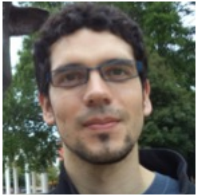
LTL and Beyond:
Formal Languages for Reward Function Specification in Reinforcement Learning

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Richard Valenzano

Sheila A. McIlraith

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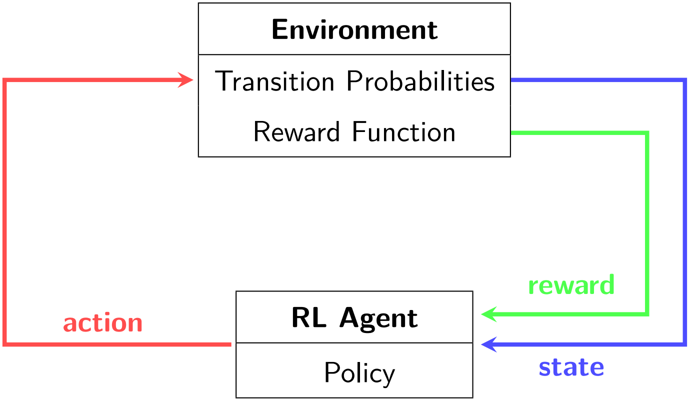
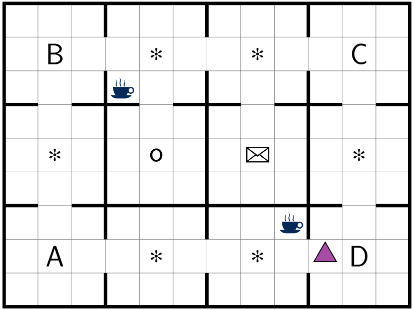
Reinforcement learning (RL)



Takeaway points

- **Reward machines (RMs)** are a form of automaton that are a way of representing (temporally extended) reward functions.
- Formulas in many temporal languages (e.g., LTL_f) can be **translated** into RMs.
- Once a reward function is represented as an RM, its structure can be exploited by various RM-specific **algorithms** for more efficient reinforcement learning.

Example (the Office World)



Symbol	Meaning
▲	Agent
✻	Decoration
☕	Coffee machine
✉	Mail room
o	Office
A,B,C,D	Marked locations

Task: Patrol A, B, C, and D.

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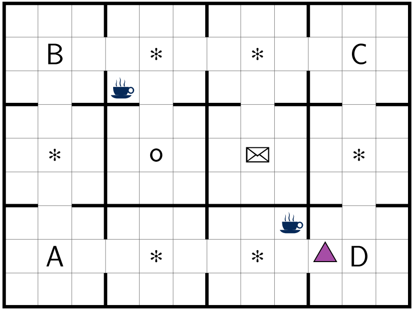

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Task: Patrol A, B, C, and D.

- For RL, the task has to be specified in terms of a reward function
  - which might be derived from a formula in **Linear Temporal Logic (LTL)** or some other formal language, or programmed directly.

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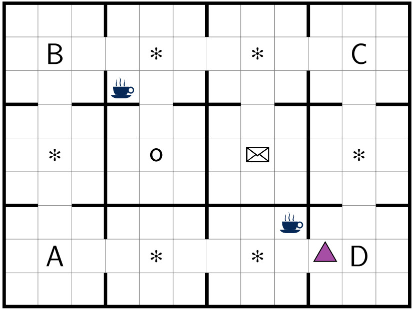


```python
m = 0 # global variable
def get_reward(s):
  if m == 0 and s.at("A"):
    m = 1
  if m == 1 and s.at("B"):
    m = 2
  if m == 2 and s.at("C"):
    m = 3
  if m == 3 and s.at("D"):
    m = 0
    return 1
  return 0
```

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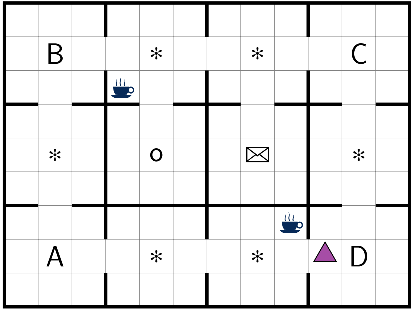

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Reward Function

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- The reward function is then often treated as a **black box**.

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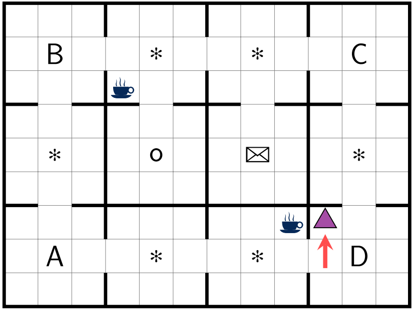

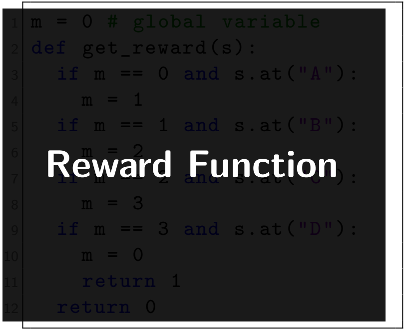

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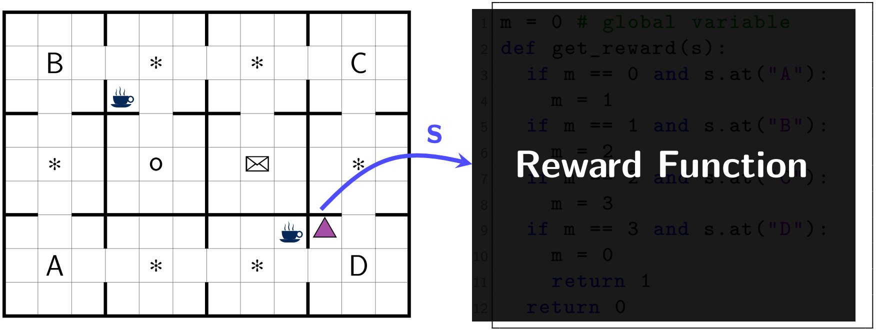

