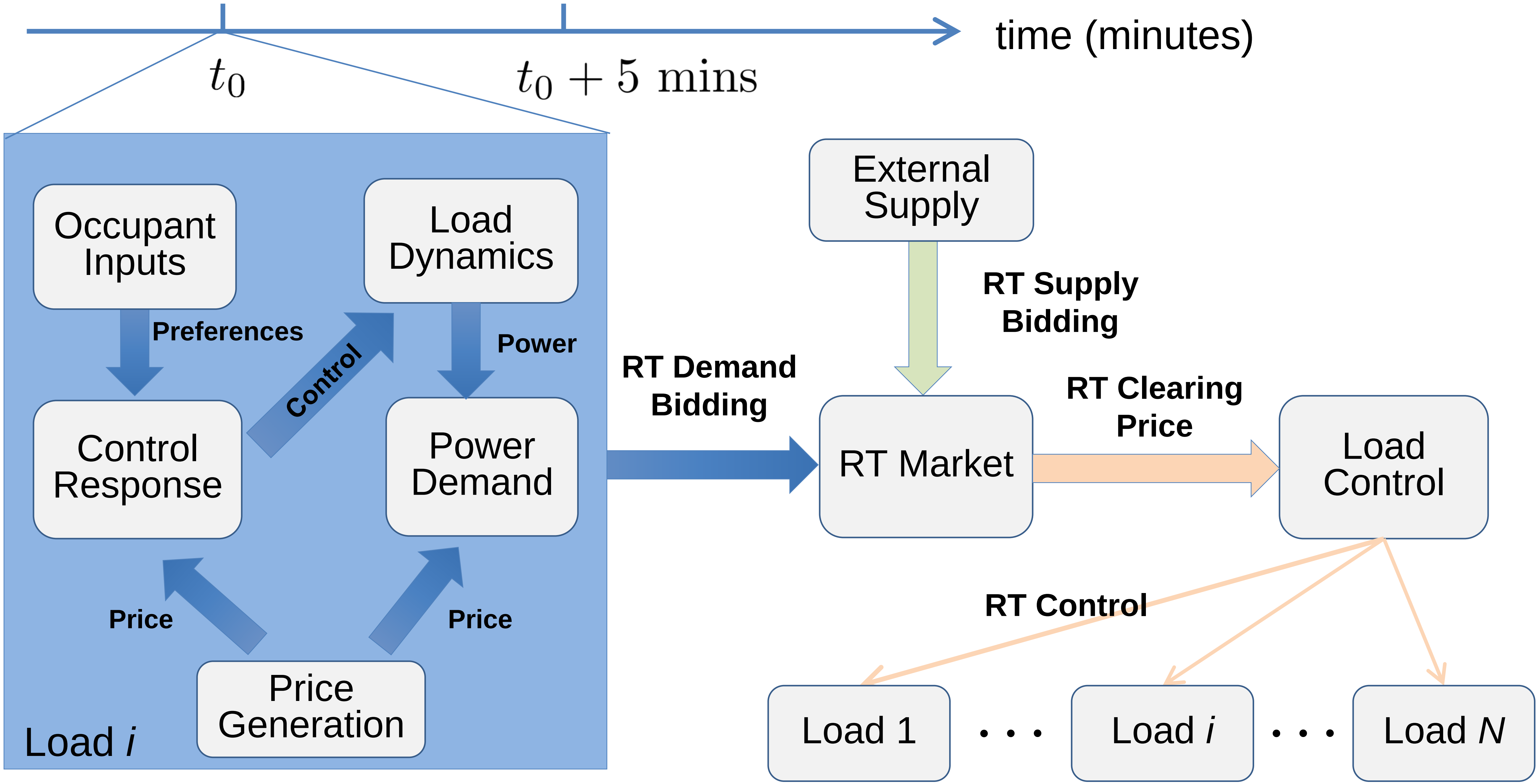
Condenser
Fan
Expansion
Valve
V2
V3
V1
Compressor
Thermal Zone
T
V4
Controller
Refrigerant Pipe
Damper
Coil
Fan
Cool Air
Fresh Air
Auxiliary
Heater
Return Air

VAV System



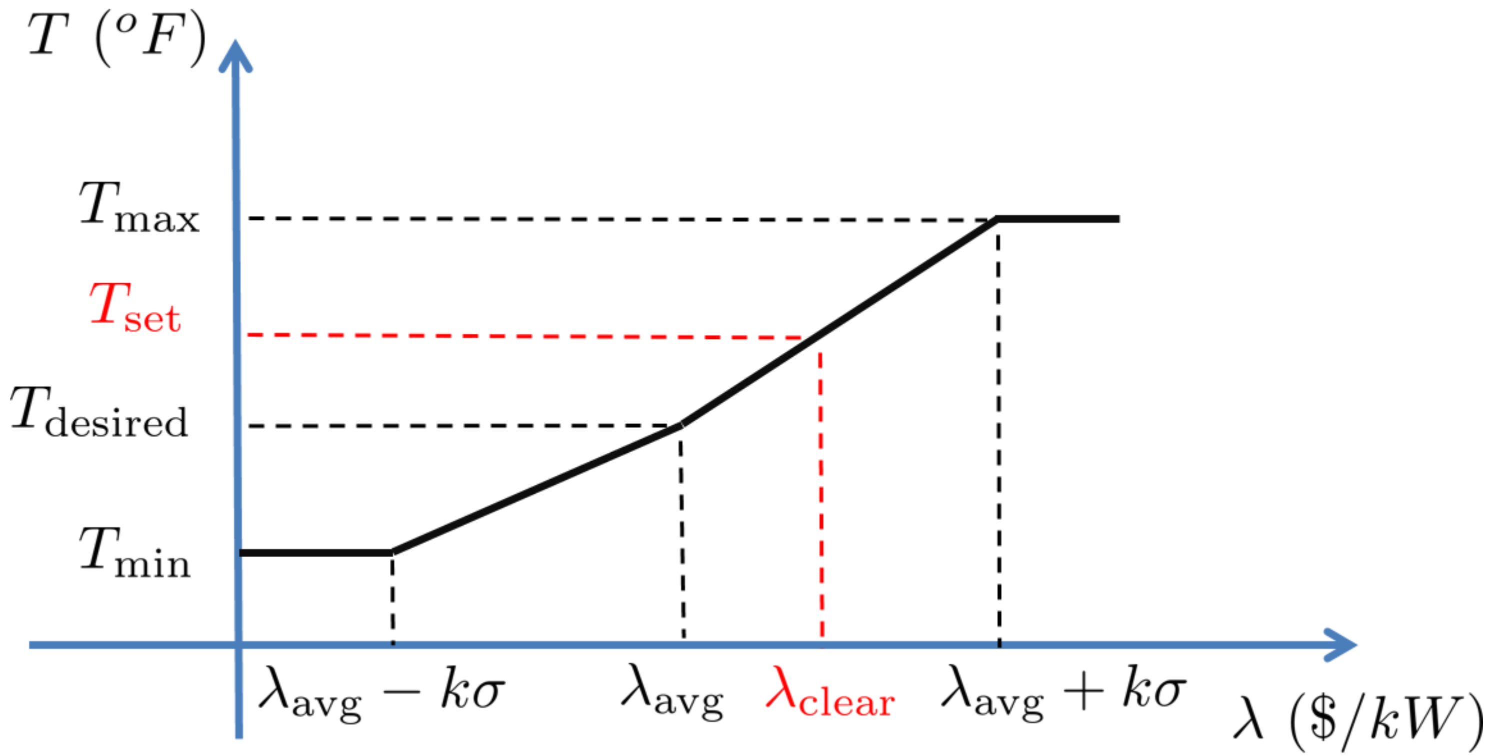
Chilled Water
Valve
Mixed Air
Cooling Coil
Fan
VFD
Duct
Air Handling Unit (AHU)
Return Air
Damper
Zone 1
Zone 2
Zone 3
Zone 4
Zone 5
VAV Box
Zone 6
Zone 7
Zone 8
Zone 9
Zone 10
Zone 11

