Interpretable Strategy Synthesis for Competitive Games

Oral Prelim Presentation

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Previous Work

- **Krishnan, Abhijeet** and Chris Martens. “Synthesizing Chess Tactics from Player Games.” In *Workshop on Artificial Intelligence for Strategy Games (SG) and Esports Analytics (EA), 18th AAAI Conference on Artificial Intelligence and Interactive Digital Entertainment*. 2022 (in press).
- **Krishnan, Abhijeet** and Chris Martens. “Towards the Automatic Synthesis of Interpretable Chess Tactics.” In *Explainable Agency in Artificial Intelligence Workshop, 36th AAAI Conference on Artificial Intelligence*. 2022.
- **Krishnan, Abhijeet**, Aaron Williams, and Chris Martens. “Towards Action Model Learning for Player Modeling.” *Proceedings of the AAAI Conference on Artificial Intelligence and Interactive Digital Entertainment*. Vol. 16. No. 1. 2020.
- **Krishnan, Abhijeet** and Chris Martens. “Rule-based Cognitive Modeling via Human-Computer Interaction”. Poster presented at: *5th LAS Research Symposium*; 2019 Dec 10; Raleigh, NC.

Story Time!

Yogender Pal

Figure 1: Priya, a normal girl

Story Time!

Netflix

Story Time!

Chess.com

Figure 2: Beth Harmon bots on Chess.com

Story Time!

Chess.com

Figure 3: Beth Harmon (bot) at 8 years old

Story Time!

ChessKid

ChessKid

Story Time!

Chess.com

Figure 4: Beth Harmon (bot) at 15 years old

Story Time!

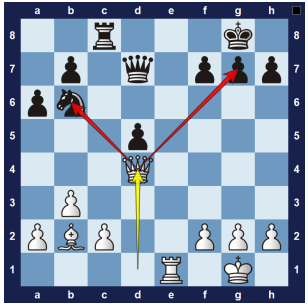
Arjun Somasekharan

Figure 5: What should Priya do now?

Story Time!

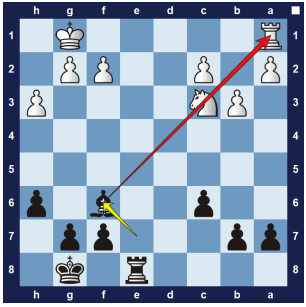
Could the Beth Harmon bots *explain* their *strategy* to Priya to help her get better?

Real-world Strategies



Chessfox

Figure 6: An example of the *fork* tactic in chess



Chessfox

Figure 7: An example of the *pin* tactic in chess

Real-world Strategies

Go Full Build

Figure 8: A *cannon rush* in progress against a Terran opponent in the game *StarCraft II*

Value of Strategies

- Esports is a *massive* industry
- Could be used to *coach players* at all levels of skill
  - Over 200,000 active ChessKid users
- Better strategies $\rightarrow$ higher player skill $\rightarrow$ *more earning* potential

Tournament	**Game**	**Prize Pool (USD)**
World Blitz Chess Championship	Chess	350,000
IEM Katowice	StarCraft II	500,000

Thesis Statement

Thesis Statement

A *computational model* of a game strategy, along with a *learning method*, could meet the goals of discovering good, communicable strategies and impact the fields of competitive esports and explainable AI.

Summary

Research Thrust	RQ	Sub-RQ	Publication
ISS Framework	RQ1	–	EAAI '22 (Krishnan and Martens 2022b)
ISS for Chess	RQ2	RQ2(a)	EAAI '22 (Krishnan and Martens 2022b)
		RQ2(b)	SG+EA Workshop @ AIIDE '22 (Krishnan and Martens 2022a)
		RQ2(c)	*(under review)* (Krishnan, Martens, and Jhala 2023)
ISS for MicroRTS	RQ3	RQ3(a)	*Proposed Work* (ACG 2023)
		RQ3(b)	*Proposed Work* (xAI 2024)

RQs

RQs

RQ1

How do we formally define the problem of *Interpretable Strategy Synthesis* (ISS)?

