Shields to Guarantee Probabilistic Safety in MDPs

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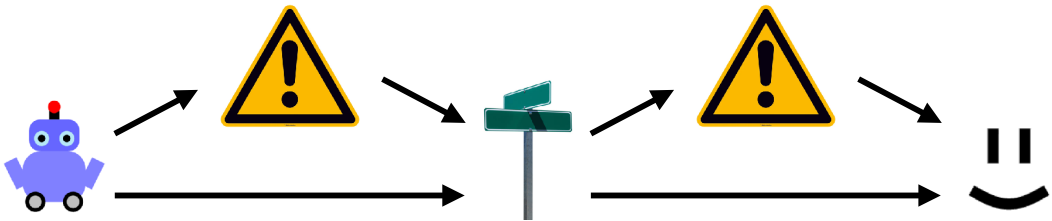
July 8, 2026

Classical Shielding: Example



- Robot can choose going the dangerous or the safe path
- Dangerous path has probability 0.1 of crashing
- Specification: Robot should never crash

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- Shielding is a two-player game played on a Markov decision process
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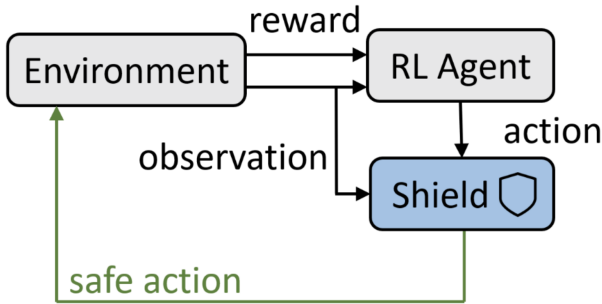
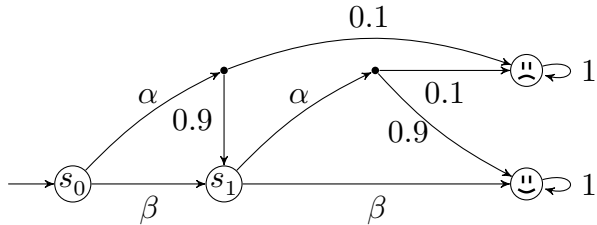
- The shield wants to prevent an agent from violating a formal specification
- At each step:
  - The shield decides which actions to allow
  - Then, the agent plays some strategy / policy
- Goal: Whatever the agent does, the shielded agent should be safe

Shielding an Agent



Picture: Könighofer et al., “Shields for Safe Reinforcement Learning”

Qualitative Shielding on an MDP



Ensure: Agent crashes with probability zero

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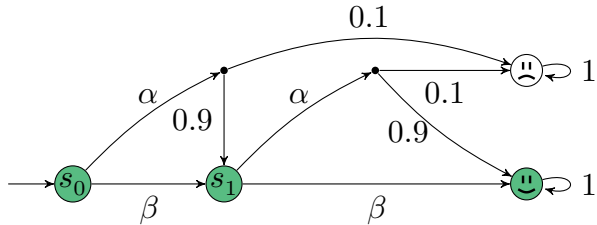
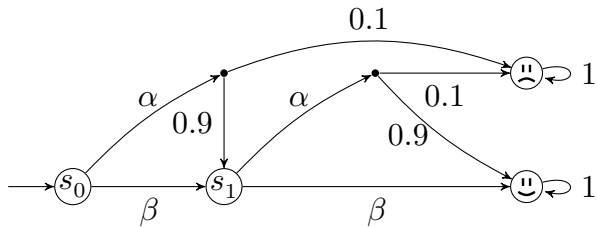


Ensure: Agent crashes with probability zero

$\Rightarrow$ there is a straightforward winning set.

Shielding strategy: Precompute the winning set and ensure the agent stays in it.