Real-time Market w/ Transactive Control



Transactive Control – VAV/RTU System

- Control response curve for RTU or VAV Systems (Cooling for illustration)

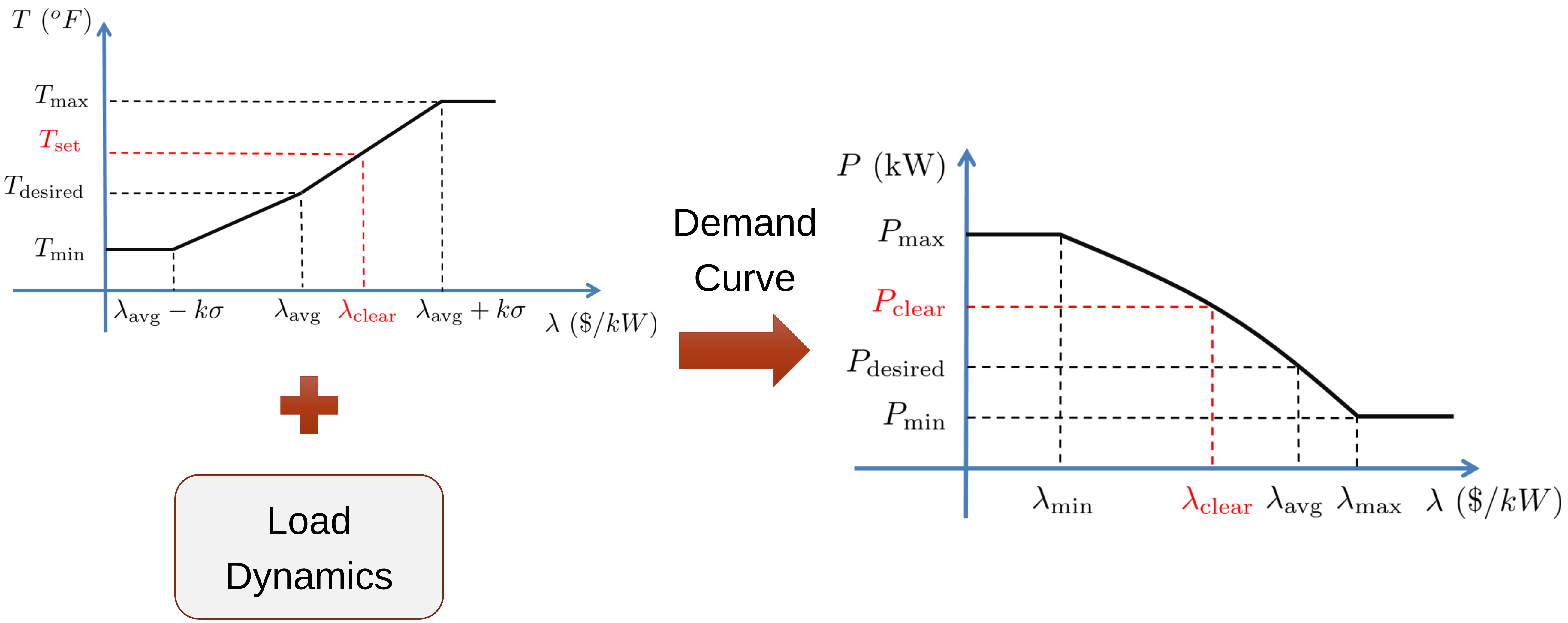


Local Input = T_{set}

Parameter = $\left\{ \begin{matrix} T_{\min}, T_{\max}, T_{\text{desired}} \\ \lambda_{\text{avg}}, \sigma, k \end{matrix} \right\}$

Demand Curve – VAV/RTU System

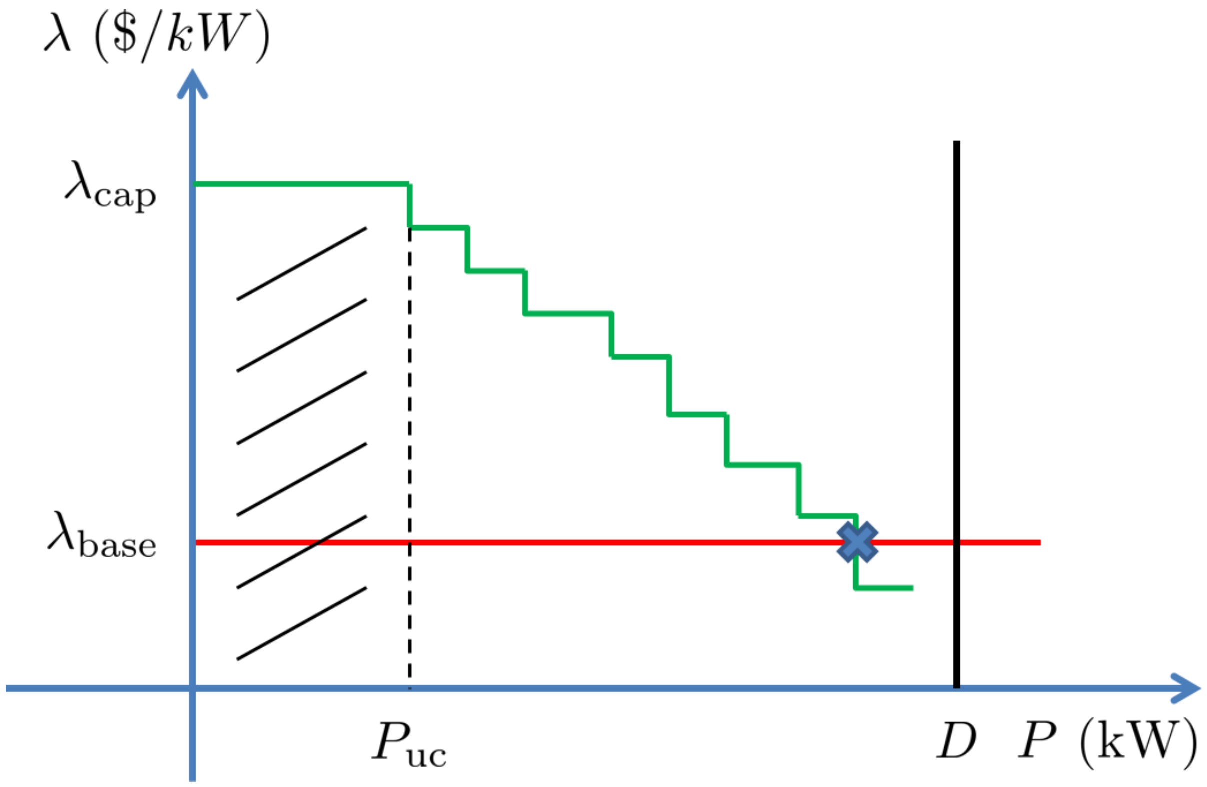
- Coupling control response curve with load dynamics leads to demand curve



