A Regulation Adaptation Model for Multi-Agent Systems

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*Mines Saint-Etienne, Univ Clermont Auvergne, INP Clermont Auvergne, CNRS, UMR 6158 LIMOS, F-42023 Saint-Etienne France
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June 23, 2025

Focus on. . .

1 Introduction

2 Regulation Management Overview

3 Regulation Adaptation Model

4 Regulation Adaptation Prototype

5 Conclusions and Future Work

Context

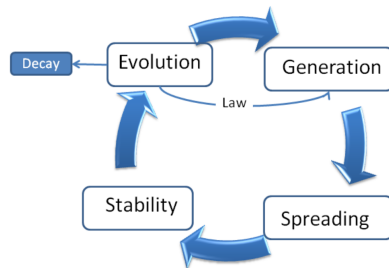In a multi-agent system (MAS), agents can be governed by *regulations*.

Regulation management denotes the capabilities (i.e., functionalities, procedures, mechanisms) and the representations (e.g., norms, rules, sanctions) used to regulate MAS.

$\rightarrow$ The ability to *adapt regulation* at runtime is essential for maintaining system flexibility and robustness.

Problematic

Sparse literature on regulation adaptation:

- **theoretical**: norm dynamics and evolution [Andrighetto et al., 2013]
  [Boella and van der Torre, 2004, Castelfranchi, 2016]

- **social simulation**: norm emergence and evolution in agent
  societies [Agrawal et al., 2022, Conte et al., 2013, Mashayekhi et al., 2022, Li et al., 2024]

- **computational**: mechanisms for revising norms or sanc-
  tions [Bou et al., 2006, Campos et al., 2013, Cardoso and Oliveira, 2009, Centeno et al., 2011]
  [Dell'Anna et al., 2020]

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- **representation**: programming constructs for norm
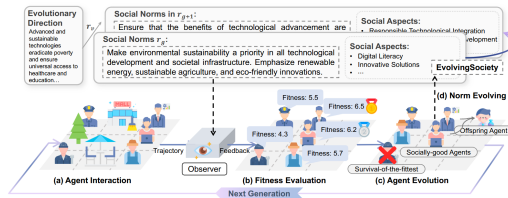 change [Dastani et al., 2012]

Social norm dynamics [Andrighetto et al., 2013]

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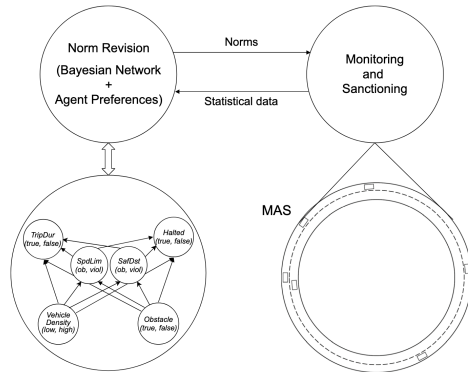

Agent alignment in evolving social norms [Li et al., 2024]

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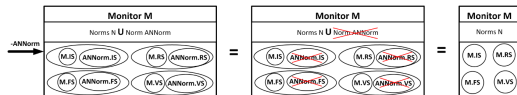 change [Dastani et al., 2012]

Sanction revision [Dell'Anna et al., 2020]

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Norm annulments [Gómez-Sebastià et al., 2012]

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\begin{array}{ll}
\langle\text{ic-rule}\rangle & = \langle\text{ant}\rangle \text{ "=>" } \langle\text{ic-cons}\rangle; \\
\langle\text{ant}\rangle & = \langle\text{b-lit}\rangle \mid \langle\text{i-lit}\rangle \mid \langle\text{r-lit}\rangle \mid \langle\text{ni}\rangle \mid \langle\text{ant}\rangle \text{ "and" } \langle\text{ant}\rangle; \\
\langle\text{ni}\rangle & = \text{"(" } \langle\text{id}\rangle \text{ "," } \langle\text{OP}\rangle \text{ "," } \langle\text{ddln}\rangle \text{ ")";} \\
\langle\text{ic-cons}\rangle & = \langle\text{ic-list}\rangle \langle\text{ic-list}\rangle; \\
\langle\text{ic-list}\rangle & = \text{"[" } \langle\text{ni}\rangle \text{ \{ "," } \langle\text{ni}\rangle \text{ \} "]" } \mid \text{"[ ]";} \\
\langle\text{sc-rule}\rangle & = \langle\text{ant}\rangle \text{ "=>" } \langle\text{sc-cons}\rangle \mid \langle\text{ant}\rangle \text{ "=>*" } \langle\text{sc-cons*}\rangle; \\
\langle\text{sc-cons}\rangle & = \langle\text{sc-list}\rangle \langle\text{sc-list}\rangle; \\
\langle\text{sc-cons*}\rangle & = \langle\text{sc-list}\rangle \langle\text{sc-list*}\rangle; \\
\langle\text{sc-list}\rangle & = \text{"[" } \langle\text{norm}\rangle \text{ \{ "," } \langle\text{norm}\rangle \text{ \} "]" } \mid \text{"[ ]";} \\
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\langle\text{norm*}\rangle & = \langle\text{norm}\rangle \mid \text{"nil";}
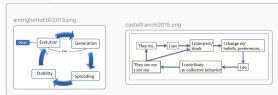\end{array}
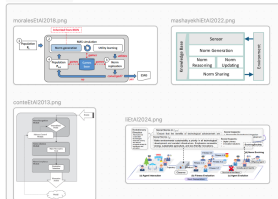$$