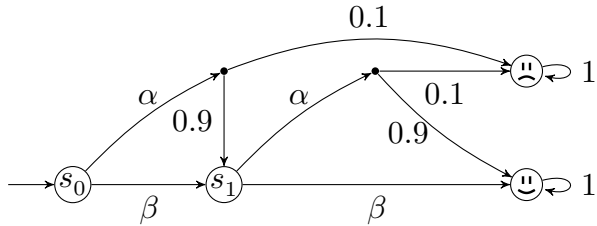
Probabilistic Shielding



Ensure: Agent crashes with probability at most 0.1 ($\Pr(s_0 \vDash \Diamond \text{☹}) \leq 0.1$)

Q: Should we allow taking α at s_1?

Probabilistic Shielding



Ensure: Agent crashes with probability at most 0.1 ($\Pr(s_0 \vDash \Diamond \text{☹}) \leq 0.1$)

Q: Should we allow taking α at s_1?

A: It depends on what the policy played at s_0!

$\Rightarrow$ It's not that easy if we want to enforce a probabilistic guarantee.

Shielding with Guarantees

Two desirable properties:

- Safety: The shielded policy is safe (i.e., satisfies the specification)
- Permissiveness: If the policy was already safe, the shield does not interfere

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Is a shield with these guarantees possible?

- $\varphi = \Pr(s_0 \vDash \Diamond \text{⚠}) \leq 0$: Yes! (Alshiekh et al., “Safe Reinforcement Learning via Shielding”)
- $\varphi = \Pr(s_0 \vDash \Diamond \text{⚠}) \leq \nu$ for $\nu > 0$: No! (Our result, in a few slides)

Shields: Definitions

A history is a sequence $h := s_0\, d_1\, \alpha_1\, s_1\, d_2\, \alpha_2 \cdots s_t$ such that $s_0\alpha_1 s_1\alpha_2 \cdots s_t$ is a path, and for all $0 \leq k \leq t-1$: $d_{k+1} \in \Delta(\mathsf{Act}(s_k))$.

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A shield $\shield$ allows a policy π if $\mathcal{T}_{\shield}(\pi) = \pi$.

We write $\mathsf{Allow}(\shield) := \{\pi \in \Pi_{\mathcal{M}} \mid \mathcal{T}_{\shield}(\pi) = \pi\}$.

Strong Guarantees

Let $\mathcal{M}$ be an MDP and $\shield$ a shield.

(S+): Strong Safety. $\mathcal{T}_{\shield}(\Pi_{\mathcal{M}}) \subseteq \text{Safe}(\Pi_{\mathcal{M}})$.

(P+): Strong Permissiveness. $\text{Safe}(\Pi_{\mathcal{M}}) \subseteq \text{Allow}(\shield)$.

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Let $\mathcal{M}$ be an MDP and U a shield.
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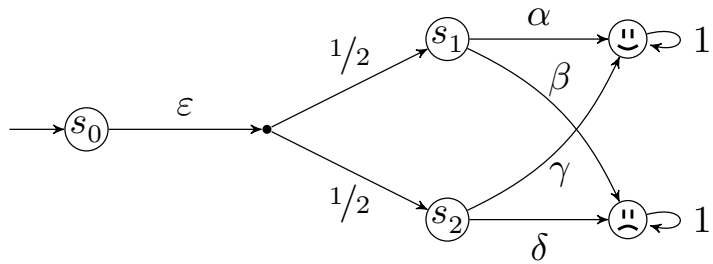
Theorem. For safety threshold $\nu = 0$, the qualitative shield satisfies **(S+)** and **(P+)**.

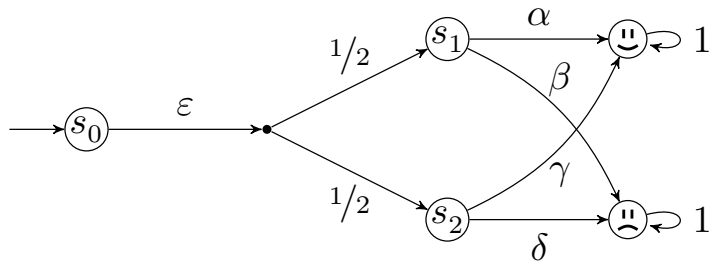
Theorem. For a safety threshold $0 < \nu < 1$, there is an (acyclic, 5-state) MDP such that no shield satisfies **(S+)** and **(P+)**.