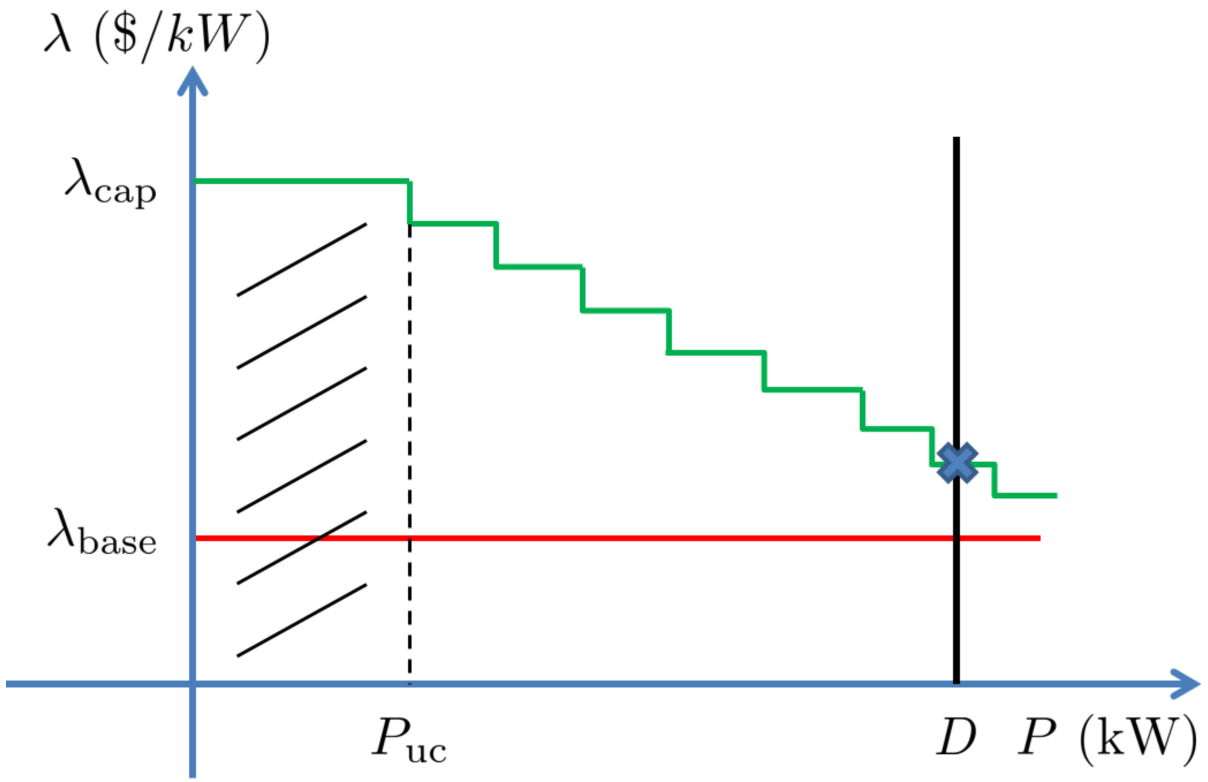
Hierarchical Market Clearing inside Building

- Market coordinator clears the market in one time through demand bidding

Without demand violation



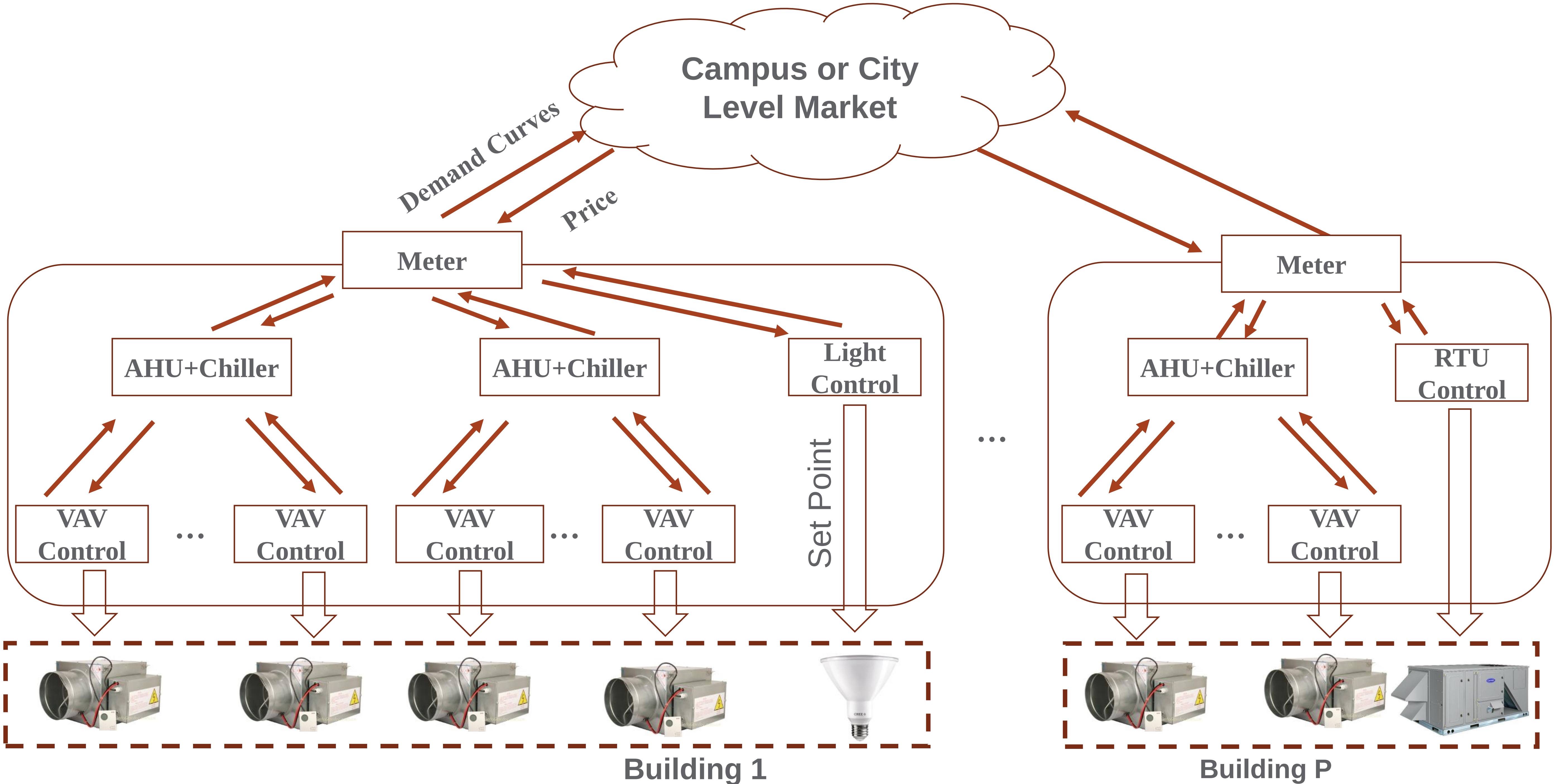
With demand violation



λ_{base} Base energy price

λ_{cap} Price cap

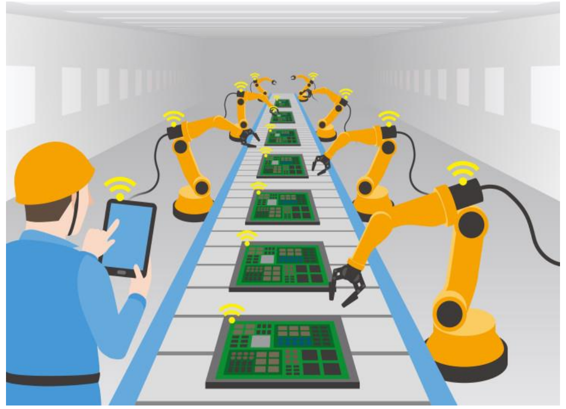
A typical Distributed Control System
- transactive control for commercial buildings