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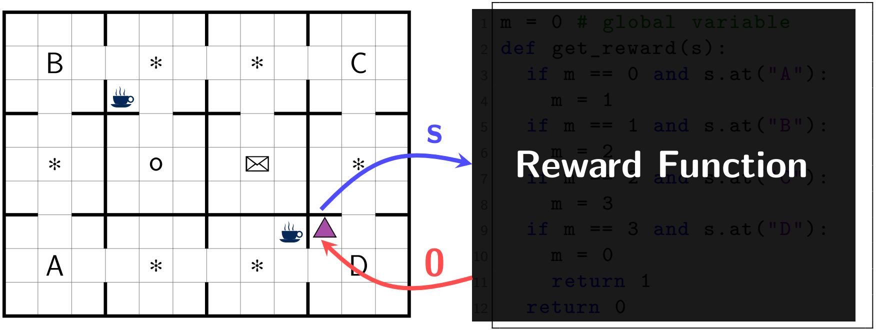

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What if we exposed the reward function structure?

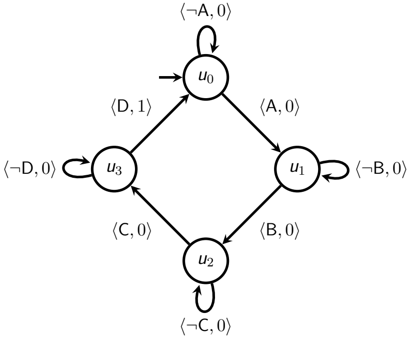
We previously introduced **reward machines** in an ICML paper.[1]

Suppose we have a vocabulary $\mathcal{P}$ to label environment states, e.g.,

$$\mathcal{P} = \{☕, \boxtimes, \mathsf{o}, \circledast, \mathsf{A}, \mathsf{B}, \mathsf{C}, \mathsf{D}\}.$$

A **reward machine (RM)** has

- A finite set of states, with an initial state u_0
- A set of transitions labelled by:
  - a logical condition (using the vocabulary) and
  - a reward (or more generally a reward function).



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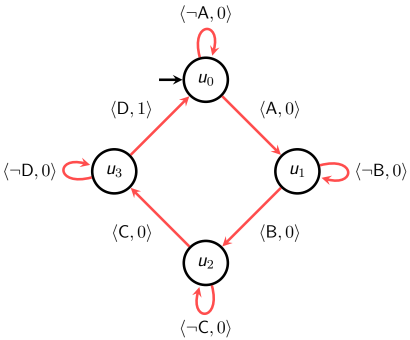

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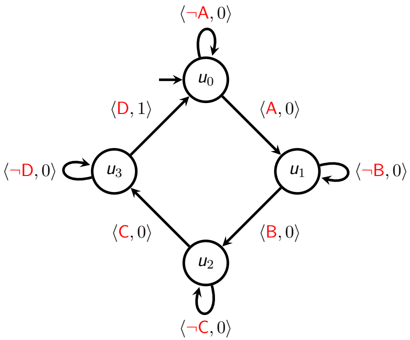

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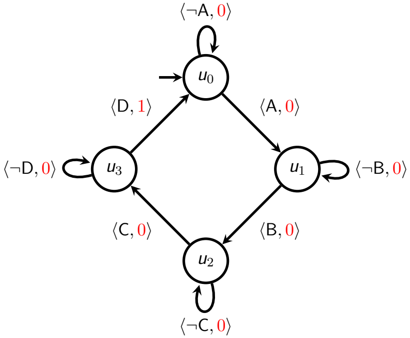

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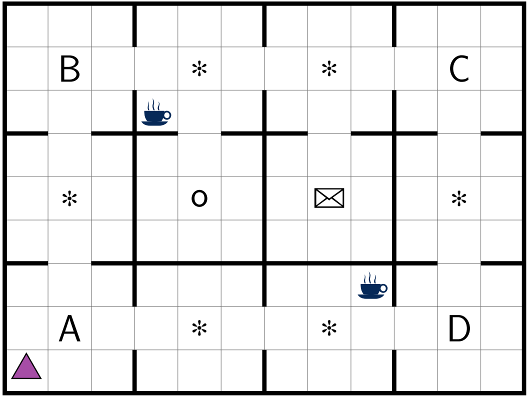
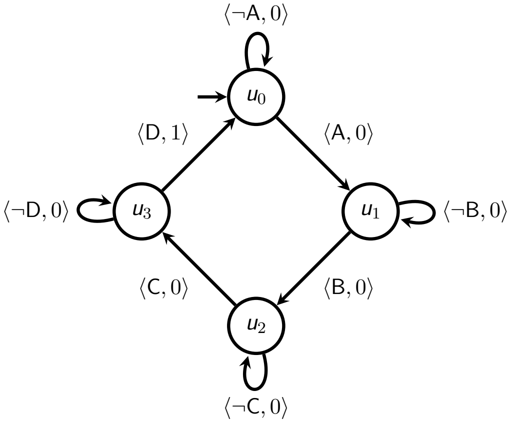
How does a reward machine work?