Proof: No shield satisfies **(S+)** and **(P+)**



Assume: $\mathcal{O}$ satisfies **(S+)** and **(P+)** for $\nu = 0.5$.

Proof: No shield satisfies **(S+)** and **(P+)**



Assume: $\shield$ satisfies **(S+)** and **(P+)** for $\nu = 0.5$.

Unsafe policy: $\pi := \{s_1 \mapsto \beta, s_2 \mapsto \delta\}$. $\shield$ cannot allow π! (Otherwise: violate **(S+)**)

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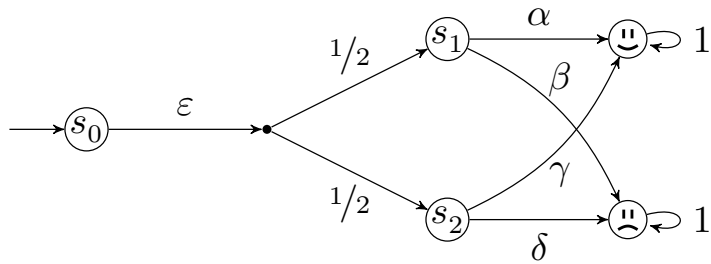

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$\mathcal{O}$ blocks $\beta \Rightarrow \mathcal{O}$ blocks safe policy $\pi := \{s_1 \mapsto \beta, s_2 \mapsto \gamma\} \Rightarrow \mathcal{O}$ violates **(P+)**.

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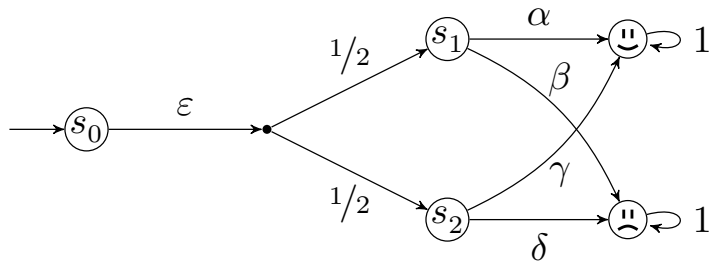

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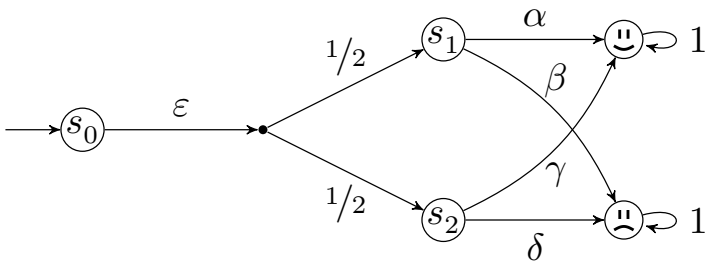
$\mathcal{O}$ blocks $\delta \Rightarrow$ symmetric argument.

The Best Safe Shields on this MDP



Intuitively, “good safe shields” on this MDP for $\nu = 0.5$ block either β or δ.

We’ll formalize this notion.

Saturated Permissiveness

Guarantee (P*): Saturated Permissiveness. For all $\pi \in \Pi_{\mathcal{M}} \setminus \text{Allow}(\shield)$, there is no safe shield $\shield'$ such that $\text{Allow}(\shield) \cup \{\pi\} \subseteq \text{Allow}(\shield')$.

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Lemma. Allow sets of distinct saturated shields are incomparable.

Theorem. Zorn's lemma implies that for any MDP and any $\nu \in [0, 1]$, a saturated shield exists.

(On acyclic MDPs, this is true without Zorn's lemma.)