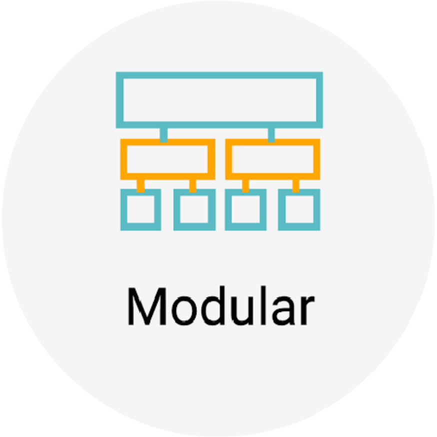


A typical Distributed Control System
- Requirement for large-scale deployment

A scalable deployment of the transactive control should be

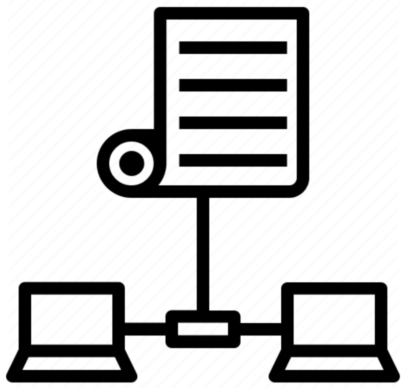
- **Automated in terms of the control setup process**
  - Standardizing the control process
- **Extensible and adaptable to different applications with the minimized modifications**
  - Modular programming for realized different functionalities
- **Capable to handle large-scale communication at various time-resolutions with different protocols**
  - Data management auxiliary functions combined with databases
  - Generic communication interfaces