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RQ2

How do we approach the problem of ISS for the game of *chess*?

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RQ1

How do we formally define the problem of *Interpretable Strategy Synthesis* (ISS)?

RQ2

How do we approach the problem of ISS for the game of *chess*?

RQ3

How do we approach the problem of ISS for the game of *MicroRTS*?

ISS Framework

RQ1

How do we formally define the problem of *Interpretable Strategy Synthesis* (ISS)?

Elements of a Good Framework

- Facilitates *comparison*
  - multiple *algorithms*
  - multiple *strategy representations*
  - multiple *games*
- Provides a clear definition of interpretability

The Need for a Framework

Paper	Number Used			Interpretability
	Domains	Models	Algorithms	
Spronck, Sprinkhuizen-Kuyper, and Postma (2004)	2	1	1	✗
Mesentier Silva et al. (2016)	1	1	4	✓
Butler, Torlak, and Popović (2017)	1	1	1	✗
Canaan et al. (2018)	1	1	1	✗
Freitas, Souza, and Bernardino (2018)	1	1	1	✗
Mariño et al. (2021)	1	1	1	✗
Krishnan and Martens (2022a)	1	1	1	✗
Mariño and Toledo (2022)	1	1	1	✗
Medeiros, Aleixo, and Lelis (2022)	2	1	2	✗

Table 1: List of works in ISS

Interpretable Strategy Synthesis (ISS)

Definition (ISS)

Given a —

- Game environment $\mathcal{G}$
- Strategy model $\mathcal{M}$
- Performance measure $\mathcal{R}\colon \mathcal{M} \to \mathbb{R}$
- Interpretability measure $\mathcal{I}\colon \mathcal{M} \to \mathbb{R}$

The problem of ISS is to find a strategy σ^* s.t. —

$$\sigma^* \doteq \arg\max_{\sigma} \mathcal{R}(\sigma)\mathcal{I}(\sigma), \sigma \in \mathcal{M}$$

Strategy (σ) Formal Definition

- Strategy $=$ RL policy $-$ universal applicability
- Strategy *not* applicable to all states
- Describes an *oft-seen pattern* in gameplay

Strategy Model ($\mathcal{M}$)

- Defines the *space* of strategies
- Examples —
  - if-then rules
  - decision trees
  - programmatic scripts

Performance Measure ($\mathcal{R}(\sigma)$)

- How *good* a strategy is
- Players generally study good strategies
- Examples —
  - win rate
  - material advantage (chess)
  - resources harvested (MicroRTS)

Interpretability Measure ($\mathcal{I}(\sigma)$)

- How *interpretable* a strategy is
- Players need to be able to *understand* a strategy to benefit from it
- Examples —
  - number of statements (programmatic script)
  - number of nodes (decision tree)
  - set of conditions and actions used (if-then rule)
  - improvement in player win rate upon being explained strategy

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ISS for Chess

RQ2

How do we approach the problem of Interpretable Strategy Synthesis for the game of *chess*?

Why Chess?

- *Popular* game with a *long* competitive history
- Has a large number of *player-discovered strategies*
- Extensive use as a *testbed for AI*

Towards ISS for Chess

- Strategy model for chess
- Performance measure for chess
- Interpretability measure for chess

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RQ2(a)

Could we represent known chess tactics as a strategy model for chess and develop metrics to show that they suggest better moves than a random baseline?

Towards ISS for Chess

- *Strategy model* for chess
- Performance measure for chess
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RQ2(a)

Could we represent known chess tactics as a *strategy model* for chess and develop metrics to show that they suggest better moves than a random baseline?