Norm change rules [Dastani et al., 2012]

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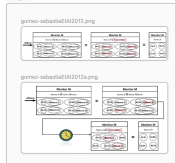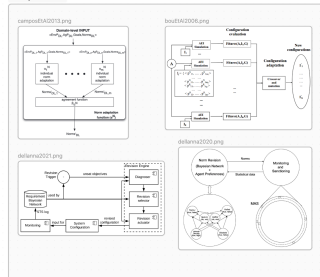- **legal**
- **representation**

$\rightarrow$ *There is no comprehensive computational model defining the representations and capabilities
involved in the process to adapting regulations in MAS*
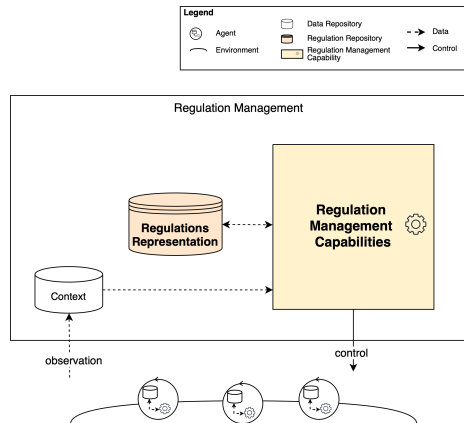
Objective

Propose a *general adaptation model for MAS* that defines *representations* and *capabilities* to manage the process to adapt regulations

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Regulation Management Overview

- Regulation Representation
- Regulation Management Capabilities
- Context

Regulation Representation

Regulation Specification *REG*

- s-reg = ⟨constitutive, *condition*, *brute*, *institutional*⟩

- s-reg = ⟨regulative, *condition*, *subject*, *modality*, *object*⟩

- s-reg =
  ⟨sanction, *condition*, *sanctioned*, {⟨*s-reg*, *status*⟩}, *content*⟩

Regulations' State *RS*

- i-reg = ⟨*s-reg*, θ, *status*⟩

Regulations' Fact *RF*

- *constitutive facts*

- *normative facts*

- *sanction facts*

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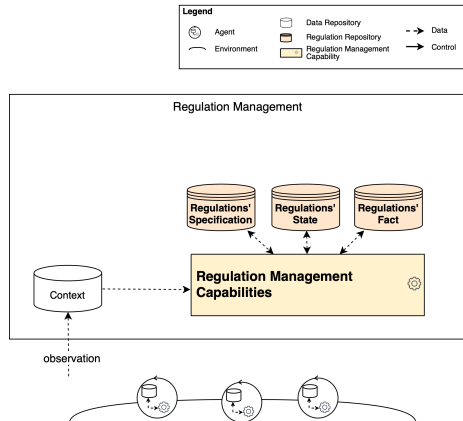
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Regulation Management Capabilities

- Regiment Capability
- Enforce Capability
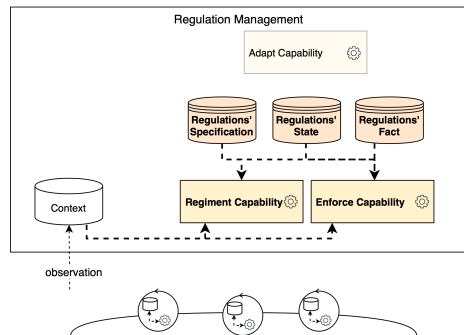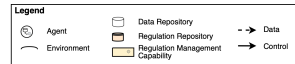- Adapt Capability