Lattice of Shields

Idea: Order all shields by permissiveness.

Definition (Lattice of Shields). The lattice of shields is $L_{\mathcal{U}} := (\text{CShields}, \sqsubseteq)$ such that $\mathcal{U} \sqsubseteq \mathcal{U}'$ iff $\text{Allow}(\mathcal{U}) \subseteq \text{Allow}(\mathcal{U}')$.

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Theorem. $L_{\mathcal{S}} = (\text{CShields}, \sqsubseteq)$ is a complete lattice, where for $\mathcal{S}, \mathcal{S}' \in L$:

$$(\mathcal{S} \sqcup \mathcal{S}')(h, d) = d \text{ iff } \mathcal{S}(h, d) = d \text{ or } \mathcal{S}'(h, d) = d,$$
$$(\mathcal{S} \sqcap \mathcal{S}')(h, d) = d \text{ iff } \mathcal{S}(h, d) = d \text{ and } \mathcal{S}'(h, d) = d.$$

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Proof sketch. A saturated shield is a maximal element within the set of safe shields. Need to show: Every chain of safe shields has a safe upper bound.

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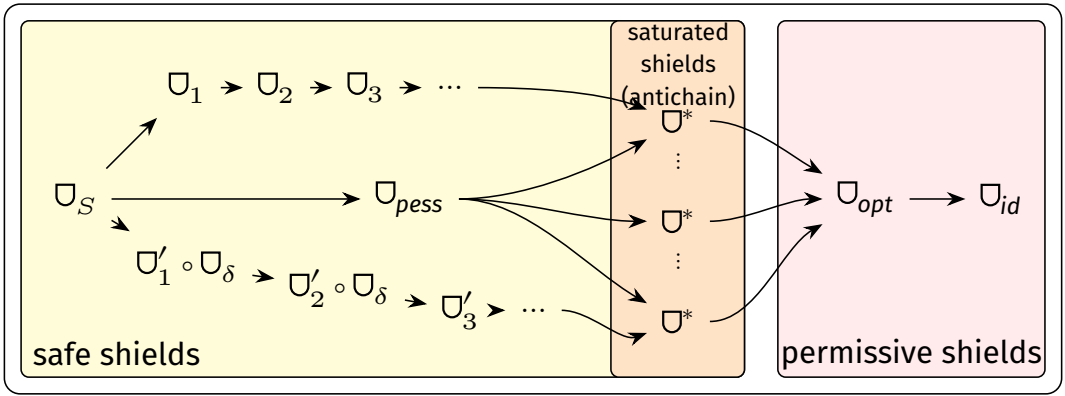
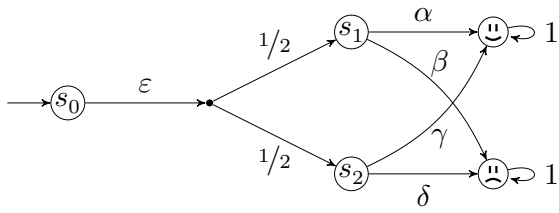
- Strict violation can be witnessed by a finite set of history-choice pairs.
- Each of these history-choice pairs is allowed by some shield in X.
- As X is totally ordered, some shield in X allows all of these history-choice pairs $\implies$ Some shield in X is unsafe. Contradiction.

Lattice of Shields



Constructed Shields: Intuition



- Ensure $\varphi = \mathsf{Pr}(s_0 \vDash \Diamond \frownie) \leq 0.5$

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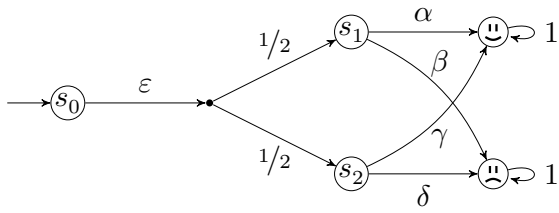

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- Start from shield $\shield_S$ only allowing α and γ