Strategy Model for Chess

First-Order (FO) Logic Rule

Strategy Model for Chess

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Predicate Vocabulary

Strategy Model for Chess

First-Order (FO) Logic Rule

$$\texttt{tactic}(\text{Position, Move}) \leftarrow \texttt{feature\_1}(\cdots), \texttt{feature\_2}(\cdots), \vdots \texttt{feature\_n}(\cdots)$$

Figure 9: Our chess strategy model expressed in Prolog pseudocode

Predicate Vocabulary

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Figure 9: Our chess strategy model expressed in Prolog pseudocode

Predicate Vocabulary

- Position =

```
[contents(c2,pawn,white),
 contents(g8,knight,black),
 contents(e8,king,black),

 turn(white),kingside_castle(white),...]
```

Strategy Model for Chess

First-Order (FO) Logic Rule

```
tactic(Position, Move) ←
        feature_1(···),
        feature_2(···),
        ⋮
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- Move = `[a7,a8,queen]`

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Predicate Vocabulary

- Position =
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[contents(c2,pawn,white),
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```
- Move = `[a7,a8,queen]`
- Features =
  - `attacks(Pos,Sq1,Sq2)`
  - `in_check(Pos,Side)`
  - `is_empty(Pos,Squares)`

Example

```
fork(Position,Move) ←
    legal_move(Position,Move),
    move(Move,_,To,_),
    make_move(Position,Move,NewPosition),
    can_capture(NewPosition,To,ForkSquare1),
    can_capture(NewPosition,To,ForkSquare2),
    different(ForkSquare1,ForkSquare2).
```

Figure 10: An interpretation of the *fork* tactic from the chess literature using our predicate vocabulary.

Example

```
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Towards ISS for Chess

- ~~Strategy model for chess~~
- Performance measure for chess
- Interpretability measure for chess

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Could we represent known chess tactics as a strategy model for chess and develop metrics to show that they suggest better moves than a random baseline?

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Could we represent known chess tactics as a strategy model for chess and develop *metrics* to show that they suggest better moves than a random baseline?

Performance Measure

Divergence Equation

- How *different* is one strategy from another?
- High divergence $\rightarrow$ strategies are very different
- Low divergence $\rightarrow$ strategies are quite similar
- Difference in terms of *perceived evaluation* of moves
- Who is “perceiving”?
  - Chess-playing agents with an *evaluation function* (chess “engines”)
  - e.g., Stockfish 14, Leela Chess Zero

Interpretability Measure

Interpretability Measure

- *No explicit interpretability measure!* Only qualitative arguments

Interpretability Measure

- *No explicit interpretability measure!* Only qualitative arguments
- Human players *think* and *train* using chess tactics (Szabo 1984; Gobet and Jansen 2006)
- FO-logic used extensively to model chess patterns (Berliner 1975; Pitrat 1977; Wilkins 1979; Huberman 1968; Bramer 1977; Bratko 1982; Morales 1992)
- Logic rules are *acknowledged to be interpretable* (Zhang et al. 2021)

Towards ISS for Chess

- ~~Strategy model for chess~~
- ~~Performance measure for chess~~
- ~~Interpretability measure for chess~~

RQ2(a)

Could we represent known chess tactics as a strategy model for chess and develop metrics to *show that they suggest better moves than a random baseline*?

Evaluating Chess Tactics[1]

[1] Krishnan and Martens 2022b.

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- PAL (Morales 1992) $\xrightarrow{\text{learn}}$ *known* chess patterns (tactics) PAL

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- Divergence(*random baseline*, human beginner)

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- tactics $\xrightarrow{\text{translate}}$ chess strategy model
- Divergence(chess strategies, human beginner)
- Divergence(random baseline, human beginner)
- Both using strong/weak engine

[1] Krishnan and Martens 2022b.

