

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!



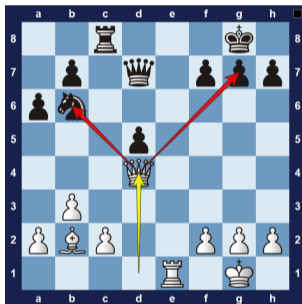
Arjun Somasekharan

Figure 5: What should Priya do now?

Story Time!

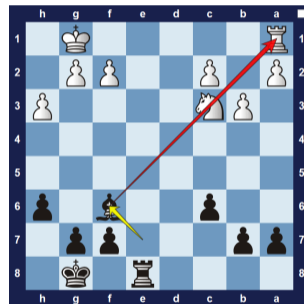
Could the Beth Harmon bots *explain* their *strategy* to Priya to help her get better?

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 → higher player skill → *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)	<i>(under review)</i> (Krishnan, Martens, and Jhala 2023)
ISS for MicroRTS	RQ3	RQ3(a)	<i>Proposed Work</i> (ACG 2023)
		RQ3(b)	<i>Proposed Work</i> (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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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 $\mathcal{R}: \mathcal{M} \rightarrow \mathbb{R}$
- Interpretability measure $\mathcal{I}: \mathcal{M} \rightarrow \mathbb{R}$

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

First-Order (FO) Logic Rule

Predicate Vocabulary

Strategy Model for Chess

First-Order (FO) Logic Rule

```
tactic(Position, Move) ←  
    feature_1(⋯),  
    feature_2(⋯),  
    ⋮  
    feature_n(⋯)
```

Predicate Vocabulary

Figure 9: Our chess strategy model expressed in Prolog pseudocode

Strategy Model for Chess

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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

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- Position =
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- Move = [a7, a8, queen]

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Predicate Vocabulary

- Position =
 - [contents(c2,pawn,white),
 - contents(g8,knight,black),
 - contents(e8,king,black),
 - turn(white),kingside_castle(white),...]
- 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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fork(Position,Move) ←  
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- Performance 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?

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?

Performance Measure

Divergence Equation

- How *different* is one strategy from another?
- High divergence → strategies are very different
- Low divergence → 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
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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?*

Evaluating Chess Tactics¹

¹Krishnan 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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Evaluating Chess Tactics¹

- PAL (Morales 1992) $\xrightarrow{\text{learn}}$ known chess patterns (tactics) PAL
- tactics $\xrightarrow{\text{translate}}$ chess strategy model
- Divergence(chess strategies, human beginner)
- Divergence(random baseline, human beginner)
- Both using strong/weak engine

¹Krishnan 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
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- Strategy model for chess
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- 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 ILP²

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

²Krishnan and Martens 2022a.

Learning Chess Strategies using ILP²

- Inductive Logic Programming (ILP): *symbolic ML* technique ILP
- ISS for chess $\langle \mathcal{G}, \mathcal{M}, \mathcal{R} \rangle \xrightarrow{\text{translate}} \text{ILP problem } \langle E^+, E^-, B \rangle$

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Learning Chess Strategies using ILP²

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- ISS for chess $\langle \mathcal{G}, \mathcal{M}, \mathcal{R} \rangle \xrightarrow{\text{translate}}$ ILP problem $\langle E^+, E^-, B \rangle$
- ILP system($\langle E^+, E^-, B \rangle$) $\xrightarrow{\text{learn}}$ chess strategies

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- ILP system($\langle E^+, E^-, B \rangle$) $\xrightarrow{\text{learn}}$ chess strategies
- Use *divergence* to evaluate learned chess strategies

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

²Krishnan and Martens 2022a.

Results

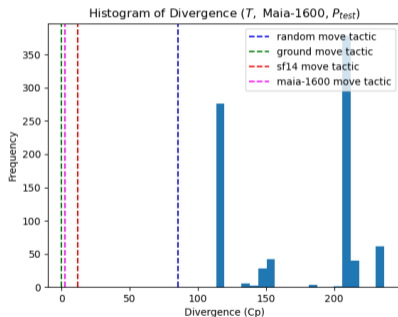


Figure 11: Divergence histogram for T evaluated using *weak* engine

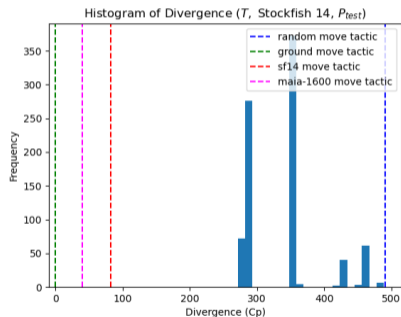


Figure 12: Divergence histogram for T evaluated using *strong* engine

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 Constraints³

- Modifications —

³Krishnan, Martens, and Jhala 2023.

Improvements using Precision/Recall-based Constraints³

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

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Improvements using Precision/Recall-based Constraints³

- 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 Constraints³

- 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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Improvements using Precision/Recall-based Constraints³

- 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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Improvements using Precision/Recall-based Constraints³

- Modifications —
 - 1 *Limit* chess strategy search space using precision/recall constraints
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 - Learn strategies using systems with/without constraints, predicate vocabulary
 - Measure average strategy divergence

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Improvements using Precision/Recall-based Constraints³

- 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
 - Measure average strategy divergence
 - Test decrease vs. old system using *one-sided Welch's t-test*

³Krishnan, Martens, and Jhala 2023.