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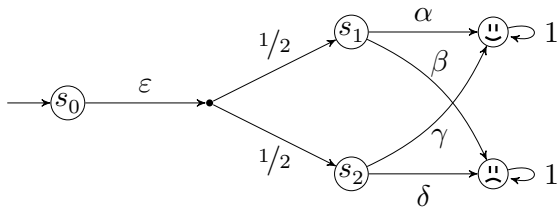

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- Policy tries to play $\beta \implies$ check for safety of additionally allowing β
- Allowing β is safe $\implies$ permanently allow β

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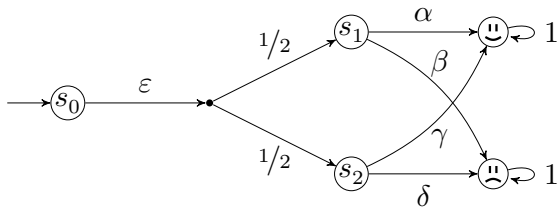
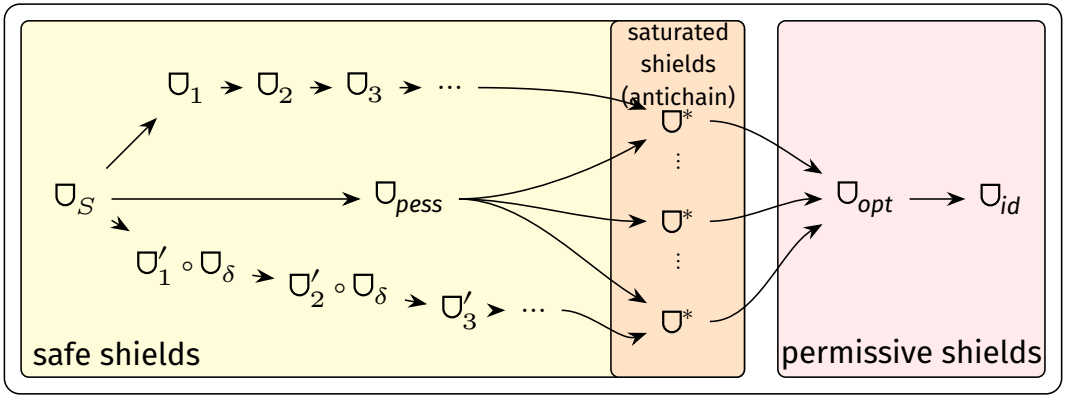


- Ensure $\varphi = \Pr(s_0 \vDash \Diamond$ 😞$) \leq 0.5$
- Start from shield $\mathcal{V}_S$ only allowing α and γ
- Policy tries to play $\beta \implies$ check for safety of additionally allowing β
- Allowing β is safe $\implies$ permanently allow β
- Policy tries to play $\delta \implies$ for safety of additionally allowing δ
- Allowing δ is unsafe $\Rightarrow$ do not allow δ

Lattice of Shields



Safely Extending Shields

Definition (Safe Extension). Let $\mathcal{O}, \mathcal{O}' \in L_{\mathcal{O}}$. Then the safe extension of $\mathcal{O}$ by $\mathcal{O}'$ is the following (non-commutative and non-associative!) operation:

$$\mathcal{O} \oplus_{safe} \mathcal{O}' := \begin{cases} \mathcal{O} \sqcup \mathcal{O}' & \text{if } \mathcal{O} \sqcup \mathcal{O}' \text{ is safe,} \\ \mathcal{O} & \text{otherwise.} \end{cases}$$

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Safety can be checked in polynomial time.

Constructing Shields

Definition (Constructing Shields). Given a sequence of history-choice pairs $H = ((h_0, d_0), \dots, (h_t, d_t))$,

$$\shield_0 := \shield_S, \quad \shield_{i+1} := \shield_i \oplus_{\mathit{safe}} \shield_{(h_i, d_i)}.$$

- Constructed shields agree with some saturated shield on H.
- Constructed shields converge towards saturated permissiveness.