Streaming workflow

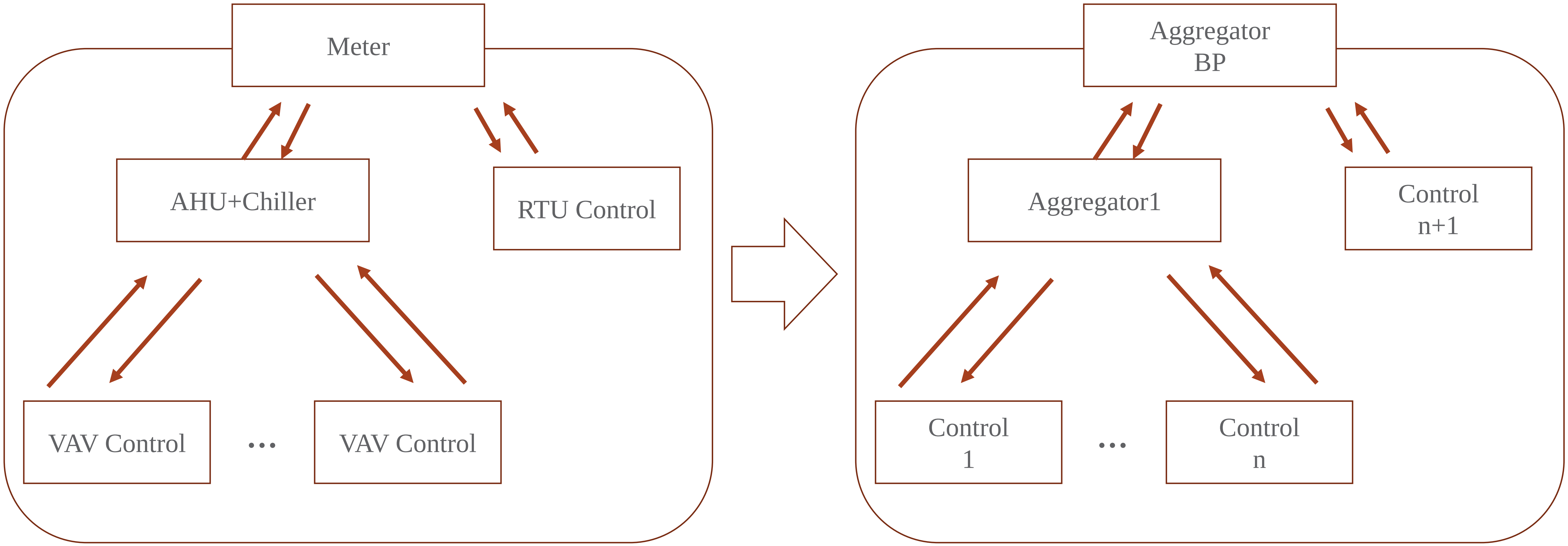


Modular implementation

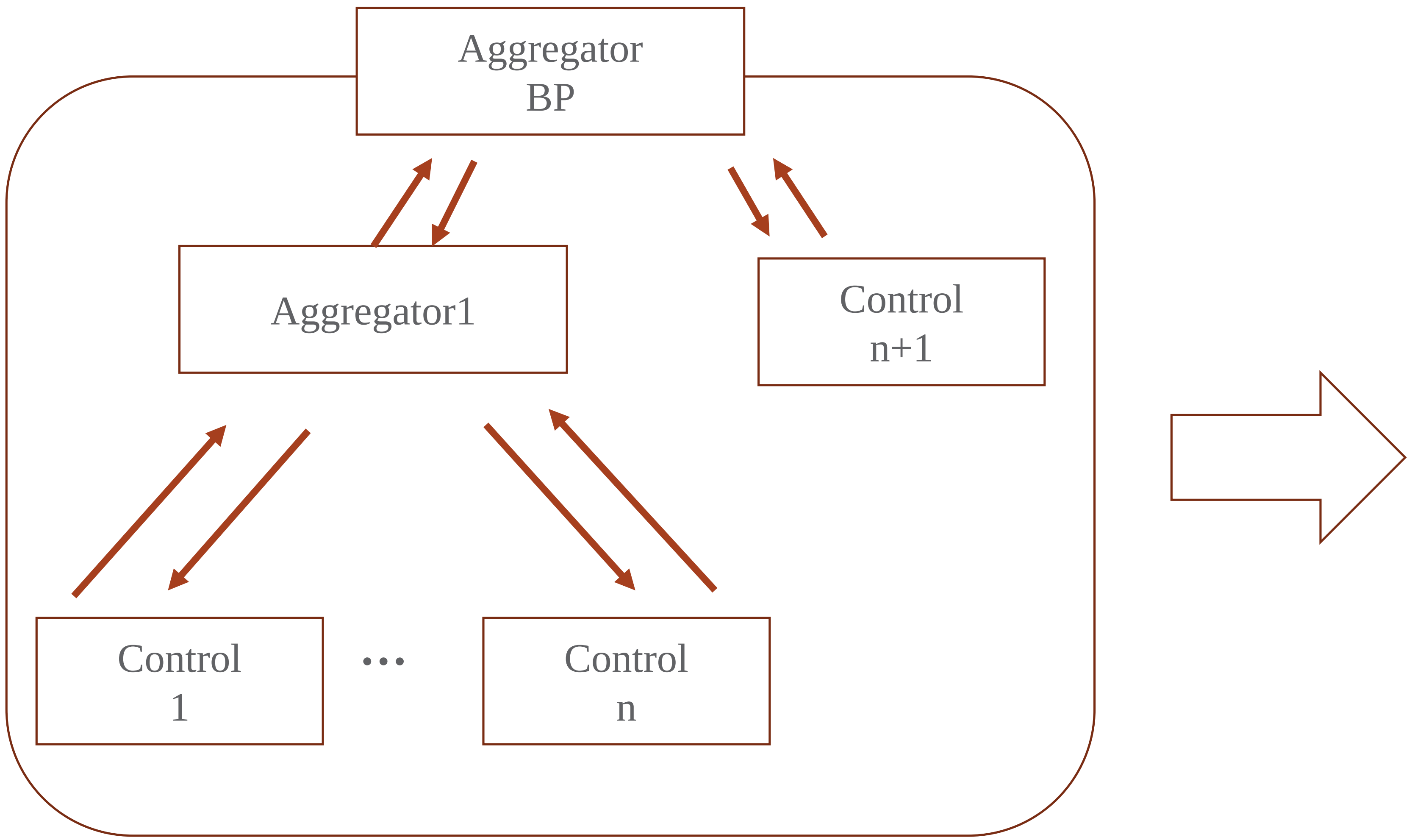

Data management


Protocol

Deployment of transactive control
- Standardizing the control process

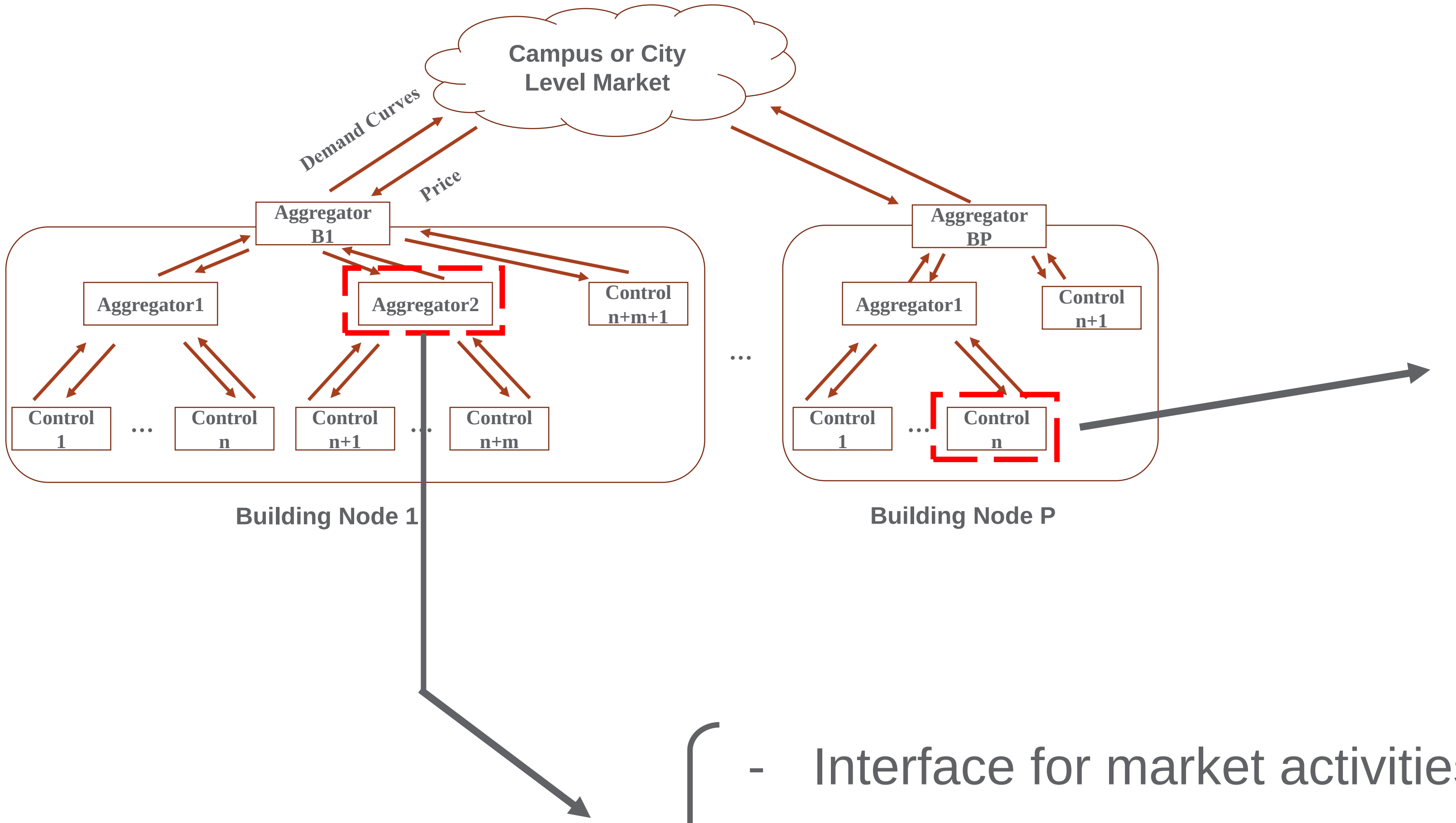


Deployment of transactive control
- Standardizing the control structure description




```
{ "Aggregator 1":
      {"type": "aggregator",
       "config":"./aggregaor1",
       "elements":
           {"Control 1":
               {name":"vav1",
                "config ":"/aggregaor1/vav1"},
                …
           }
        …
       },
    "Control n+1":
       { "name":"light1",
         "config":"./light1",
         ….
       }
}
```

Deployment of transactive control
- Separating functionality



- Quantity estimation
- Price response control
- Interface for control actuation
- Interface for market activities

- Interface for market activities: reservation, biding, and clearing
- Price conversion
- Commodity conversion