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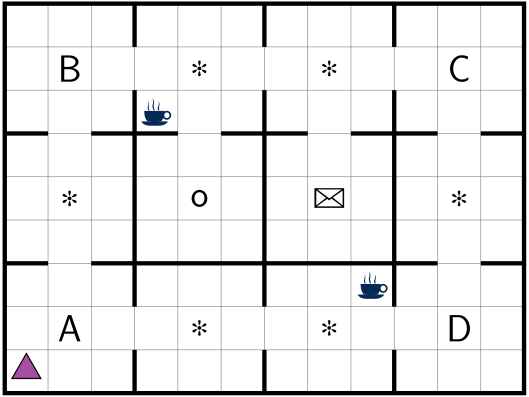

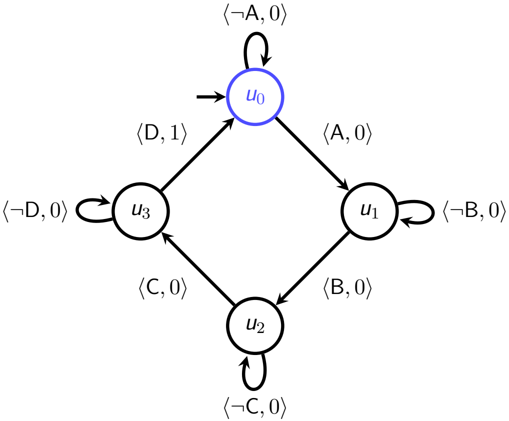

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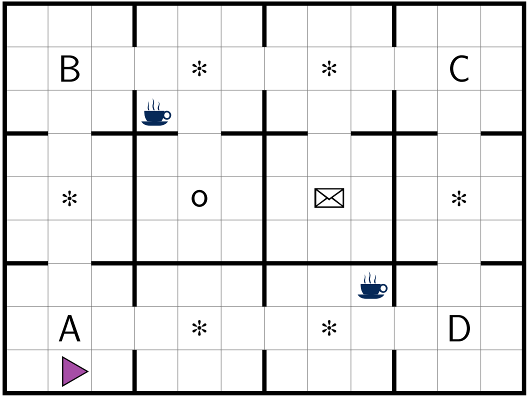

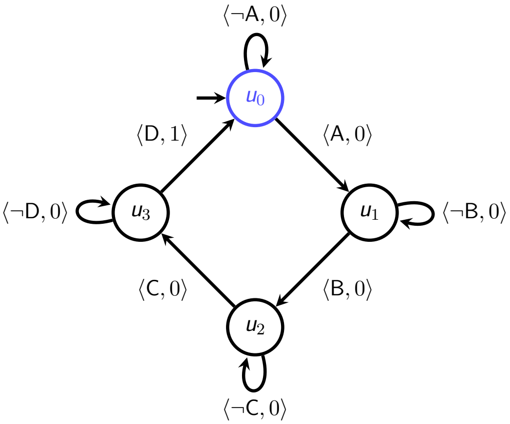

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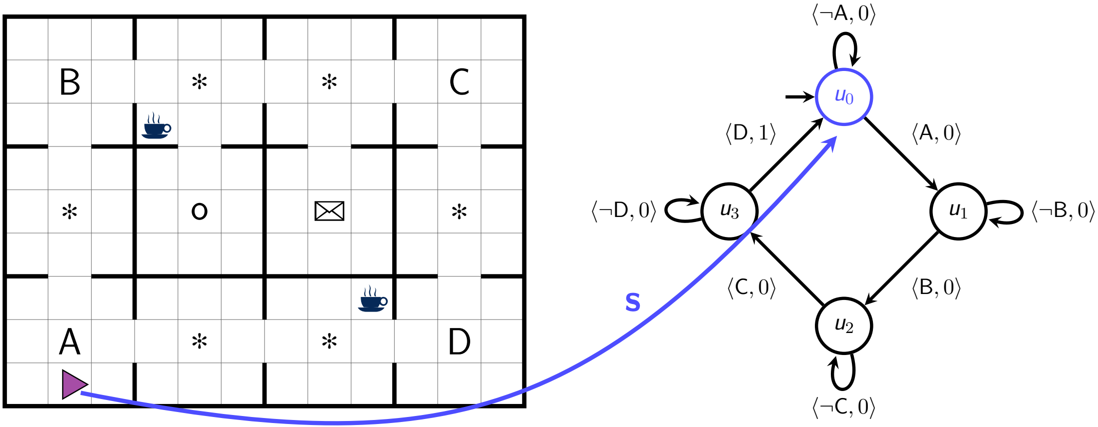

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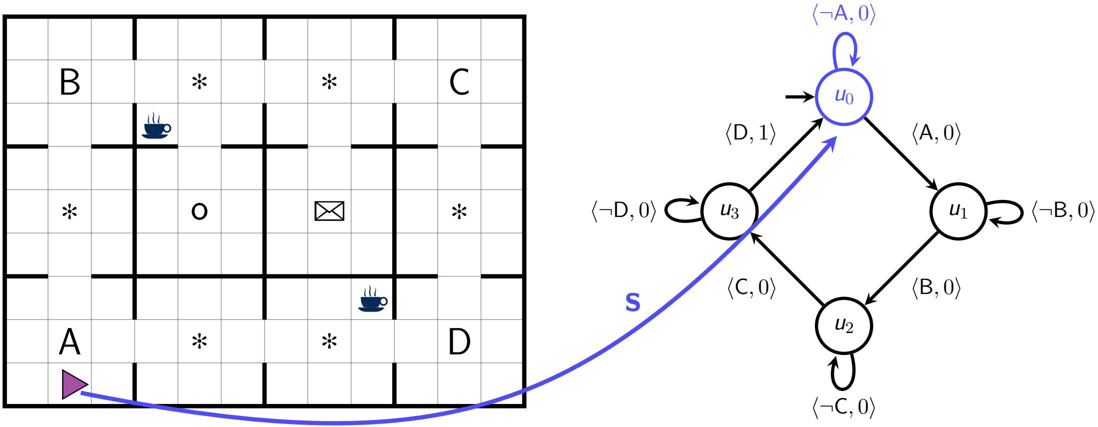