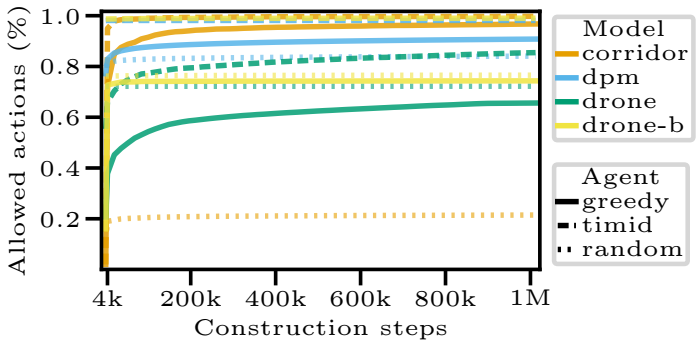
Online Shielding

- Online Shielding: Construct a shield while shielding
- When should we swap our shield with a more permissive one?

Online Shielding

- Online Shielding: Construct a shield while shielding
- When should we swap our shield with a more permissive one?
- One must be careful: Switching from one safe shield to another safe shield during an execution can break probabilistic guarantees!
- Solution: only modify shields between executions

Experiments: Convergence of Constructed Shields



Experiments: Safety and Permissiveness of Shields

Model	Agent (value)	ν	$\mho_{\text{Safe}}$ SAFE		$\mho_{\delta^+}$ UNSAFE		$\mho_{onl}$ SAFE		$\mho_{off}$ SAFE		$\mho_{ML}$ SAFE	
drone	greedy (.240)	0.01	.000	.207	.001	.211	.009	.214	**.010**	**.218**	.000	.208
		0.05	.000	.207	.001	.211	.049	.254	**.050**	**.259**	.000	.208
		0.2	.000	.207	.240	=1	.160	.538	**.200**	**.656**	.054	.239
	timid (.014)	0.01	.000	.554	.002	.728	.009	.808	**.010**	**.830**	.000	.554
		0.05	.000	.554	.002	.728	.008	.811	**.011**	**.855**	.000	.554
		0.2	.000	.554	**.014**	**=1**	.009	.810	.011	.855	.001	.640
	random (.962)	0.01	**.000**	**.722**	.052	.839	.000	.721	**.000**	**.722**	**.000**	**.722**
		0.05	.000	.722	.052	.839	.000	.723	.000	.722	**.006**	**.749**
		0.2	.000	.722	**.052**	**.839**	.000	.722	.000	.722	.027	.812

Experiments: Shield Queries per Second

Model	$\lvert M \rvert$	$\bigcirc_S$	$\bigcirc_{\delta^+}$	$\bigcirc_\delta$	$\bigcirc_{opt}$	$\bigcirc_{pes}$	$\bigcirc_{onl}$	$\bigcirc_{off}$	$\bigcirc_{nom}$
corridor	15	2.5k	2.0k	2.0k	1.9k	1.9k	1.7k	2.0k	2.0k
dpm	797	2.8k	2.8k	2.8k	2.4k	2.6k	1.4k	2.2k	2.2k
drone	1859	2.5k	1.8k	1.8k	1.8k	2.3k	0.6k	1.6k	1.6k
drone-b	87k	1.9k	1.3k	1.3k	1.3k	1.5k	0.4k	1.3k	1.3k

Takeaways

- Shielding is a way to enforce safety for agents in MDPs
- It's harder with probabilistic guarantees
- Still, constructed shields can give you good shields in practice!