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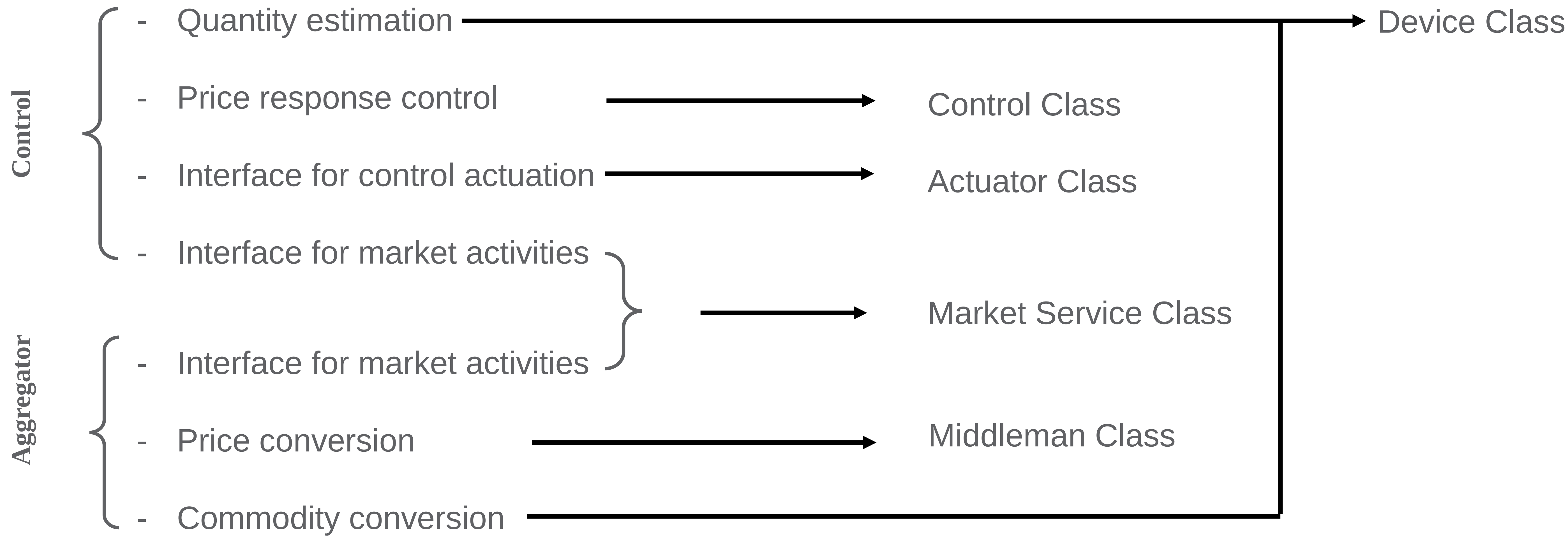
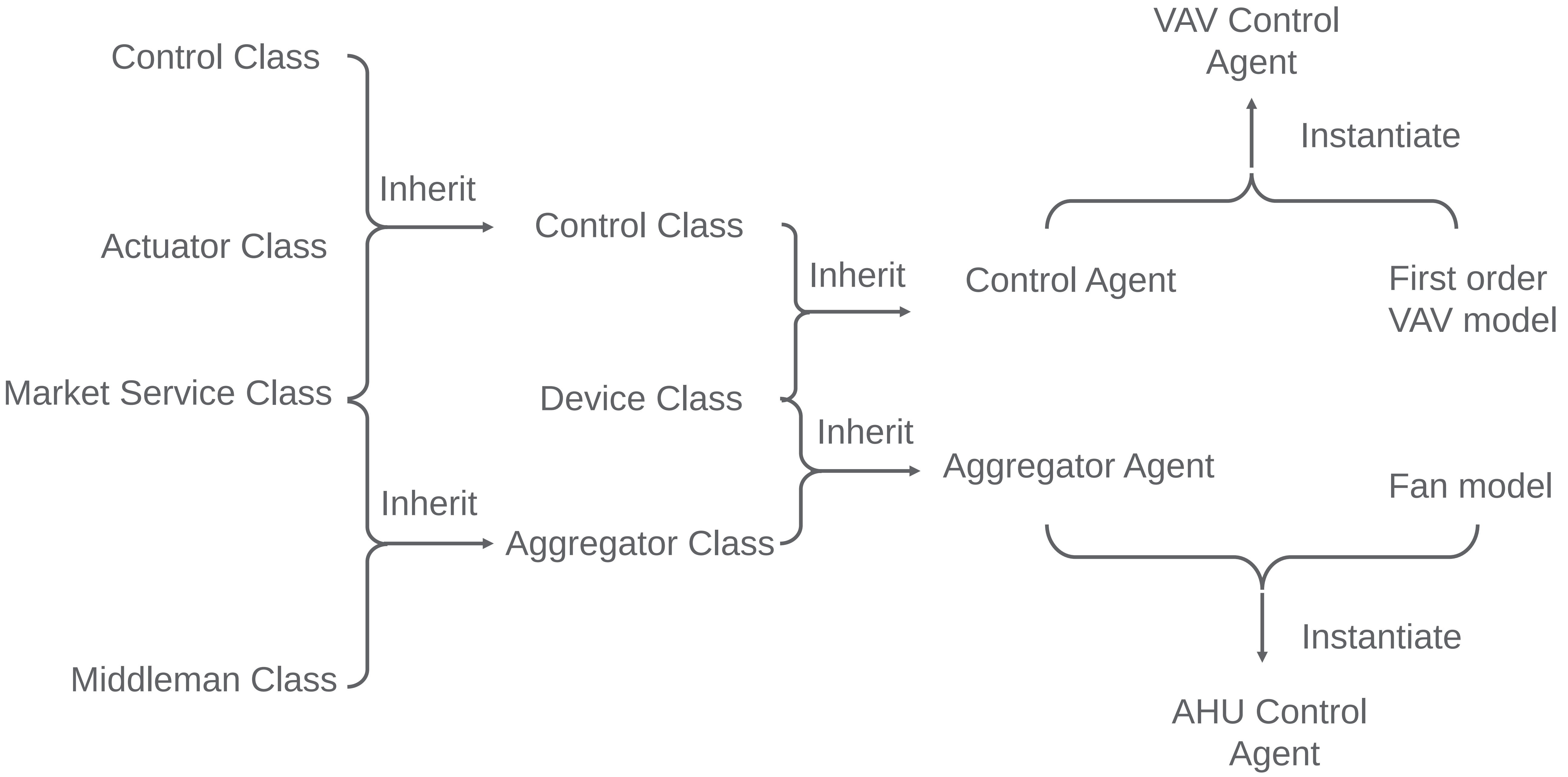
Deployment of transactive control
- Separating functionality



Deployment of transactive control
- Separating functionality



Deployment of transactive control
- First order VAV model

First-order zone model

$$C_i \frac{T_i^{k+1} - T_i^k}{\Delta t} = \frac{T_a^k - T_i^k}{R_i} + Q_{i,hvac}^k + Q_{i,dis}^k$$

Assuming Q_{dis}^k is constant:

$$Q_{i,hvac}^k = \frac{C_i}{\Delta t} T_i^{k+1} + \frac{\Delta t - C_i R_i}{R_i \Delta t} T_i^k - \frac{1}{R_i} T_a^k - Q_{i,dis}$$

Assuming $T_i^{k+1} = T_{set,i}^{k+1}$:

$$Q_{i,hvac}^k = \frac{C_i}{\Delta t} T_{set,i}^{k+1} + \frac{\Delta t - C_i R_i}{R_i \Delta t} T_i^k - \frac{1}{R_i} T_a^k - Q_{i,dis}$$

Short-term prediction $\quad Q_{i,hvac}^k = a_i^0 T_{set,i}^{k+1} + a_i^1 T_i^k + a_i^2 T_a^k + a_i^3$

Long-term prediction $\quad Q_{i,hvac}^k = a_i^0 T_{set,i}^{k+1} + a_i^1 T_{set,i}^k + a_i^2 T_a^k + a_i^3$

T: Temperature
C: Thermal capacitance
R: Thermal resistance
c: Specific heat for air
Q: Heat flux
m: Mass flow rate
Δt: Discrete time interval
a: Regression coefficient

sub/superscript
k: Discrete time index
d: Discharge
i: Zone index
dis: Disturbance
a: Ambient

Deployment of transactive control
- AHU model

AHU Fan power

$$P_m^k = b_m^1\left(m_m^k\right) + b_m^2\left(m_m^k\right)^2 + b_m^3\left(m_m^k\right)^3$$

Chiller Power:

$$P_m^k = \begin{cases} 0 \quad if\ unoccupied\ or\ T_a^k \le T_{m,dis}^k \\ \dfrac{m_m^k C_{air}\left(T_{m,mix}^k - T_{m,dis}^k\right)}{\xi COP} \quad else \end{cases}$$