Results

Tactic	Divergence	
	Strong	Weak
can_threat	378.94	9.22
can_check	549.19	4.02
can_fork	676.45	4.67
discovered_check	338.55	18.64
discovered_threat	375.97	1.19
skewer	748.40	5.41
pin	526.45	4.90
random	328.09	8.28

Table 2: Divergence for each tactic

Analysis

- *Higher than random* divergence from human beginners (strong engine)
- *Lower than random* divergence from human beginners (weak engine)
- Known chess strategies approximate human beginners better than random according to a weak engine

Learning Chess Strategy Models

- ~~Strategy model for chess~~
- ~~Performance measure for chess~~
- ~~Interpretability measure for chess~~

Learning Chess Strategy Models

- ~~Strategy model for chess~~
- ~~Performance measure for chess~~
- ~~Interpretability measure for chess~~
- *Learning algorithm* for chess strategies

RQ2(b)

Do the chess strategies learned using inductive logic programming outperform a random baseline in how closely their divergence scores approximate a beginner player?

Learning Chess Strategies using ILP[2]

- Inductive Logic Programming (ILP): *symbolic ML* technique ILP

[2]Krishnan and Martens 2022a.

Learning Chess Strategies using ILP[2]

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- ILP system($\langle E^+, E^-, B \rangle$) $\xrightarrow{\textit{learn}}$ chess strategies
- Use *divergence* to evaluate learned chess strategies
- Compare to random, strong/weak engine baselines

[2]Krishnan and Martens 2022a.

Results

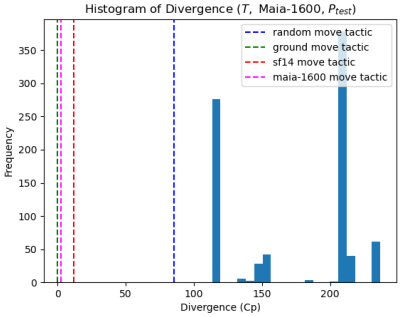

Figure 11: Divergence histogram for T evaluated using *weak* engine

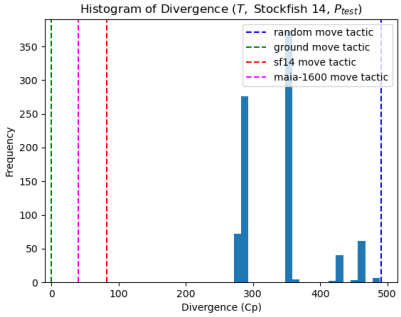

Figure 12: Divergence histogram for T evaluated using *strong* engine

Analysis

- *Lower than random* divergence from human beginners (strong engine)
- *Higher than random* divergence from human beginners (weak engine)
- Learned chess strategies approximate human beginners better than random according to a strong engine

Improving the ILP Learning Method

- How do we *improve* upon “better than random”?

Improving the ILP Learning Method

- How do we *improve* upon “better than random”?

RQ2(c)

Do the chess strategies learned by an ILP system incorporating the changes of the new predicate vocabulary and precision/recall-based constraints produce moves better than those learned by an ILP system without these modifications?

Improvements using Precision/Recall-based Constraints[3]

- Modifications —

[3] Krishnan, Martens, and Jhala 2023.

Improvements using Precision/Recall-based Constraints[3]

- Modifications —
  1. *Limit* chess strategy search space using precision/recall constraints

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Improvements using Precision/Recall-based Constraints[3]

- Modifications —
  1. *Limit* chess strategy search space using precision/recall constraints
  2. Introduce a *new* predicate vocabulary

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Improvements using Precision/Recall-based Constraints[3]

- Modifications —
  1. *Limit* chess strategy search space using precision/recall constraints
  2. Introduce a *new* predicate vocabulary
- Conduct *ablative study* to measure impact of modifications

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- Modifications —
  1. *Limit* chess strategy search space using precision/recall constraints
  2. Introduce a *new* predicate vocabulary
- Conduct *ablative study* to measure impact of modifications
  - Learn strategies using systems with/without constraints, predicate vocabulary

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- Conduct *ablative study* to measure impact of modifications
  - Learn strategies using systems with/without constraints, predicate vocabulary
  - Measure average strategy divergence

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Improvements using Precision/Recall-based Constraints[3]

- Modifications —
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  2. Introduce a *new* predicate vocabulary
- Conduct *ablative study* to measure impact of modifications
  - Learn strategies using systems with/without constraints, predicate vocabulary
  - Measure average strategy divergence
  - Test decrease vs. old system using *one-sided Welch's t-test*

[3] Krishnan, Martens, and Jhala 2023.