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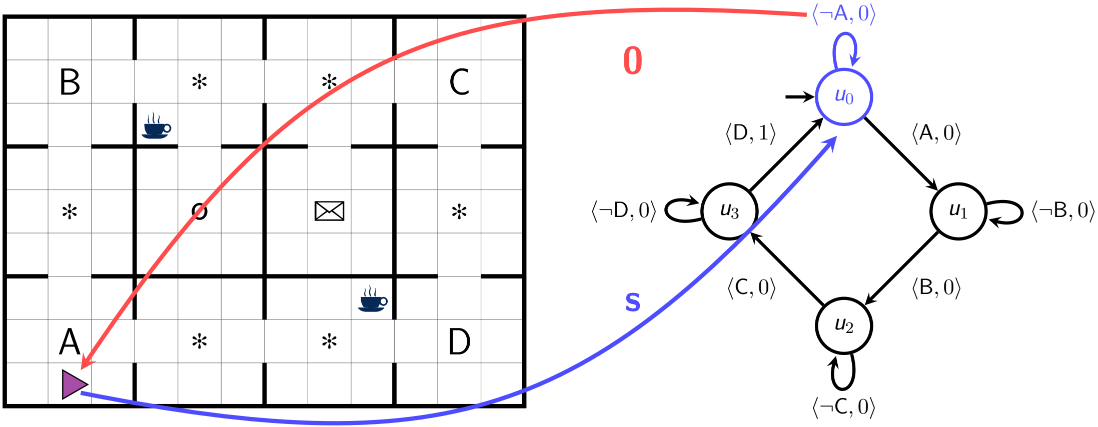

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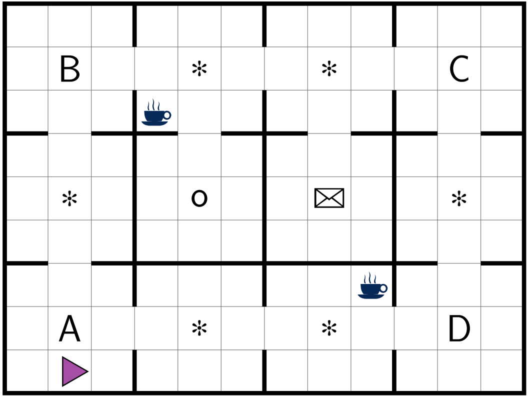

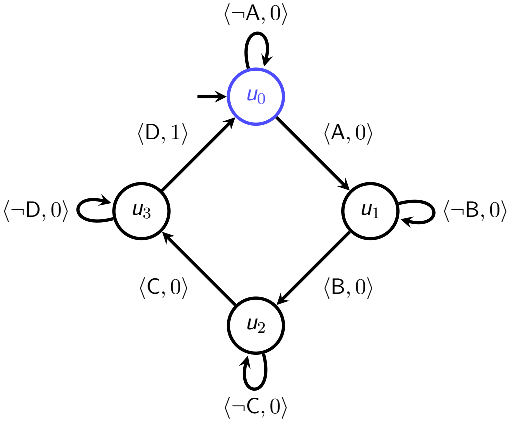

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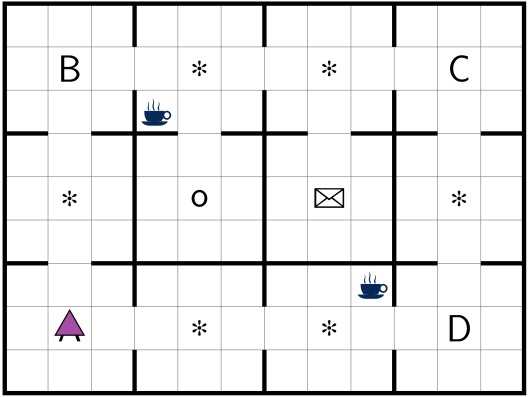

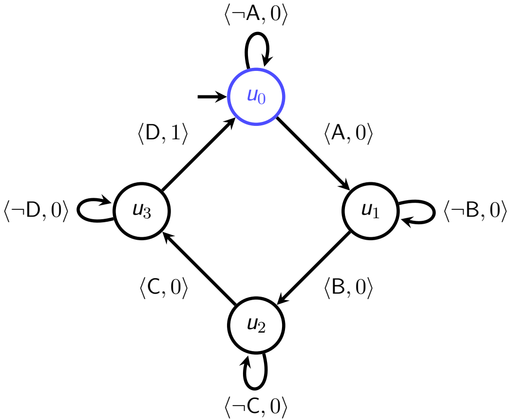

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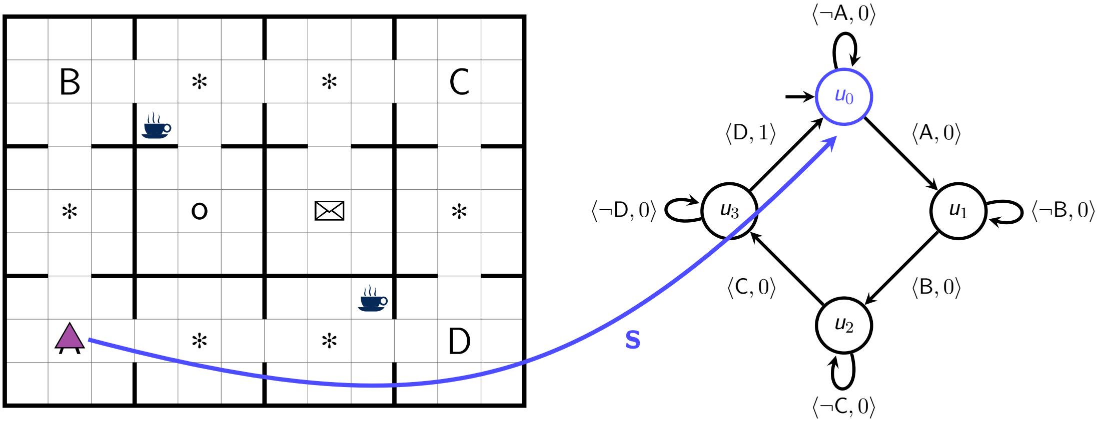