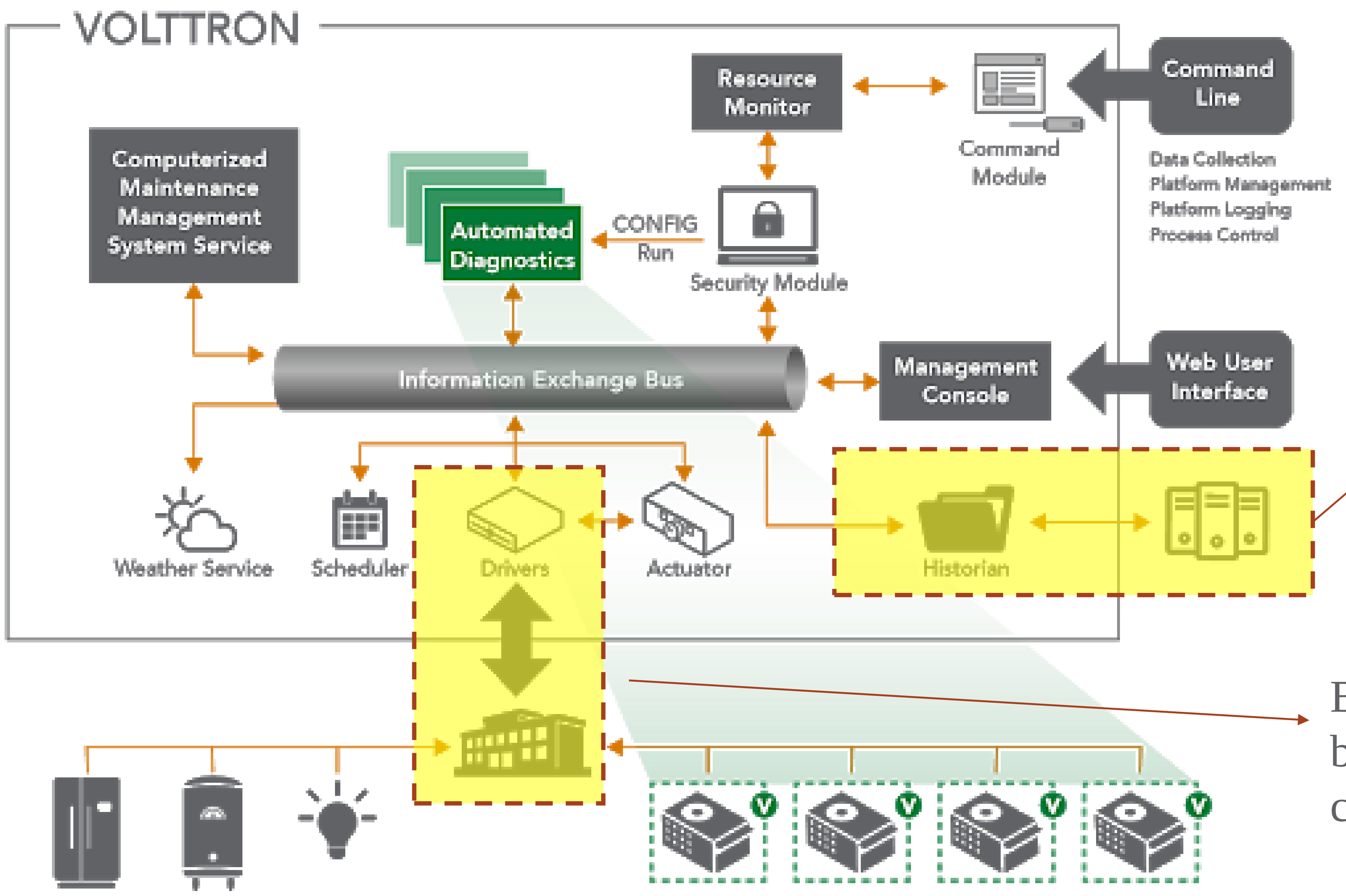
where $T_{m,mix}^k = \begin{cases} T_a^k \quad if T_a^k \le T_{eco} \\ \varphi T_a^k + (1-\varphi) T_{m,ret} \quad else \end{cases}$

for VAV, $T_{m,dis}^k = T_{m,dis}$

P: Power
b: Regression coefficient
n: Number of Zones
ξ: Sensible heat ratio
COP: Coefficient of performance

sub/superscript
j: AHU index
l: Chiller index
eco: Air-side economizer
mix: Mixed air
ret: Return air
φ: Outdoor air ratio

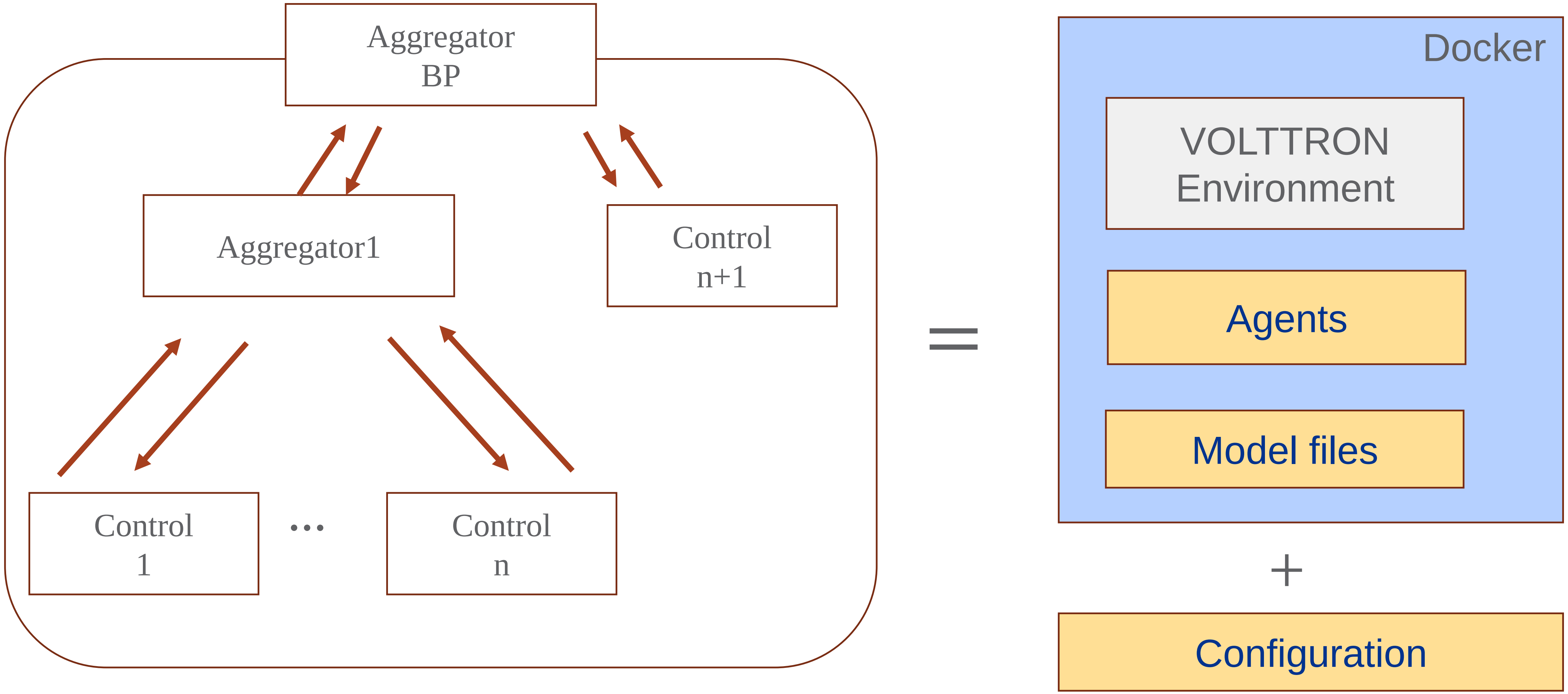
Deployment of transactive control
- Communication support from VOLTTRON



