Formal Explainability for Artificial Intelligence in Dynamic Environments

Jime Cuartas Granada

Supervisors:
Alexey Ignatiev
Peter J. Stuckey
Julian Gutierrez

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Abstract

In dynamic environments, a goal of Artificial Intelligence (AI) is to build intelligent agents capable of addressing sequential decision-making settings. In this context, there are two important challenges for humans to understand decisions made by agents: (1) the sequential decisions are connected, (2) the environment can play a role in the outcome and (3) the agents may use opaque black-box models for each decision.

Despite the success of AI in sequential decision-making (e.g. Reinforcement Learning), the lack of transparency in understanding their decisions can make the agents hard to validate. To address the need for transparency, there are efforts to develop Explainable Artificial Intelligence (XAI). XAI is a set of methods designed to make AI models easier to comprehend. Despite the importance of Explainable Reinforcement Learning in developing trustworthy intelligent agents, there are gaps in current research to make sequential decision-making explainable.

This project proposes to explain sequential decision-making using formal reasoning. To achieve this goal, the proposal focuses on (1) Formal Explainability for Finite Automata, to address sequential actions in deterministic environments, (2) Formal Explainability for Pushdown Automata, to address sequential actions with stack-based memory, and (3) Formal Explainability for stochastic models, where outcomes are subject to environmental uncertainty.

Contents

Chapter 1

Introduction

The deployment of Artificial Intelligence (AI) algorithms has necessitated the need for eXplainability AI (XAI) methods to ensure transparency, trust, and accountability. While much of the field has focused on heuristic explanations for opaque models, there is an interest in formal approaches that provide rigorous guarantees about the explanations generated [1, 2].

A fundamental challenge in dynamic environments is explaining sequential decision-making. To address this, we model these processes using Automata, which provide a symbolic and tractable representation of sequential decision functions. This approach allows us to generate formal explanations, why a specific sequence of actions leads to a particular outcome. Automata are widely used in software verification [3], design of communication protocols [4],and sintax parsing in compiler [5]. When a computational model, such as a Finite Automaton (FA) or a Pushdown Automaton (PDA), accepts or rejects an input string, the reasoning behind that decision can be non-trivial. Understanding why a specific input was accepted or rejected is crucial for debugging, and refinement purposes.

This research project investigates the formalization of explanations for sequential decision-making. Having addressed an approach to deliver formal explanations for Finite Automata (FA) in the first stage of this research and submitting it to a ICALP 2026. I now move to address explanations for Context-Free Languages (CFG) / Pushdown Automata (PDA) decisions.

Current literature focuses on the *performance* of parsing rather than the *interpretability* of the decision. Modern parsing algorithms, such as Tree-sitter [6] and ANTLR 4 [7], utilise sophisticated incremental parsing and adaptive LL(*) algorithms to ensure low-latency feedback for integrated development environments (IDEs). While these methods are efficient at error recovery [5, 8], often scaling linearly with input size, they treat the decision process as the main objective. In this work, we prioritize interpretability by formally defining and computing the minimal reasons for a parsing error with minimal sets of corrections required to resolve it.

1.1 Formal Explainability

In this chapter I present some important concepts of Formal Explainability that are foundational for this work. Two types of explanations widely used in classification problems, and a brief illustration of our work developed during my first year to explain Finite Automata Decisions.

1.1.1 Classification Problems and Formal Explanations

Following XAI literature for classification problems [2, 9], we consider a classifier $\kappa : \mathbb{F} \to \mathcal{K}$ over a feature space $\mathbb{F} = \prod_{i=1}^{m} \mathbb{D}_i$ and a set of classes $\mathcal{K}$.

For an instance $\mathbf{v} \in \mathbb{F}$ with prediction $\kappa(\mathbf{v}) = c \in \mathcal{K}$, an *abductive explanation* is a minimal subset of features $\mathcal{X} \subseteq \{1, \ldots, m\}$ *sufficient* for the prediction. Formally, $\mathcal{X}$ is defined as:

$$\forall(\mathbf{x} \in \mathbb{F}). \left[\bigwedge\nolimits_{i \in \mathcal{X}} (x_i = v_i)\right] \rightarrow (\kappa(\mathbf{x}) = c) \tag{1.1}$$

Similarly, a *contrastive explanation* (CXp) is a minimal subset of features $\mathcal{Y} \subseteq \{1, \ldots, m\}$ that, if allowed to change, enables the prediction's alteration. Formally, a contrastive explanation $\mathcal{Y}$ is defined as follows:

$$\exists(\mathbf{x} \in \mathbb{F}). \left[\bigwedge\nolimits_{j \notin \mathcal{Y}} (x_j = v_j)\right] \wedge (\kappa(\mathbf{x}) \neq c) \tag{1.2}$$

Observe that abductive explanations are used to explain *why* a prediction is made by the classifier κ for a given instance, while contrastive explanations can be seen to answer *why not* another prediction is made by κ. Alternatively, CXps can be seen as answering *how* the prediction can be changed.