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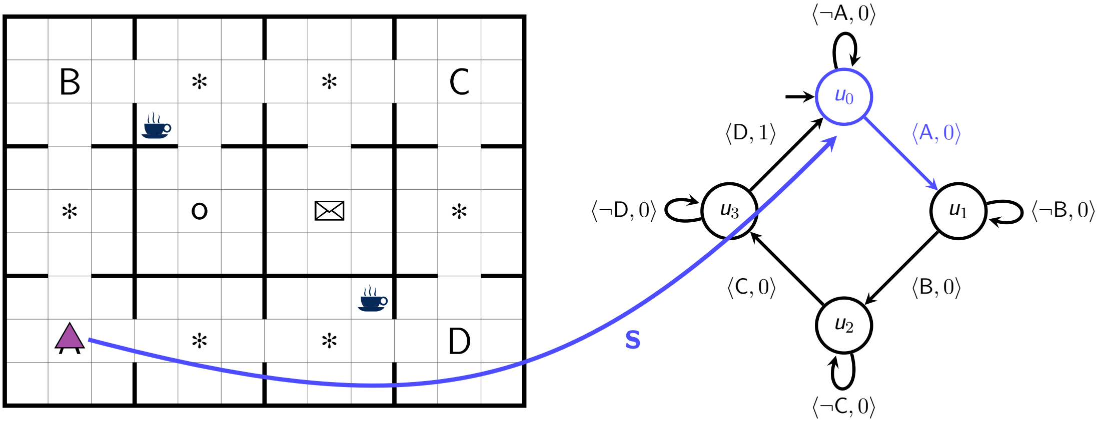

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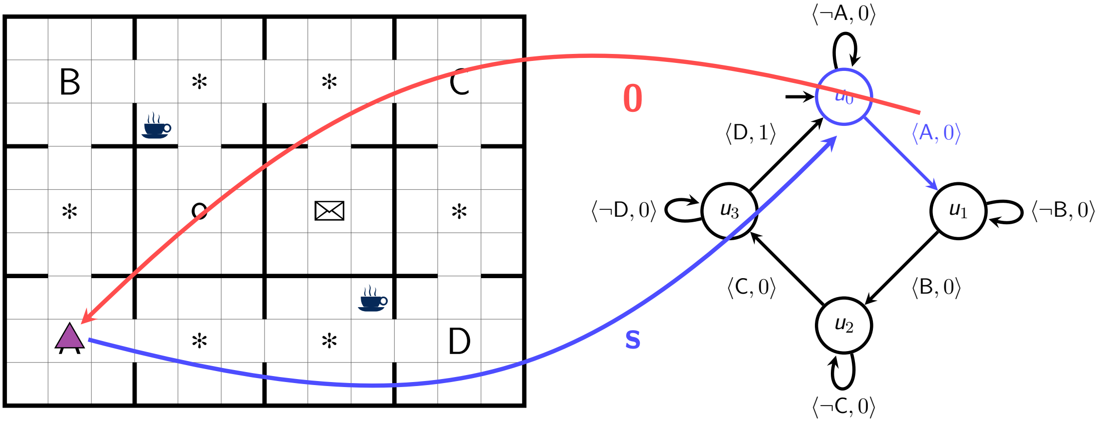

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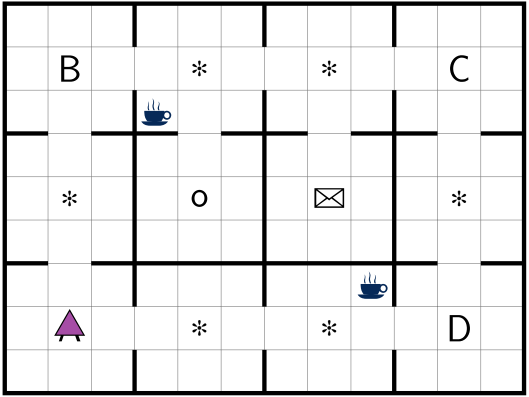

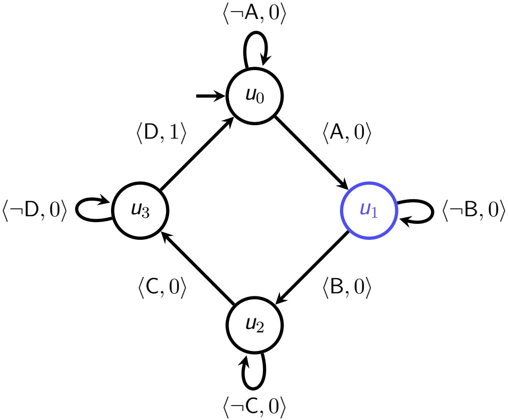

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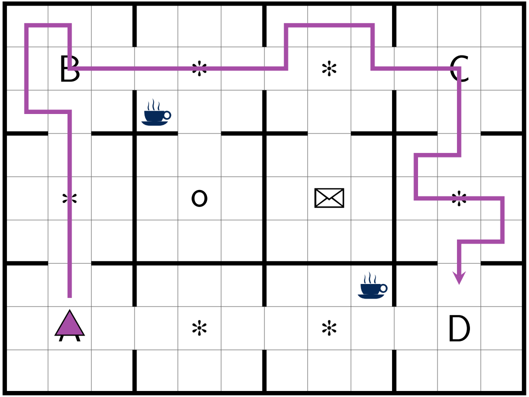