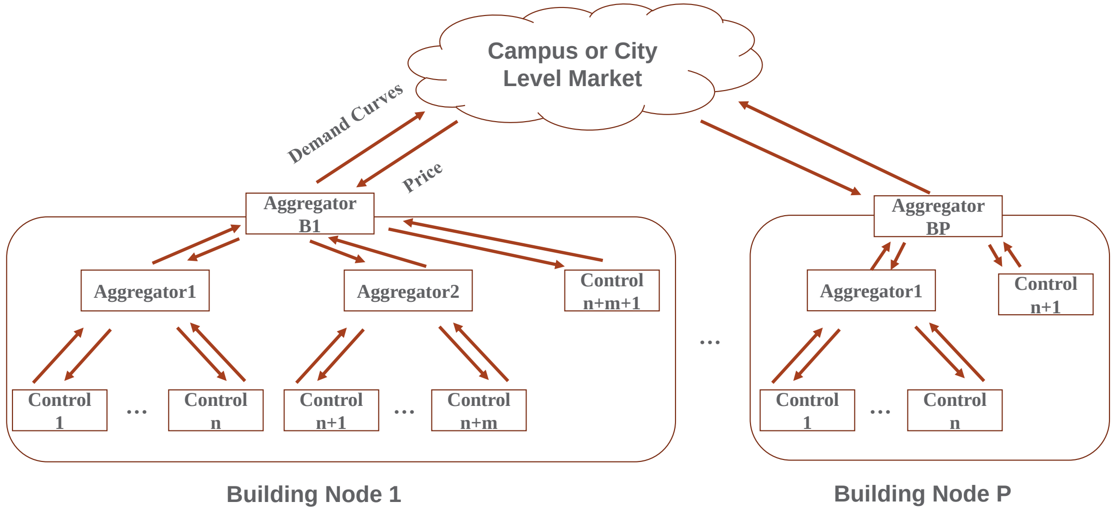
Data management auxiliary functions

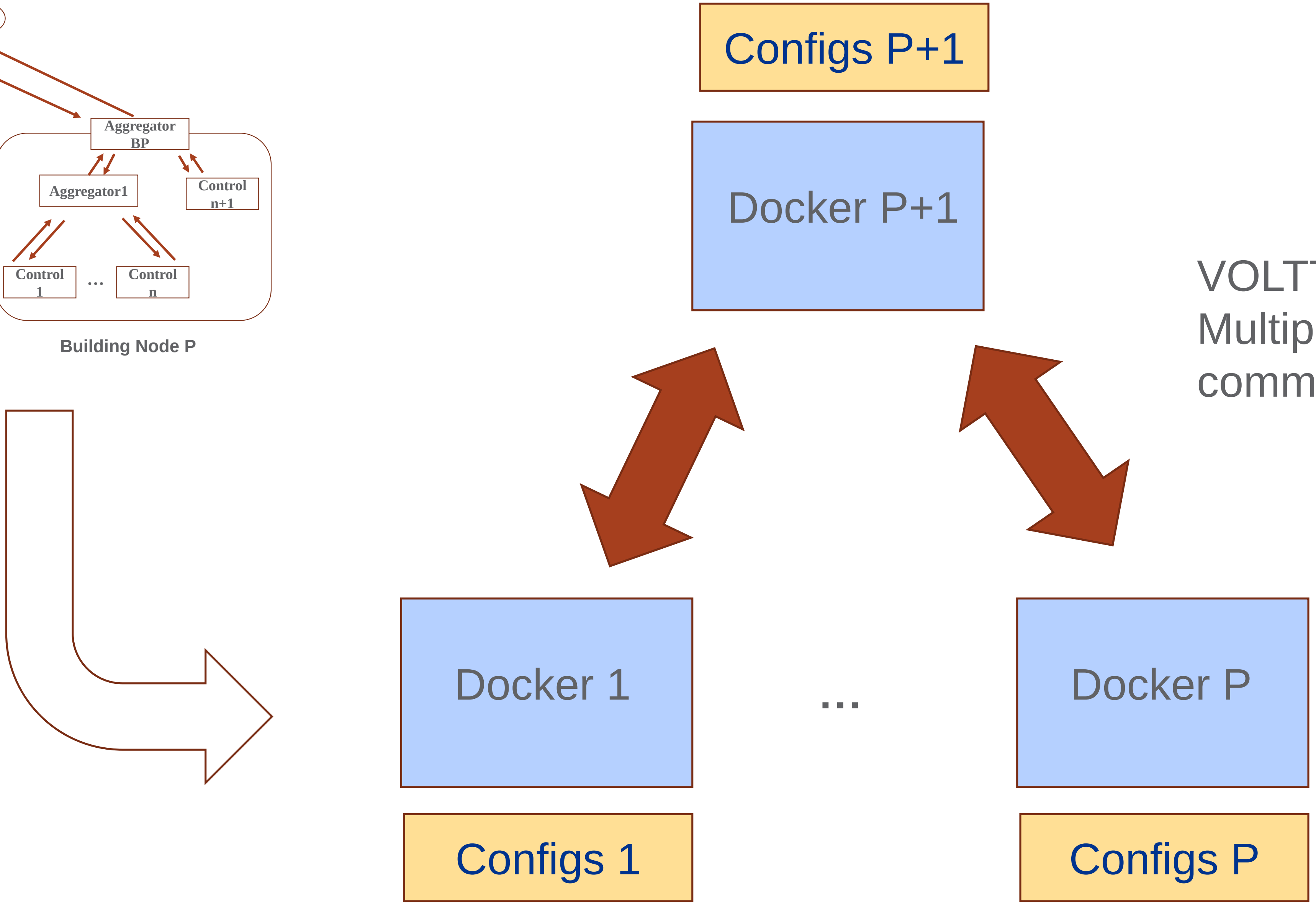
BACnet/Modbus based communication

Deployment of transactive control
- VOLTTRON-based Implementation



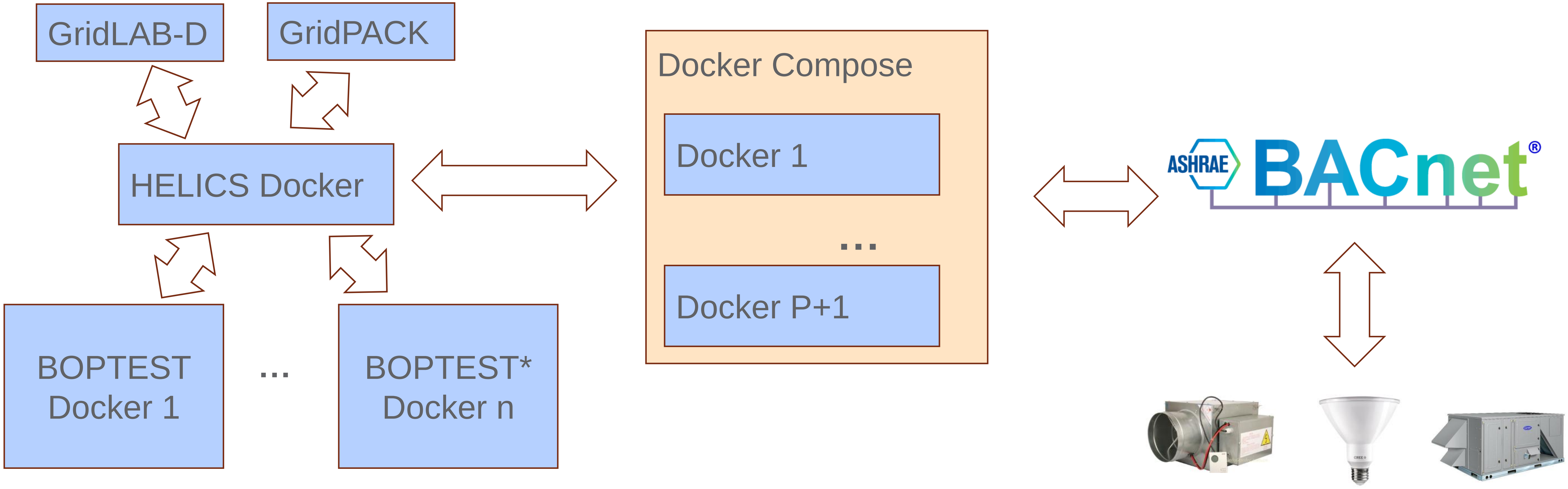
Deployment of transactive control
- VOLTTRON-based Implementation





VOLTTRON Multiple-platform communication

Deployment of transactive control
- Vision for future integration



simulation tests

real building tests

* BOPTEST: Building Operations Testing Framework :https://www.energy.gov/eere/buildings/boptest-building-operations-testing-framework

Conclusions

- Distributed control is promising for operating large scale infrastructures
- Distributed control may pose new challenges in the real world deployment
- VOLTTRON can be used to facilitate the deployment of distributed control such as transactive control for building systems

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