Regulation Management Capabilities

- *Regiment Capability*
  regiment : $\mathcal{P}(REG) \times \mathcal{P}(RS) \times \mathcal{P}(RF) \times \mathcal{P}(CTX) \rightarrow \mathcal{P}(RS) \times \mathcal{P}(RF)$
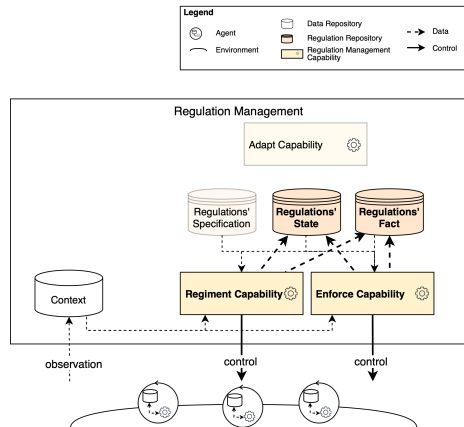- *Enforce Capability*
  enforce : $\mathcal{P}(REG) \times \mathcal{P}(RS) \times \mathcal{P}(RF) \times \mathcal{P}(CTX) \rightarrow \mathcal{P}(RS) \times \mathcal{P}(RF)$
- Adapt Capability

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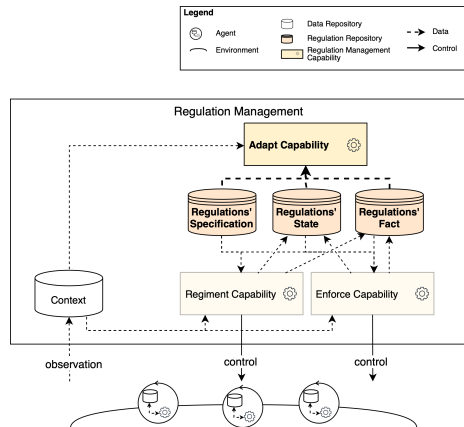- Regiment Capability
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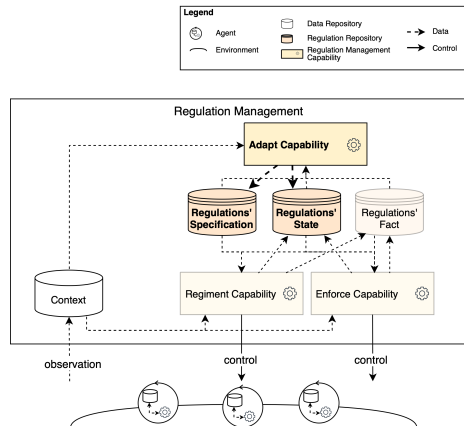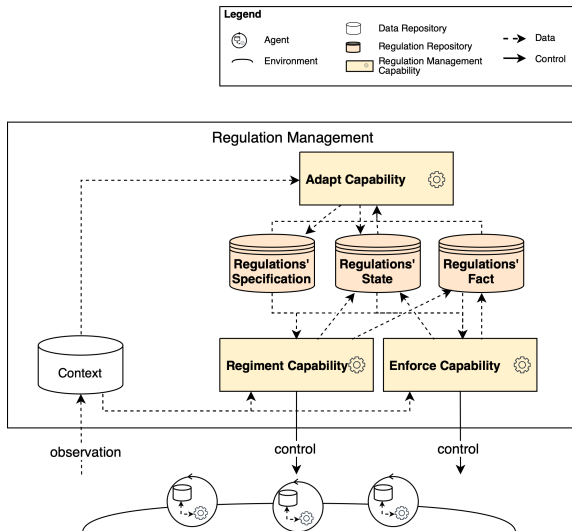- Enforce Capability
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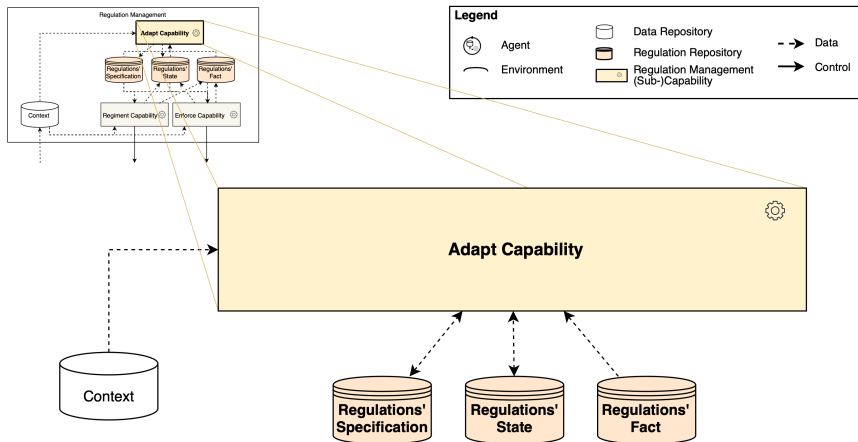 $\mathcal{P}(REG) \times \mathcal{P}(RS)$
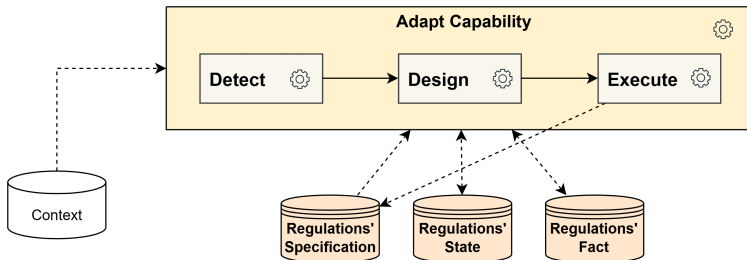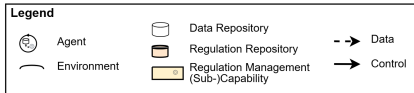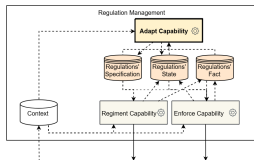
Regulation Management Model