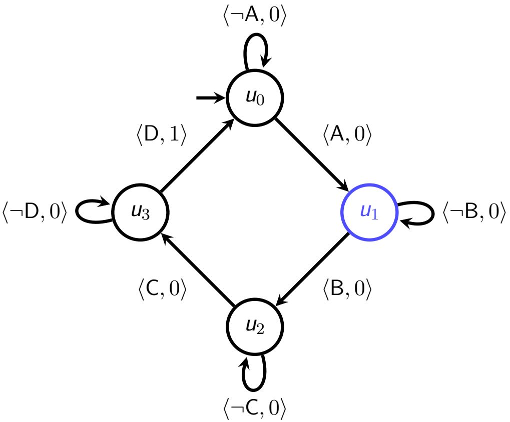

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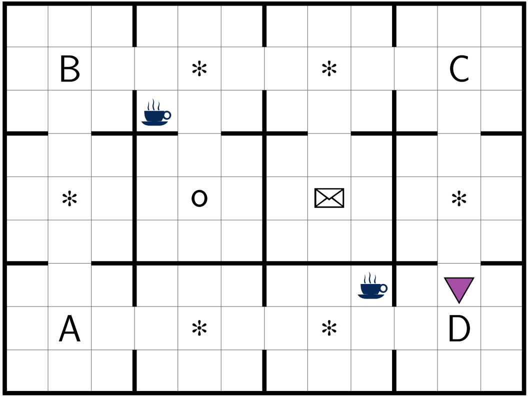

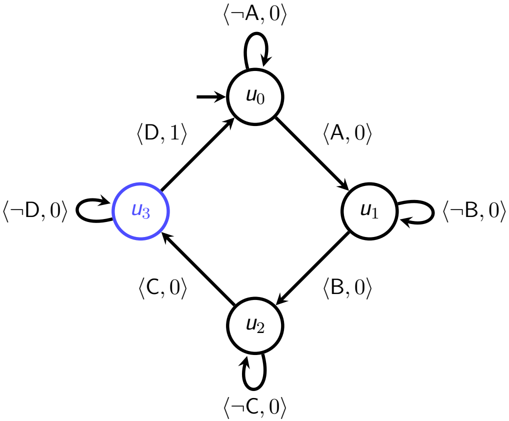

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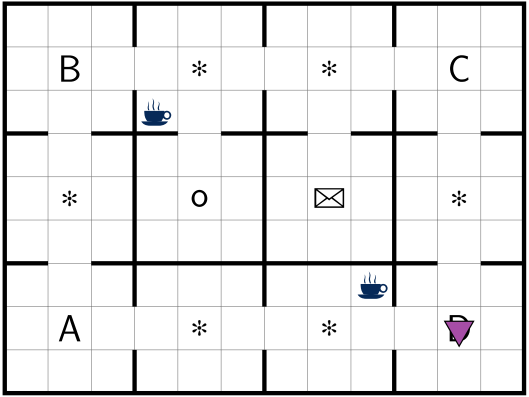

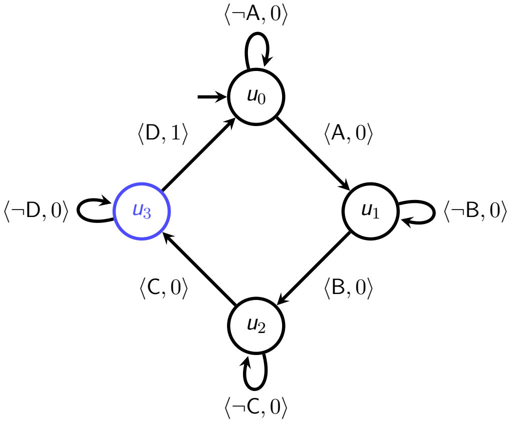

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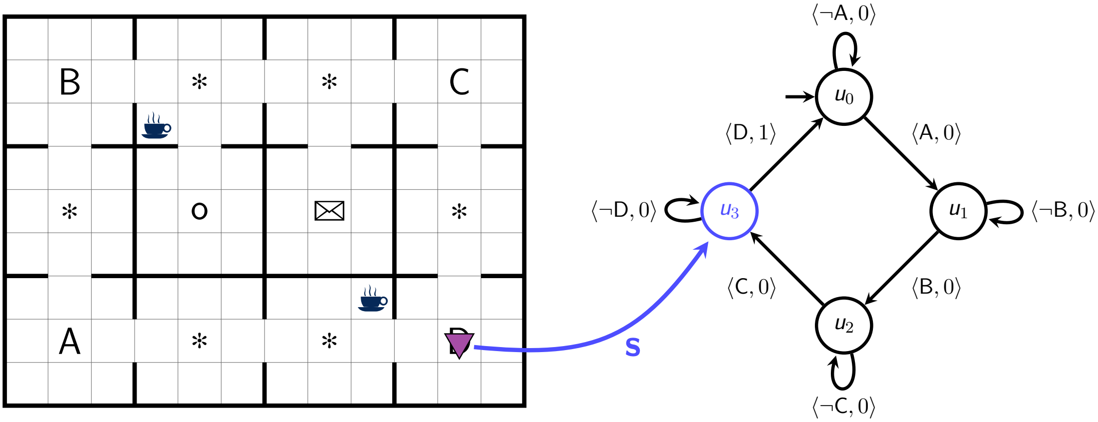