Importantly, abductive and contrastive explanations are known to enjoy a minimal hitting set duality relationship [10]. Given $\kappa(\mathbf{v}) = c$, let $\mathbb{A}_{\mathbf{v}}$ be the complete set of AXps and $\mathbb{C}_{\mathbf{v}}$ be the complete set of CXps for this prediction. Then each AXp $\mathcal{X} \in \mathbb{A}_{\mathbf{v}}$ is a minimal hitting set of $\mathbb{C}_{\mathbf{v}}$ and, vice versa, each CXp $\mathcal{Y} \in \mathbb{C}_{\mathbf{v}}$ is a minimal hitting set of $\mathbb{A}_{\mathbf{v}}$.[1] This fact is the basis for the algorithms used for formal explanation *enumeration* [9, 11].

1.1.2 Explaining Finite Automata Decisions

Here, we adopt standard definitions and notations for *finite automata* and *regular expressions* [12–14]. $\emptyset$ denotes the empty language, $c \in \Sigma$ denotes the language $\{c\}$, and Σ denotes the language containing the wildcard character (representing any single character), the set of all strings of length 1. In general, given a regular expression R, the language it defines is denoted by $L(R)$. The concatenation of two regular expressions R_1R_2 denotes the regular language $\{r_1r_2 \mid r_1 \in L(R_1), r_2 \in L(R_2)\}$.

[1] Given a collection of sets $\mathbb{S}$, a *hitting set* of $\mathbb{S}$ is a set H such that for each $S \in \mathbb{S}$, $H \cap S \neq \emptyset$. A hitting set is *minimal* if no proper subset of it is a hitting set.

In this work, we aim to explain the behaviour of a finite automaton $\mathcal{A}$ on an input $w \in \Sigma^*$, which can be viewed as a classifier mapping input w to a class in $\mathcal{K} = \{\text{accept}, \text{reject}\}$. Similar to classification problems, we propose two types of explanations for FA: abductive explanations (AXps) and contrastive explanations (CXps). Informally, an AXp answers "Why does $\mathcal{A}$ accept/reject w?" while a CXp answers "How can w be modified to alter the response of $\mathcal{A}$?".

In that work, we introduced a class of explanation languages based on regular expressions. They are formed by replacing selected characters in w with Σ (representing any character).

Example 1.1. *Consider the deterministic FA $\mathcal{A}$ shown in Figure 1.1. Observe that it accepts the input word* $\mathtt{bbbbb}$*. How should we explain this? One obvious way is to trace the execution of the automaton on the input word. Clearly, reading the first two* $\mathtt{b}$*'s leads to an accepting state, so an explanation could be* $\underline{\mathtt{bb}}\mathtt{bbb}$ *($L(\mathtt{bb}\Sigma\Sigma\Sigma) \subseteq L(\mathcal{A})$), where the underlined characters are those that explain the acceptance. However, other (shorter) explanations exist, e.g.* $\mathtt{bb}\underline{\mathtt{b}}\mathtt{bb}$ *($L(\Sigma\Sigma\mathtt{b}\Sigma\Sigma) \subseteq L(\mathcal{A})$) is a correct explanation, as any word of length 5 with a* $\mathtt{b}$ *in position 3 will be accepted. Once we have one type of explanation, we can easily extract the other using Minimal Hitting sets, as illustrated in Figure 1.2. AXps fix indices while CXps free them, revealing a minimal set where it is possible to flip the prediction (obtain a rejected word).* □

Formal definitions and more details about this and other languages of explanations are found in Appendix.

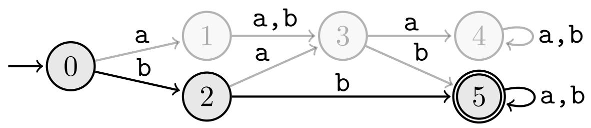

FIGURE 1.1: Input $\mathtt{bbbbb}$ is accepted by this automata. Opaque states indicate transitions that are not traversed for the input $\mathtt{bbbbb}$. Two valid explanations are $\underline{\mathtt{bb}}\mathtt{bbb}$ and (a shorter one) $\mathtt{bb}\underline{\mathtt{b}}\mathtt{bb}$.