Focus on...

Regulation Adaptation Model

Regulation Adaptation Sub-Capabilities

Regulation Adaptation Representations

Adaptation Facts *(who, what, where, when, why, how* **has to** *detect/design/execute)*

$$\text{detect-fact} = \langle \textit{who}, \textit{what}, \textit{where}, \textit{when}, \textit{why}, \textit{how} \rangle,$$
$$\text{design-fact} = \langle \textit{who}, \textit{what}, \textit{where}, \textit{when}, \textit{why}, \textit{how} \rangle,$$
$$\text{execute-fact} = \langle \textit{who}, \textit{what}, \textit{where}, \textit{when}, \textit{why}, \textit{how} \rangle.$$

e.g., design-fact = $\langle$alice, reg1, REG, new_object, unfulfillment_count(X) $\wedge$ X > T, modify(reg1, object)$\rangle$

alice **has to** *design an adaptation for* reg1 *in* REG, *when* new_object *holds, because the* unfulfillment_count(X) *is greater than the threshold* T, *by* modify *the* object *of* reg1.

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Detect

Let $R = REG \times RS$

$detect : \mathcal{P}(R) \times \mathcal{P}(RF) \times \mathcal{P}(CTX) \rightarrow \mathcal{P}(R)$

Require: $R : REG \cup RS, RF, CTX$
Ensure: $DET\text{-}R \subseteq REG \cup RS$
1: $DET\text{-}R \leftarrow \emptyset$
2: **for all** $r \in R$ **do**
3:     **if** $detectDecision(r, R, RF, CTX)$ **then**
4:         $DET\text{-}R \leftarrow DET\text{-}R \cup r$
5:     **end if**
6: **end for**
7: **return** $DET\text{-}R$
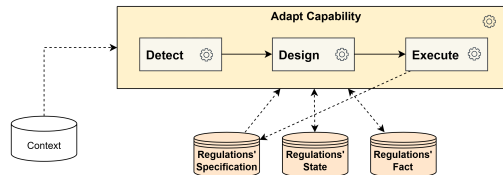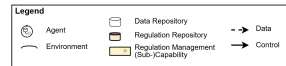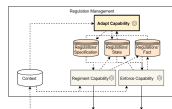
Design

Let $R = REG \times RS$

$$design : \mathcal{P}(R) \times \mathcal{P}(R) \times \mathcal{P}(RF) \times \mathcal{P}(CTX) \rightarrow \mathcal{P}(OP \times R \times R)$$