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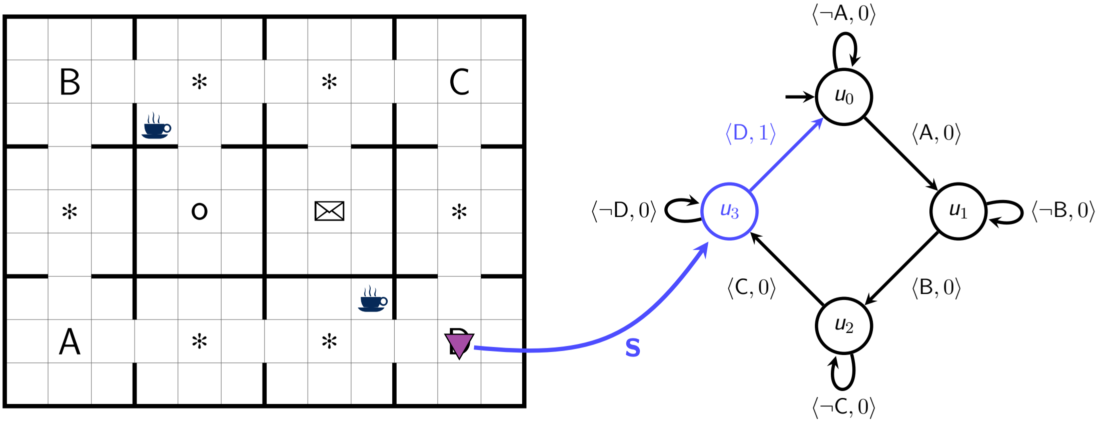

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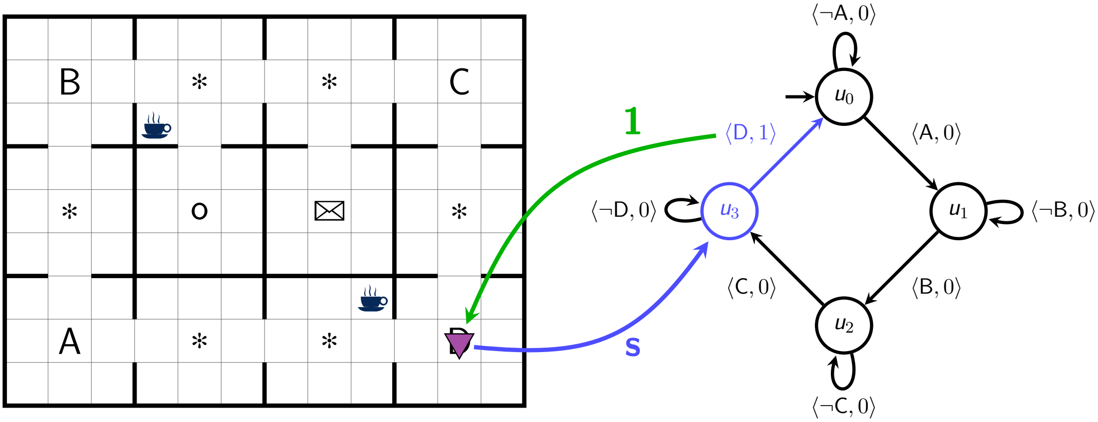

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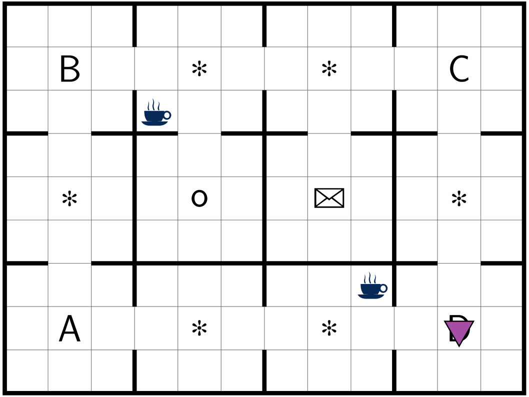
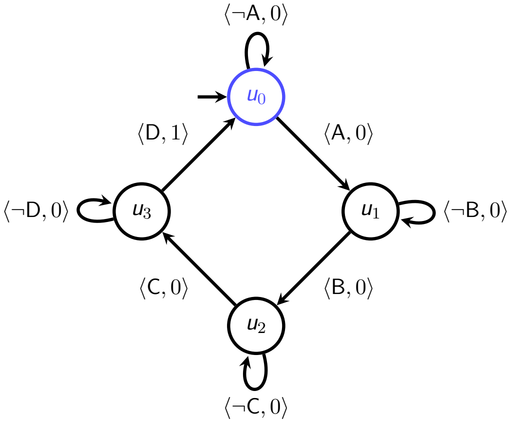
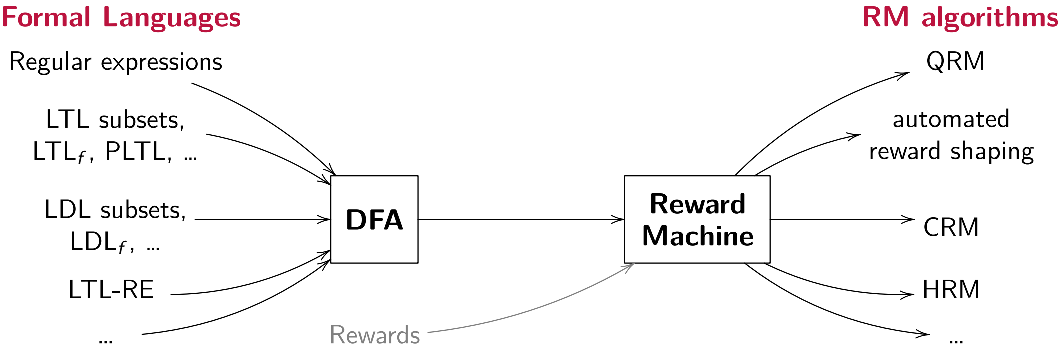