Results

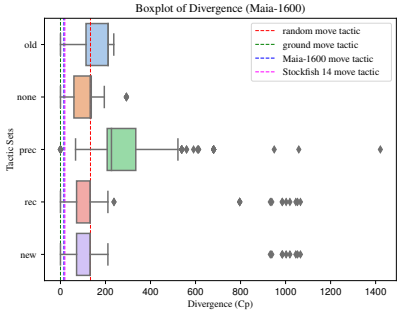


Figure 13: Boxplot of tactic divergence (evaluated using *weak* engine) for each system

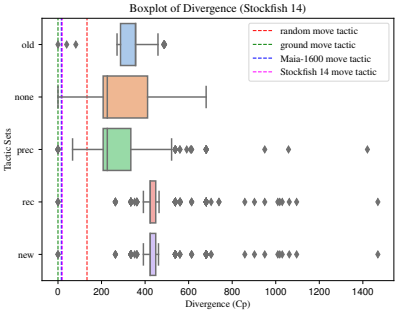


Figure 14: Boxplot of tactic divergence (evaluated using *strong* engine) for each system

Analysis

- New predicate vocabulary $\rightarrow$ improves divergence! ($p < 0.01$)
- precision constraint $\rightarrow$ improves divergence *only* when measured using strong engine
- recall constraint $\rightarrow$ improves divergence *only* when measured using weak engine

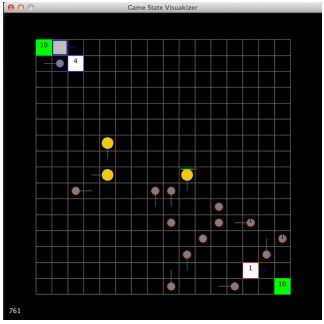
ISS for MicroRTS

RQ3

How do we approach the problem of Interpretable Strategy Synthesis for the game of *MicroRTS*?

Why MicroRTS?

- Simplified **r**eal-**t**ime **s**trategy game *for AI research* (Ontanon 2021)
- Active *research community*
- *Qualitatively different* from chess – *real-time*, *partially observable*
- *Popular genre* for esport titles



Google Code Archive

Figure 15: A MicroRTS game in progress

Towards ISS for MicroRTS

- Strategy model for MicroRTS
- Performance measure for MicroRTS
- Interpretability measure for MicroRTS
- Learning method for MicroRTS strategies

Towards ISS for MicroRTS

- ~~Strategy model for MicroRTS~~
- ~~Performance measure for MicroRTS~~
- ~~Interpretability measure for MicroRTS~~

} SynProS

- Learning method for MicroRTS strategies

SynProS Competition

- SynProS: **Syn**thesis of **Pro**grammatic **S**trategies

SynProS Competition

- SynProS: Synthesis of Programmatic Strategies
- Research competition (Moraes 2021) to test ISS approaches for MicroRTS with a *fixed strategy model*

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- MicroRTS strategy model = *CFG*