Appendix

Value of a Shield

Definition (Value of Shield). Given a finite set of history-choice pairs $J \subseteq \mathsf{Hist}(\mathcal{M}) \times \Delta(Act)$, let $\mathcal{O} = \bigsqcup_{(h,d)\in J} \mathcal{O}_{(h,d)}$. We define the value $V_{\mathcal{O}}(h)$ of $\mathcal{O}$ for history $h \in \mathsf{Hist}(\mathcal{M})$ as:

$$
\begin{aligned}
V_{\mathcal{O}}(h) &:= \max\{C_{\mathcal{O}}(h,d) \mid (h,d) \in J'\} \cup \{V_{\mathsf{min}}(\mathit{last}(h))\}, \text{ where} \\
J' &:= J \cup \{(h, d|_{\mathsf{Act}^{\mathsf{Safe}}(\mathit{last}(h))}) \mid (h',d) \in J \text{ s.t. } h' \text{ suffix of } h\}, \text{ and} \\
C_{\mathcal{O}}(h,d) &:= \sum_{\alpha \in \mathsf{Supp}(d)} d(\alpha) \sum_{s' \in S} \mathcal{P}(\mathit{last}(h), \alpha, s') \cdot V_{\mathcal{O}}(h \cdot d \cdot \alpha \cdot s').
\end{aligned}
$$

Shields and their Allowed Policies

Given a set of policies $P \subseteq \Pi_{\mathcal{M}}$, the history mixing is the set $\mathit{mix}(P) \subseteq \Pi_{\mathcal{M}}$ such that $\pi \in \mathit{mix}(P)$ if:

$$\forall h \in \text{Hist}(\mathcal{M}).\ h \text{ is consistent with } \pi \implies (\exists \pi' \in P.\ h \text{ is consistent with } \pi').$$

Lemma. Given shield U and policies $P \subseteq \text{Allow}(\mathrm{U})$. Then $\mathit{mix}(P) \subseteq \text{Allow}(\mathrm{U})$.

Lemma. Let P be a mix-closed set of policies that covers all safe actions. There is a unique canonical shield U with $\text{Allow}(\mathrm{U}) = P$.

Q1: Safety and Permissiveness of Shields

Model	Agent (value)	ν	∇_{Safe} SAFE		$\nabla_{\hat{s}+}$ UNSAFE		∇_{oml} SAFE		∇_{off} SAFE		∇_{ML} SAFE	
corridor	greedy (.125)	0.05	**.000**	**.020**	**.000**	**.020**	**.000**	**.020**	**.000**	**.020**	**.000**	**.020**
		0.1	.000	.020	.000	.020	**.100**	**.204**	.100	.202	.000	.020
		0.2	.000	.020	.125	.735	.125	.936	**.125**	**.968**	.125	.735
	timid (.125)	0.05	**.000**	**.020**	**.000**	**.020**	**.000**	**.020**	**.000**	**.020**	**.000**	**.020**
		0.1	.000	.020	.000	.020	**.100**	**.406**	**.100**	**.406**	.000	.020
		0.2	.000	.020	**.125**	**=1**	.124	.993	.125	.997	.125	.925
	random (.733)	0.05	.000	.116	.000	.116	.049	.134	**.050**	**.142**	.000	.116
		0.1	.000	.116	.000	.116	**.098**	**.153**	.100	.148	.000	.116
		0.2	.000	.116	.000	.116	.199	.190	**.200**	**.215**	.000	.116
dpm	greedy (.479)	0.01	.000	.771	.479	=1	.010	.790	.010	.792	**.009**	**.794**
		0.05	.000	.771	.479	=1	.047	.839	**.050**	**.848**	.044	.844
		0.2	.000	.771	.479	=1	.062	.870	.097	.908	**.155**	**.924**
	timid (.063)	0.01	**.000**	**.981**	.063	=1	.000	.979	**.000**	**.981**	**.000**	**.981**
		0.05	.000	.981	.063	=1	.000	.979	.000	.981	**.010**	**.984**
		0.2	.000	.981	**.063**	**=1**	.000	.979	.000	.981	**.063**	**=1**
	random (.131)	0.01	.000	.798	.131	=1	.005	.831	**.006**	**.841**	.006	.839
		0.05	.000	.798	.131	=1	.005	.831	.006	.841	**.037**	**.989**
		0.2	.000	.798	**.131**	**=1**	.005	.831	.006	.841	**.131**	**=1**