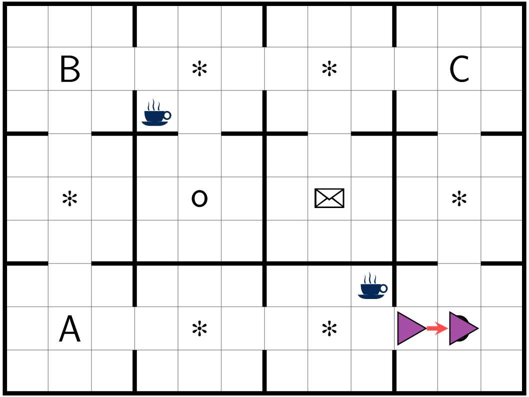


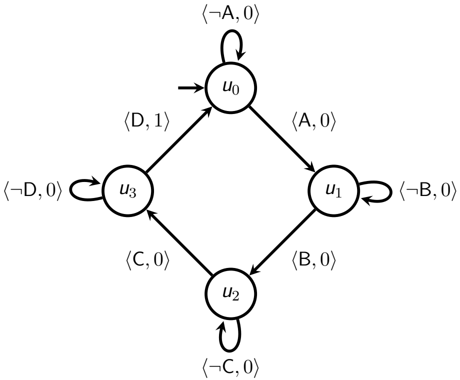
Transforming formal language specifications into reward machines



The QRM algorithm[2]

When the agent acts while in RM state u_i, we can compute what reward **would have been** received if had acted in any other RM state u_j.



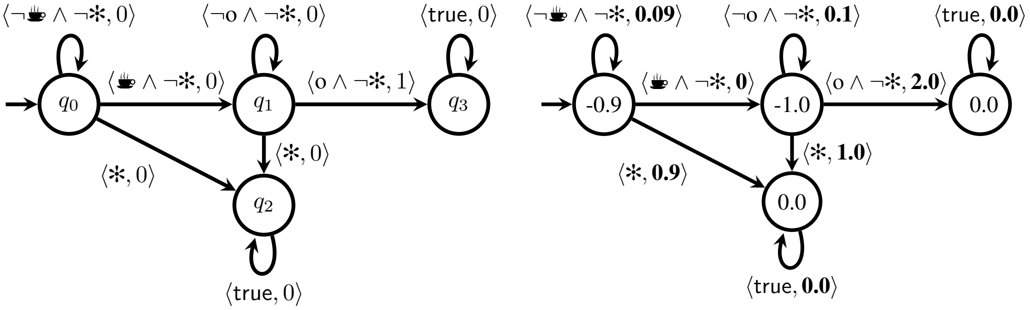


QRM generates such synthetic, **counterfactual** experiences for use in training.

[2] Rodrigo Toro Icarte et al. "Using Reward Machines for High-Level Task Specification and Decomposition in Reinforcement Learning". In: *ICML*. 2018, pp. 2112–2121.

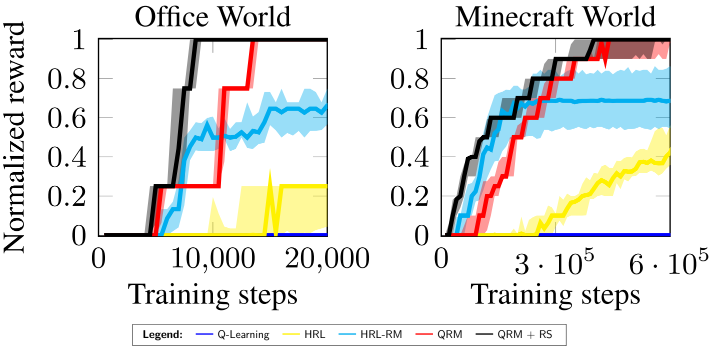
Automated reward shaping

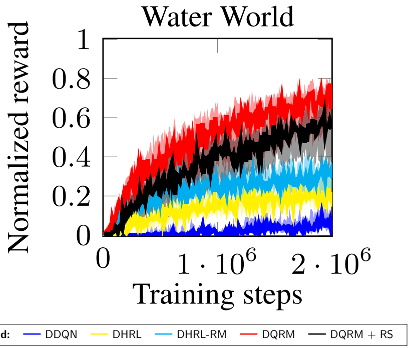
- Treat the RM itself as a (deterministic) MDP, and use **value iteration** to determine the value of each state.
- Then, use these values to define potentials for **potential-based**[3] reward shaping.



[3] Andrew Y. Ng et al. "Policy invariance under reward transformations: Theory and application to reward shaping". In: *ICML*. 1999, pp. 278–287.

Experimental results





By exploiting reward machine structure, our algorithms outperform the baselines.

Conclusion

- **Reward machines (RMs)** are a form of automaton that are a way of representing (temporally extended) reward functions.
- Formulas in many temporal languages (e.g., LTL_f) can be **translated** into RMs.
- Once a reward function is represented as an RM, its structure can be exploited by various RM-specific **algorithms** for more efficient reinforcement learning.

Code:

- Reward machine **algorithms**: https://bitbucket.org/RToroIcarte/qrm
- **Translating** formal languages into reward machines: http://fl-at.jaimemiddleton.cl/[4]

[4] Jaime Middleton et al. *FL-AT: A Formal Language–Automaton Transmogrifier*. System demonstration at ICAPS 2020. 2020.