Require: $R : REG \cup RS$, $DET\text{-}R : Reg \cup Rs$, RF, CTX
Ensure: $DES\text{-}R \in OP \times DET\text{-}R \times DES\text{-}R$
1: $DES\text{-}R \leftarrow \emptyset$
2: **for all** $det\text{-}r \in DET\text{-}R$ **do**
3:     $\langle op, des\text{-}r \rangle = designDecision(det\text{-}r, R, RF, CTX)$
4:     $DES\text{-}R \leftarrow DES\text{-}R \cup \langle op, det\text{-}r, des\text{-}r \rangle$
5: **end for**
6: **return** $DES\text{-}R$
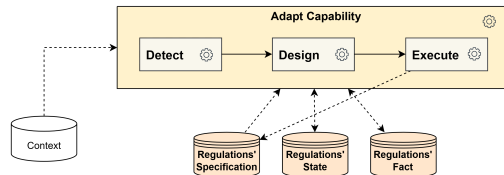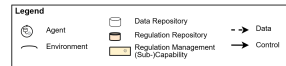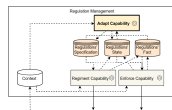
Execute

Let $R = REG \times RS$

execute :
$\mathcal{P}(R) \times \mathcal{P}(OP \times R \times R) \times \mathcal{P}(RF) \times \mathcal{P}(CTX) \rightarrow \mathcal{P}(R)$

Require: $R : REG \cup RS, DES\text{-}R : OP \times R \times R, RF, CTX$
Ensure: $R : REG' \cup RS'$
 1: **for all** $\langle op, det\text{-}r, des\text{-}r \rangle \in DES\text{-}R$ **do**
 2:   **if** $executeDecision(op, det\text{-}r, des\text{-}r, R, RF, CTX)$ **then**
 3:     **if** $op = \texttt{create}$ **then**
 4:       $R \leftarrow R \cup des\text{-}r$
 5:     **else if** $op = \texttt{modify}$ **then**
 6:       $R \leftarrow R \setminus det\text{-}r \cup des\text{-}r$
 7:     **else if** $op = \texttt{remove}$ **then**
 8:       $R \leftarrow R \setminus det\text{-}r$
 9:     **end if**
10:   **end if**
11: **end for**
12: **return** R

Adaptation Facts with Regulations

Constitutive Norms *(creates the adaptation facts based on brute or other regulation facts)*

$$\text{s-reg} = \langle \texttt{constitutive}, \textit{conditions}, \textit{brute}, \boxed{\textit{adapt-fact}} \rangle$$

Regulative Norms *(consumes the adaptation facts and regulate the behaviors producing adapt goals)*

$$\text{s-reg} = \langle \texttt{regulative}, \boxed{\textit{adapt-fact}} \wedge \textit{conditions}, \textit{subject}, \textit{modality}, \boxed{\textit{adapt-goal}} \rangle$$

Adaptation Goals *(who, what, where, when, why, how* **has been** *detected/designed/executed)*

$$\text{detected} = \langle \textit{who}, \textit{what}, \textit{where}, \textit{when}, \textit{why}, \textit{how} \rangle$$
$$\text{designed} = \langle \textit{who}, \textit{what}, \textit{where}, \textit{when}, \textit{why}, \textit{how} \rangle$$
$$\text{executed} = \langle \textit{who}, \textit{what}, \textit{where}, \textit{when}, \textit{why}, \textit{how} \rangle$$

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Adaptation Facts with Regulations

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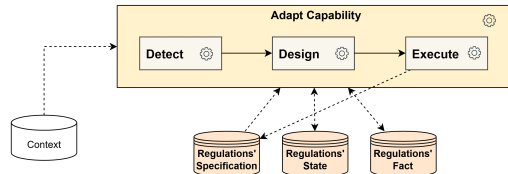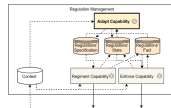$$\text{executed} = \langle who, what, where, when, why, how \rangle$$

Regulation Adaptation Process

Require: $R : REG \cup RS, RF, CTX$
Ensure: $R : REG' \cup RS'$
 1: $DET\text{-}F \subseteq RF, DES\text{-}F \subseteq RF, EXE\text{-}F \subseteq RF$
 2: **for all** $detect\text{-}fact \in DET\text{-}F$ **do**
 3:    $DET\text{-}R = detect\ (R, RF, CTX, detect\text{-}fact)$
 4:    **for all** $design\text{-}fact \in DES\text{-}F$ **do**
 5:       $DES\text{-}R = design\ (R, DET\text{-}R, RF, CTX, design\text{-}fact)$
 6:       **for all** $execute\text{-}fact \in EXE\text{-}F$ **do**
 7:          $R = execute\ (R, DES\text{-}R, RF, CTX, execute\text{-}fact)$
 8:       **end for**
 9:    **end for**
10: **end for**
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3. Regulation Adaptation Model