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- Research competition (Moraes 2021) to test ISS approaches for MicroRTS with a *fixed strategy model*
- MicroRTS strategy model = *CFG*

$$
\begin{aligned}
S_1 &\rightarrow C\ S_1 \mid S_2\ S_1 \mid S_3\ S_1 \mid \epsilon \\
S_2 &\rightarrow \text{if } (S_5) \text{ then } \{C\} \mid \text{if } (S_5) \text{ then } \{C\} \text{ else } \{C\} \\
S_3 &\rightarrow \text{for (each unit } u) \{S_4\} \\
S_4 &\rightarrow C\ S_4 \mid S_2\ S_4 \mid \epsilon \\
S_5 &\rightarrow \text{not } B \mid B \\
B &\rightarrow b_1 \mid b_2 \mid \cdots \mid b_m \\
C &\rightarrow c_1\ C \mid c_2\ C \mid \cdots \mid c_n\ C \mid c_1 \mid c_2 \mid \cdots \mid c_n \mid \epsilon
\end{aligned}
$$

Figure 16: The production rules of a context-free grammar (CFG) describing the strategy model for MicroRTS.

Performance Measure

- *win rate* (against fixed set of test scripts)

Interpretability Measure

- Inversely proportional to *number of statements*

Interpretability Measure

- Inversely proportional to *number of statements*
- *No justification* for use! $\rightarrow$ proposed study in RQ3b

Learning MicroRTS Strategies using ASP

RQ3(a)

How does an ASP-based approach towards developing a synthesizer for the *SynProS competition* compare to other synthesizers in this competition?

Answer Set Programming (ASP)

- **A**nswer **S**et **P**rogramming ASP

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- ASP $\rightarrow$ *declarative programming* paradigm (like Prolog)

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- Can *model* and *generate* game levels (Smith and Mateas 2011; Smith, Andersen, et al. 2012)

Answer Set Programming (ASP)

- **A**nswer **S**et **P**rogramming ASP
- ASP $\rightarrow$ *declarative programming* paradigm (like Prolog)
- Can *model* and *generate* game levels (Smith and Mateas 2011; Smith, Andersen, et al. 2012)
- Can model and generate *optimized* data viz. layouts (Moritz et al. 2018)

Learning MicroRTS Strategies using ASP

- MicroRTS strategy model (CFG) $\xrightarrow{\text{convert}}$ ASP model

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- MicroRTS strategy model (CFG) $\xrightarrow{\text{convert}}$ ASP model
- MicroRTS strategy $\xrightarrow{\text{encode}}$ $\langle f_{\theta,1}, f_{\theta,2}, \cdots, f_{\theta,i} \rangle$ using predicate vocabulary θ

Learning MicroRTS Strategies using ASP

- MicroRTS strategy model (CFG) $\xrightarrow{\text{convert}}$ ASP model
- MicroRTS strategy $\xrightarrow{\text{encode}}$ $\langle f_{\theta,1}, f_{\theta,2}, \cdots, f_{\theta,i} \rangle$ using predicate vocabulary θ
- Train a *linear model* ($\mathcal{L}$) to *predict* win rate given feature encoding

Learning MicroRTS Strategies using ASP

- MicroRTS strategy model (CFG) $\xrightarrow{\text{convert}}$ ASP model
- MicroRTS strategy $\xrightarrow{\text{encode}}$ $\langle f_{\theta,1}, f_{\theta,2}, \cdots, f_{\theta,i} \rangle$ using predicate vocabulary θ
- Train a *linear model* ($\mathcal{L}$) to *predict* win rate given feature encoding
- $\mathcal{L}$ $\xrightarrow{\text{convert}}$ ASP constraints as in Moritz et al. (2018)

Learning MicroRTS Strategies using ASP

- MicroRTS strategy model (CFG) $\xrightarrow{\text{convert}}$ ASP model
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- Train a *linear model* ($\mathcal{L}$) to *predict* win rate given feature encoding
- $\mathcal{L}$ $\xrightarrow{\text{convert}}$ ASP constraints as in Moritz et al. (2018)
- Evaluate resultant system using SynProS framework

Interpretability Factors for MicroRTS Strategies

- How to design an *evidence-based* interpretability measure for MicroRTS?

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Interpretability Factors for MicroRTS Strategies

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RQ3(b)

Which features of a MicroRTS strategy model have a statistically significant correlation with the interpretability of said strategy?