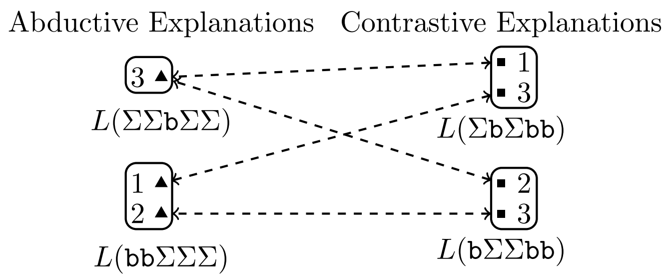

FIGURE 1.2: Duality between AXps and CXps in Σ. AXps fix the characters at given indices; CXps free them.

Chapter 2

Refined scope

While standard XAI focuses on feature attribution in classifiers, the "features" in formal languages are sequential and structural. Since the confirmation report, the research scope has been refined to address three primary gaps:

- **Research Problem 1 (Completed): Explaining Finite Automata.**
  How can we provide Formal Explanations for Finite Automata decisions?
  - To Define Formal explanations for understanding the acceptance/rejection of inputs in Finite Automata
  - To develop a method to compute Formal Explanations for Finite Automata
- **Research Problem 2: Explaining Context-Free Grammar (CFG).**
  How can we provide Formal Explanations for CFG decisions?
  - To Define Formal explanations for understanding the recognition of inputs by CFGs.
  - To develop a method to compute Formal Explanations for CFGs.
  - To propose a method to identify the most significant or "most likely" explanations among all vaid explanations.
- **Research Problem 3: Explaining Decisions of Stochastic models.**
  How can we provide formal explanations for decisions made by stochastic models?
  - To Define Formal explanations for understanding probable outcomes in Stochastic Models.
  - To develop a method to compute Formal Explanations for Stochastic Models (e.g., Probabilistic Finite Automata or Markov Models).
  - To propose a method to identify the most significant or "most likely" explanations among probabilistic paths.

2.1 Contributions - achieved and projected

This research provides both theoretical and practical contributions:

Achieved Contributions:

- Development of a theoretical and practical approach to explain Finite Automata.

- A paper submitted to ICALP 2026 tittled "A Formal Framework for the Explanation of Finite Automata Decisions"

Projected Contributions:

- Explaining Context-Free Grammar: (In Progress) Extending the formal explanation framework to CFGs, which recognize Context-Free Languages. This involves developing algorithms to identify the minimal contrastive explanations (CXps) and Abductive Explanations (AXps), and quantifying the contribution of specific tokens to the decision (acceptance or rejection).
- Explaining Decisions of Stochastic models: Extending the formal explanation framework to Stochastic Models. The goal is to provide verifiable explanations able to identify the environmental factors or decision points that lead to a particular outcomes.

Chapter 3

Progress

3.1 Model Proposal: Context-Free Grammar (CFG) Explanations

This work evolves from the study of Finite Automata (FA) to more expressive computational models. While FAs provide a baseline for explaining sequential behaviour, many complex problems require the model to "remember" an arbitrary number of previous inputs in the sequence to determine the validity of subsequent inputs.

Consider the abstract language $L = \{a^n b^n \mid n \geq 1\}$, which represents a sequence where every 'a' must be matched by a corresponding 'b'.

- The Limitation: A standard Finite Automaton (FA) possesses no stack-based memory. Therefore, it cannot count the number of a's to ensure they match the number of b's once n exceeds the number of states in the machine [5].
- The Explanation Failure: A Context-Free Grammar (CFG) can describe the language L, standard parsing algorithms only recognize whether an input is valid. Upon encountering a mismatch (e.g., a^4b^2), the parser identifies a failure but lacks the mechanisms to generate a contrastive explanation such as: "The sequence is invalid because the third or fourth 'a' was not closed by a matching 'b'." Instead, it can only report a "transition failure" at the specific index, obscuring the root cause of the error.
- **From Regular to Context-Free Languages:** We propose the use of Context-Free Languages to model decision-making processes that require stack-based memory.
  Unlike FAs, which are limited to Regular Languages, CFGs allow the description of more complex languages. The core challenge is how to explain these CFG decisions.

3.2 Motivation: The Gap between Detection and Explanation

One well established application of Context-Free Grammars is in the design of programming languages and compilers. Compilers are highly efficient at detecting when a sequence of tokens fails to belong to a grammar. However, a fundamental question is: are they able of generating a useful *explanation* for why the failure occurred or how to fix it?