4. **Regulation Adaptation Prototype**

5. Conclusions and Future Work

Extension and Integration of Regulation Representation Languages

To enable adaptive regulation, we integrated:

- NPL(s) [Yan et al., 2025] supports regulative norms and sanction rules
- SAI (Situated Artificial Institutions) [de Brito et al., 2018] supports constitutive norms

We extended NPL(s) to support the adaptation operations for regulative norms and sanction rules:

- create
- modify
- remove

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Regulation Representation

Constitutive norm in SAI:

$$id \; : \; x \; \texttt{count-as} \; y \; [\texttt{when} \; t] \; [\texttt{while} \; m] \; .$$

Regulative norm in NPL(s):

```
norm id :  φ -> ψ
    [if fulfilled:  sr₁(args), ..., srₙ(args)]
    [if unfulfilled:  srₙ₊₁(args), ..., srₘ(args)]
    [if inactive:  srₘ₊₁(args), ..., sr_z(args)] .
```

Sanction rule in NPL(s):

```
sanction-rule srᵢ(args) :  ρ -> sanction(who, what) .
```

Regulation Adaptation Dynamics

- Context

- Regulation Specification
  - → Constitutive Specification
  - → Normative Specification
- Regulation State and Regulation Fact
  - → Constitutive State
  - → Normative State

- Regiment, Enforce, and *Adapt* Capabilities
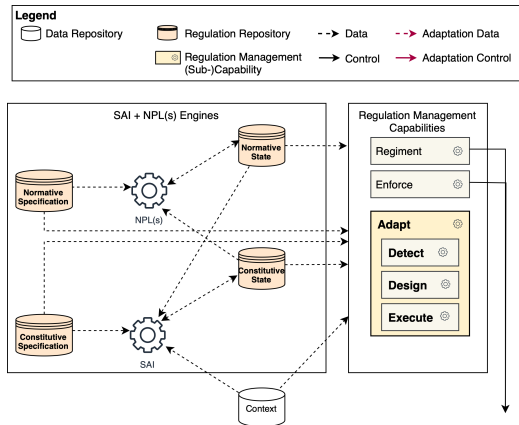
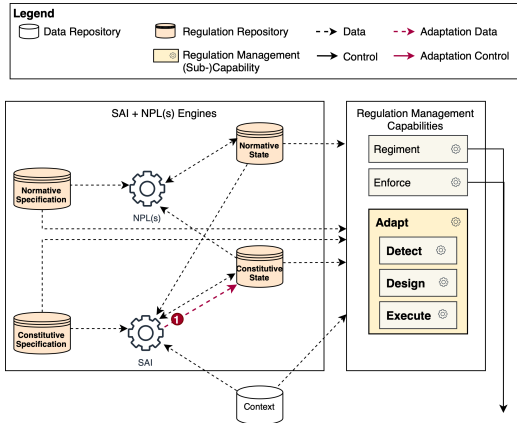# Regulation Adaptation Dynamics

Constitutive Specification:

```
1: count-as detect(alice, n, count(unfulfilled(order(N))))
     while unfulfilled(obligation(U, (order(N) & play(U, unit,
     _)), O, D)) .
```

❶

Constitutive State:

```
//detect(who, what, how)
detect(alice, n, count(unfulfilled(order(N))))
```
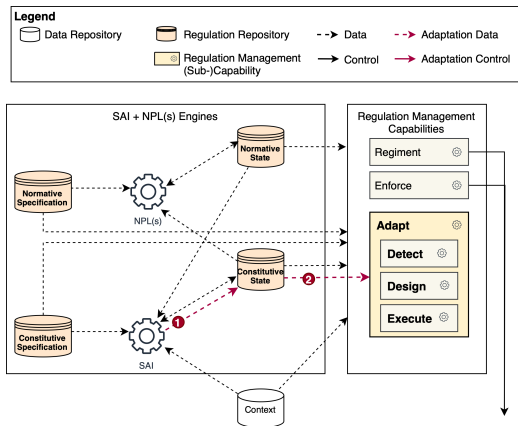
Regulation Adaptation Dynamics

Constitutive State:

`detect(alice, n, count(unfulfilled(order(N))))`

❷

Detect Capability

Regulation Adaptation Dynamics

Constitutive Specification:

```
2: unfulfilled_count(n, N, Count) count-as design(alice, n,
      modify(object, N)) while Count>=3 .
```
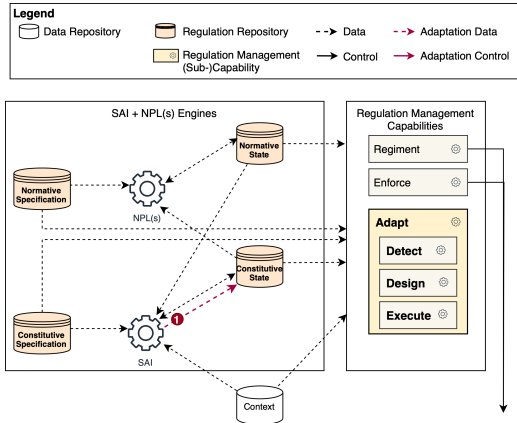
❶

Constitutive State:

design(alice, n, modify(object, N))

Regulation Adaptation Dynamics

Constitutive State:

```
design(alice, n, modify(object, N))
```

❷

Normative Specification:

```
norm des : design(alice, n, modify(object, N))
  ->obligation(alice, des, designed(alice, NewNorm,
      modify(object(n), X)), '2 minutes') .
```
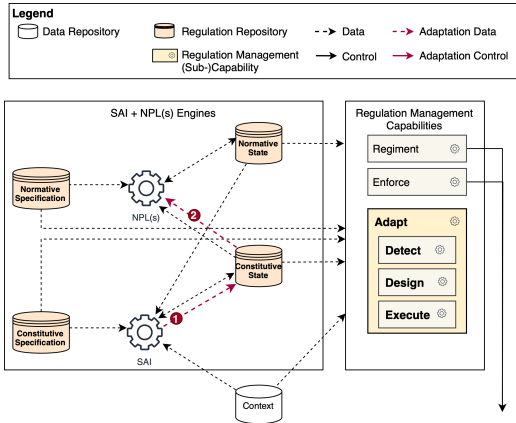
Regulation Adaptation Dynamics

Normative Specification:

```
norm des : design(Who, n, modify(object, N))
 -> obligation(Who, des, designed(alice, NewNorm,
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Normative State:

```
obligation(alice, des, designed(alice, NewNorm,
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```

Regulation Adaptation Dynamics

Normative State:

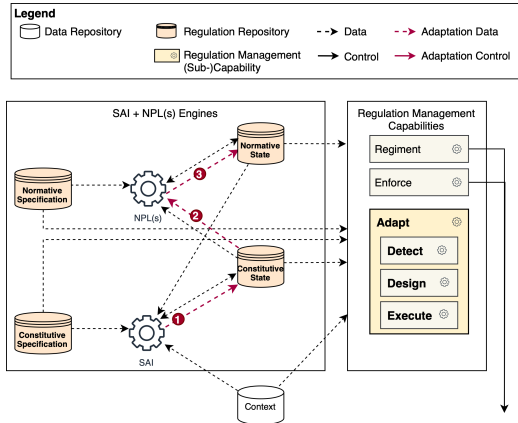`obligation(alice, des, designed(alice, NewNorm,`
`    modify(object(n), X)), '2 minutes')`

Design Capability

`designed(alice, NewNorm, modify(object(n), X))`

Regulation Adaptation Dynamics

Execute Capability

❺
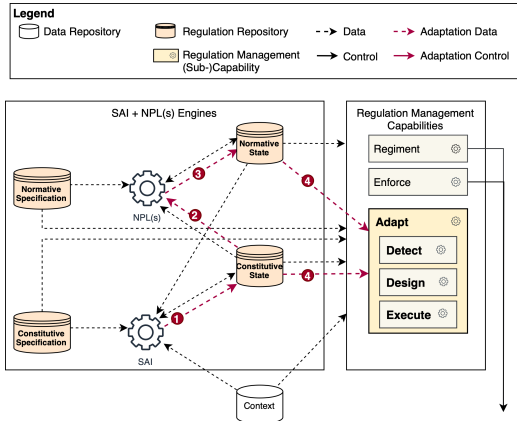
.modify_norm(Id, Norm)