Task Design

- Conduct a *human-grounded* (Doshi-Velez and Kim 2017) evaluation
- Use a *forward simulation/prediction* task
- Subjects presented with —
  - Strategy
  - Game state (current)
  - Options for future states (1 correct, 3 incorrect)
- **Task**: predict expected future state from current state if strategy is followed and select option
- Generate tasks using ASP model of MicroRTS strategy

Obtaining Significant Factors

Prior Experience			**Strategy**				**Successful?**
Programming	RTS Games	$\cdots$	$f_{\theta,1}$	$f_{\theta,2}$	$\cdots$	$f_{\theta,i}$	
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

Table 3: Sample dataset envisioned from study

- Train *decision tree* model to predict whether strategy will be correctly simulated

Obtaining Significant Factors

Prior Experience			Strategy				Successful?
Programming	RTS Games	$\cdots$	$f_{\theta,1}$	$f_{\theta,2}$	$\cdots$	$f_{\theta,i}$	
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

Table 3: Sample dataset envisioned from study

- Train *decision tree* model to predict whether strategy will be correctly simulated
- Obtain significant factors by measuring *Gini index* (Molnar 2018)

Conclusion

- **Goal**: investigate approaches to the problem of *interpretable strategy synthesis* (ISS) for games

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- Proposal to approach ISS for *MicroRTS*
- Expected outcomes –
  - Benefit esports industry $\rightarrow$ better analytics for player performance
  - Benefit explainable AI research $\rightarrow$ new ways to generate policy explanations

Proposed Work & Timeline

Semester	RQ	Task	Publication	Status
Spring '22	RQ1 RQ2(a)	ISS Framework Known Tactic Evaluation	(Krishnan and Martens 2022b)	*Completed*
Fall '22	RQ2(b)	Study	(Krishnan and Martens 2022a)	*Completed*
Spring '23	RQ2(c) RQ3(a) RQ3(a,b)	Study (*under review*) Dataset assembly MicroRTS ASP Model	(Krishnan, Martens, and Jhala 2023)	*Completed* In progress
Summer '23	RQ3(a) RQ3(b)	Study Task Design (Strategies)	Advances in Computer Games '23	
Fall '23	RQ3(b) RQ3(b)	Task Design IRB Approval		
Spring '24	RQ3(b) – –	Analysis Dissertation writing Thesis defence	World Conference on Explainable Artificial Intelligence '24	
Summer '24	–	Graduation		

Thank You!

Questions?

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Strategy (σ)

Definition (Strategy)

Given a game environment $\mathcal{G}$ modeled as a finite, episodic MDP $\langle \mathcal{S}, \mathcal{A}, \mathcal{P}, \mathcal{R}, \gamma \rangle$, a *strategy* σ is —

$$\sigma(a|s) \doteq \mathbb{P}[A_t = a | S_t = s], \forall s \in \mathrm{A}_\sigma, a \in \mathcal{A}(s)$$

A_σ: set of *applicable* states

Return

Divergence

Move Evaluation Function

Given chess engine E with position evaluation function $v_E(s)$, we can obtain a move evaluation function $q_E(s, a)$ as —

$$q_E(s,a) = \sum_{s',r} \mathcal{P}(s', r|s, a)[r + v_E(s')] \tag{1}$$

$$= v_E(s'), s' \text{ is non-terminal} \tag{2}$$

Equation 2 follows from 1 since rewards in chess are 0 for non-terminal states, $\gamma = 1$, and chess rules are deterministic.