Results

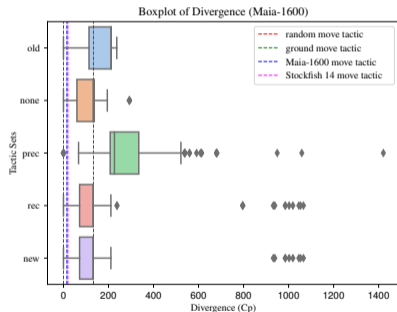


Figure 13: Boxplot of tactic divergence (evaluated using *weak* engine) for each system

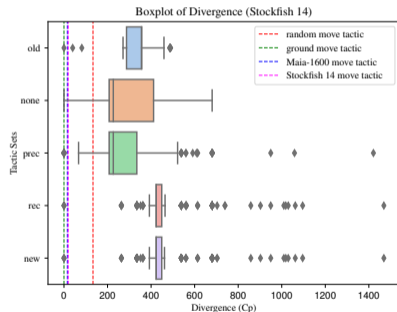


Figure 14: Boxplot of tactic divergence (evaluated using *strong* engine) for each system

Analysis

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

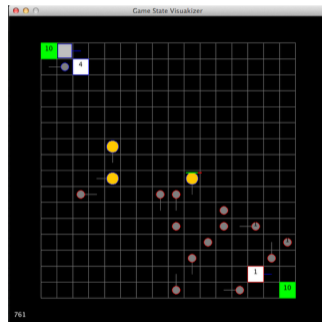
ISS for MicroRTS

RQ3

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

Why MicroRTS?

- Simplified **real-time strategy game** *for AI research* (Ontanon 2021)
- Active *research community*
- *Qualitatively different* from chess – *real-time, partially observable*
- *Popular genre* for esports 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~~
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} SynProS

SynProS Competition

- SynProS: **Synthesis of Programmatic Strategies**

SynProS Competition

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- 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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- MicroRTS strategy model = *CFG*

$$S_1 \rightarrow C S_1 \mid S_2 S_1 \mid S_3 S_1 \mid \epsilon$$

$$S_2 \rightarrow \text{if } (S_5) \text{ then } \{C\} \mid \text{if } (S_5) \text{ then } \{C\} \text{ else } \{C\}$$

$$S_3 \rightarrow \text{for (each unit } u) \{S_4\}$$

$$S_4 \rightarrow C S_4 \mid S_2 S_4 \mid \epsilon$$

$$S_5 \rightarrow \text{not } B \mid B$$

$$B \rightarrow b_1 \mid b_2 \mid \dots \mid b_m$$

$$C \rightarrow c_1 C \mid c_2 C \mid \dots \mid c_n C \mid c_1 \mid c_2 \mid \dots \mid c_n \mid \epsilon$$

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! → 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)

- **Answer Set Programming** ASP

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- ASP → *declarative programming* paradigm (like Prolog)

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- **Answer Set Programming** ASP
- ASP → *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

Learning MicroRTS Strategies using ASP

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- MicroRTS strategy $\xrightarrow{\text{encode}}$ $\langle f_{\theta,1}, f_{\theta,2}, \dots, f_{\theta,i} \rangle$ using predicate vocabulary θ

Learning MicroRTS Strategies using ASP

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- Train a *linear model* (\mathcal{L}) to *predict* win rate given feature encoding

Learning MicroRTS Strategies using ASP

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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?

Interpretability Factors for MicroRTS Strategies

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

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	...	$f_{\theta,1}$	$f_{\theta,2}$...	$f_{\theta,i}$	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	

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	...	$f_{\theta,1}$	$f_{\theta,2}$...	$f_{\theta,i}$	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

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 *ISS for games*

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- Proposal to approach ISS for *MicroRTS*
 - ASP-based learning method
 - Evidence-based interpretability measure
- Expected outcomes –
 - Benefit *esports industry* → *better analytics* for player performance
 - Benefit *explainable AI research* → 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)	<i>Completed</i>
Fall '22	RQ2(b)	Study	(Krishnan and Martens 2022a)	<i>Completed</i>
Spring '23	RQ2(c)	Study (<i>under review</i>)	(Krishnan, Martens, and Jhala 2023)	<i>Completed</i>
	RQ3(a)	Dataset assembly		In progress
	RQ3(a,b)	MicroRTS ASP Model		
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 —

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

A_σ : set of **applicable** states

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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 —

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

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

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 —

$$d_E(s, a_1, a_2) \doteq | q_E(s, a_1) - q_E(s, a_2) | \quad (3)$$

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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.

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

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

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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^-

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Target Concept

$$\begin{aligned}
 E^+ &= \left\{ \begin{array}{l} \text{last}([m,a,c,h,i,n,e], e). \\ \text{last}([l,e,a,r,n,i,n,g], g). \\ \text{last}([a,l,g,o,r,i,t,h,m], m). \end{array} \right\} \\
 E^- &= \left\{ \begin{array}{l} \text{last}([m,a,c,h,i,n,e], m). \\ \text{last}([m,a,c,h,i,n,e], c). \\ \text{last}([l,e,a,r,n,i,n,g], x). \\ \text{last}([l,e,a,r,n,i,n,g], i). \end{array} \right\} \\
 B &= \left\{ \begin{array}{l} \text{empty}(A) \quad :- \dots \\ \text{head}(A,B) \quad :- \dots \\ \text{tail}(A,B) \quad :- \dots \end{array} \right\}
 \end{aligned}$$

Possible Hypothesis

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

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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.

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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 $r_1 \leq r_2$.

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Predicate Vocabulary

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

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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

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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.