Regulation Adaptation Dynamics
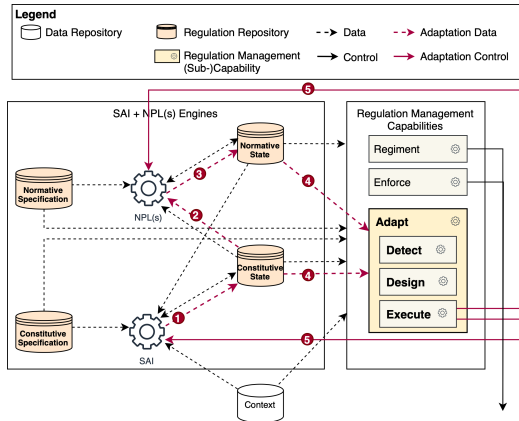
Execute Capability


```
.add_norm(Id, Norm)          .add_sanction_rule(Id, Norm)
.modify_norm(Id, Norm)       .modify_sanction_rule(Id, Norm)
.remove_norm(Id)             .remove_sanction_rule(Id, Norm)
```
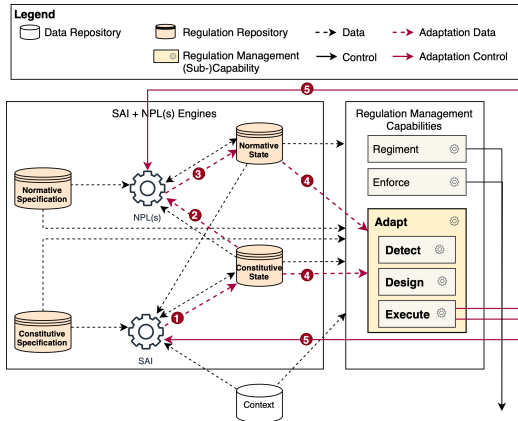
Regulation Adaptation Dynamics

`.modify_norm(Id, Norm)`

6

Normative Specification
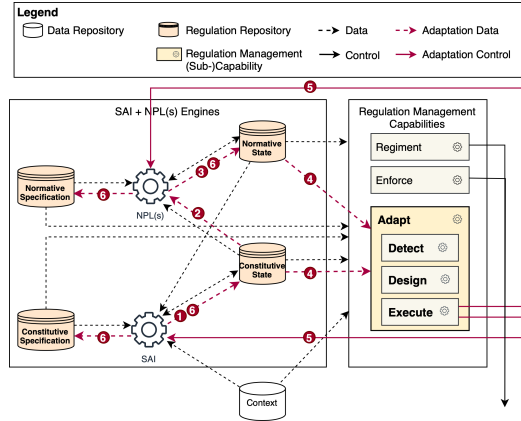
Extended Normative Agent Architecture

- Context → *Mental State*
- Regulation Specification and State → *Beliefs*
- Regulation Adaptation Capabilities → *Plans*
- Adaptation Operations → *Internal Actions*
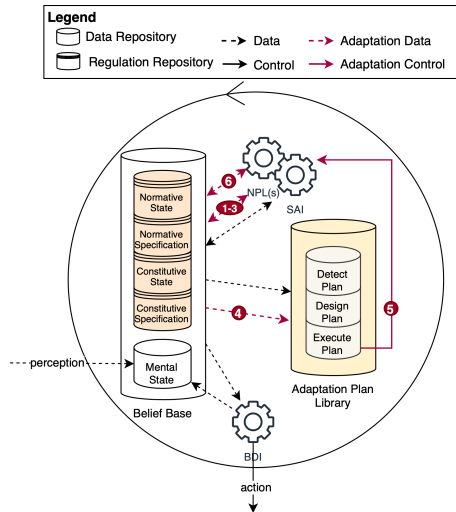
Focus on. . .

Conclusions

- Proposed a *general* regulation adaptation model for MAS defining the representations and capabilities
  - can be implemented in different MAS platforms
  - can be implemented within an organization structure or within an agent architecture

- Prototype implementation by *extending* and *integrating* SAI and NPL(s) normative engines
  - extended NPL(s) to support regulation adaptation operations
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Future Work

Conceptual side:

- explore the *regulation management model* to cover the *regiment* and *enforce* capabilities
- explore the regulation management across the *components of MAS*, i.e., within the organization, agent, environment, and interaction dimensions.

Practical side:

- complete the extension of SAI and NPL(s) to fully support the *regulation adaptation operations* proposed in our model
- validate the generality of the model by integrating it into an *organization* structure and eventually into a *hybrid* organization and agent regulation management

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Thank you for your attention!

The source code and examples are available at `https://github.com/yan-elena/nagent-adapt`

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