Divergence

Difference Function

Given two moves a_1, a_2 made in a position s, we can calculate their difference $d_E(s, a_1, a_2)$ as —

$$d_E(s, a_1, a_2) \doteq \mid q_E(s, a_1) - q_E(s, a_2) \mid \tag{3}$$

Return

Divergence

Definition (Divergence)

Divergence of a tactic from a set of examples P is the average difference in *evaluation* between the moves suggested by the tactic and the ground truth move.

$$\text{Divergence}_E(\sigma, P) \doteq \frac{1}{|P_{\text{A}}|} \sum_{(s,a_1)\in P_{\text{A}}} \sum_{a_2 \in \mathcal{A}(s)} \sigma(a_2|s) d_E(s, a_1, a_2) \tag{4}$$

Return

PAL

- **P**atterns **a**nd **L**earning (Morales 1992)
- ILP system to learn chess *patterns*
- Predicate vocabulary
- *rlgg* algorithm + heuristics to learn patterns
- Automatic *example generator* to learn target concepts

Return

Inductive Logic Programming

- *symbolic* machine learning technique
- ILP problem $\langle E^+, E^-, B \rangle$
  - E^+: positive examples (of concept)
  - E^-: negative examples (of concept)
  - B: background knowledge
- **Goal**: *induce* hypothesis that entails (fits) E^+ but not E^-

Return

Target Concept

$$E^+ = \left\{ \begin{array}{l} \texttt{last([m,a,c,h,i,n,e], e).} \\ \texttt{last([l,e,a,r,n,i,n,g], g).} \\ \texttt{last([a,l,g,o,r,i,t,h,m], m).} \end{array} \right\}$$

$$E^- = \left\{ \begin{array}{l} \texttt{last([m,a,c,h,i,n,e], m).} \\ \texttt{last([m,a,c,h,i,n,e], c).} \\ \texttt{last([l,e,a,r,n,i,n,g], x).} \\ \texttt{last([l,e,a,r,n,i,n,g], i).} \end{array} \right\}$$

$$B = \left\{ \begin{array}{l} \texttt{empty(A) :- ...} \\ \texttt{head(A,B) :- ...} \\ \texttt{tail(A,B) :- ...} \end{array} \right\}$$

Possible Hypothesis

$$H = \left\{ \begin{array}{l} \texttt{last(A,B) :- head(A,B),tail(A,C),empty(C).} \\ \texttt{last(A,B) :- tail(A,C),last(C,B).} \end{array} \right\}$$

Return

Precision/Recall-based Constraints

Definition (Precision constraint)

A precision constraint prunes the specializations of a hypothesis if its precision on a set of examples is less than some pre-defined lower limit.

Definition (Recall constraint)

A recall constraint prunes specializations of a hypothesis if its recall on a set of examples is less than some pre-defined lower limit.

Return

Precision/Recall-based Constraints

Theorem

Given hypotheses $H_1, H_2 \in \mathbb{H}$ with $H_1 \preceq H_2$ and having recall values of r_1 and r_2 on a training set respectively, then $r_1 \leq r_2$.

Return

Predicate Vocabulary

- Allows more *situational rule* expression – en passant, promotion
- Allows *more efficient* unification

Return

Answer Set Programming

- *Declarative programming* paradigm based on *stable models* (Gelfond and Lifschitz 1988)
- ASP language (Gebser et al. 2015) allows using rules to —
  - *model* a design space
  - *restrict* it using integrity constraints
  - *generate* instances in the newly restricted space

Return

Example

```
#const width=10.

param("width",width).

dim(1..width).

tile((X,Y)) :- dim(X), dim(Y).

adj((X1,Y1),(X2,Y2)) :- tile((X1,Y1)), tile((X2,Y2)), \\
    #abs(X1-X2)+#abs(Y1-Y2) == 1.

start((1,1)). finish((width,width)).

% tiles have at most one named sprite
0 { sprite(T,wall;gem;altar) } 1 :- tile(T).

% there is exactly one altar and one gem in the whole level
:- not 1 { sprite(T,altar) } 1. :- not 1 { sprite(T,gem) } 1.
```

Figure 17: An ASP program which can generate maze-like levels with integrity constraints that specify the number of game objects.