Consider the following C code, where a typo has introduced a double opening bracket {{ in the `for` loop:

```c
1 int main(){
2     for(int i=0; i<10; i++){{  // <--- Error: Double bracket
3         printf("hello");
4     }
5 }
```

When compiled (e.g., using GCC or Clang), the parser consumes the input until it reaches <<EOF>>(end-of-file), finding only then that EOF was not expected, instead there is an incomplete structure, the token '}' is expected before <<EOF>>. The resulting error message is:

```
error: expected '}' at end of input
   5 | }
     |  ^
```

The Explanation: While the compiler's output is correct, the file ended while the stack still contained an open brace that was not closed yet. It is *misleading*.

- **Root Cause:** The compiler points to line 5 (the end of the file) as the location of the error. However, the root cause is located at line 2.
- **Lack of Contrastive Reasoning:** A human (or a formal explainer) would identify that the input is "almost correct". The explanation should not just report a missing symbol at the end but rather propose a *minimal correction*.

In this case, the minimal correction is not to add a brace at the end, but to remove the redundant opening brace at the loop initialization:

```c
1 int main(){
2     for(int i=0; i<10; i++){
3         printf("hello");
4     }
5 }
```

This discrepancy motivates the need for our proposed formal framework. We aim to move beyond isolated decisions to explained decisions revealing these minimal set of edits (Contrastive Explanations).

3.3 Preliminaries

This section defines the core concepts utilised throughout this ongoing work.

Definition 3.1 (Context-Free Grammar)**.** A Context-Free Grammar (CFG) is defined as a 4-tuple $G = (V, \Sigma, R, S)$, where:

- V (Variables/Non-terminals) is a finite set of variables (non-terminal symbols).
- Σ (Terminals) is a finite set of terminal symbols, disjoint from V.
- R is a finite set of production rules of the form $A \to \alpha$, where $A \in V$ describes a variable and $\alpha \in (V \cup \Sigma)^*$ is a string of variables and terminals.
- $S \in V$ is the start variable.

The following CFG recognizes the language of balanced parentheses (a subset of the Dyck language) [1] and is used throughout the document to illustrate the proposed ideas.

Example 3.1. *Let $G = (\{Balanced\}, \{\,(,)\,\}, R, Balanced)$ be the grammar defined by the following production rules R:*

$$\begin{aligned} Balanced &\to (\, Balanced \,)\, Balanced && \textit{(Rule 1)} \\ Balanced &\to (\, Balanced \,) && \textit{(Rule 2)} \\ Balanced &\to (\,)\, Balanced && \textit{(Rule 3)} \\ Balanced &\to (\,) && \textit{(Rule 4)} \end{aligned} \tag{3.1}$$

This grammar generates the language of properly nested parentheses. For instance, the string ()() can be derived as follows.

$$\begin{aligned} Balanced &\Rightarrow (\ )\,\mathbf{Balanced} && \textit{(Rule 3: parentheses and Balanced)} \\ &\Rightarrow (\ )\ (\ ) && \textit{(Rule 4: Reduce `Balanced' to `()')} \end{aligned} \tag{3.2}$$

To analyse a CFG, we must first standardize the grammar structure (e.g. Chomsky Normal Form). This enables the use of efficient parsing algorithms like CYK (Cocke-Younger-Kasami) [16, 17].

3.3.1 Chomsky Normal Form

Parsing algorithms often require the grammar to be in a canonical form to ensure predictable execution complexity.

Definition 3.2 (Chomsky Normal Form)**.** A Context-Free Grammar $G = (V, \Sigma, R, S)$ is in *Chomsky Normal Form* (CNF) [18] if every production rule in R is of one of the following two forms:

- $A \to BC$ (where $A, B, C \in V$)
- $A \to a$ (where $a \in \Sigma$ and $a \neq \epsilon$)

[1] The Dyck language describes a set of strings with balanced and properly nested brackets (e.g., (), [], {}) [15]. The example focuses solely on non-empty sequences of balanced (and).

For every CFG G whose language contains at least one string other than ϵ, then there is a grammar G_1 in Chomsky Normal Form, such that $L(G_1) = L(G) \setminus \{\epsilon\}$.

Example 3.2. *Consider the grammar G from Example 3.1. We transform G into an equivalent grammar $G' = (V', \Sigma, R', S)$ in CNF.*

Step 1: Terminals to Non-terminals. *Introduce variables L and R for terminals '(' and ')'.*

$$L \to (\quad \text{and} \quad R \to)$$

Step 2: Binary decomposition. *Rewrite the original rules using new variables and break down productions into binary steps.*

The resulting production rules R' are:

$$
\begin{array}{rcll}
\textit{Balanced} & \to & \textit{Nested Balanced} & \text{(Represents '(Balanced) Balanced')} \\
 & | & \textit{Unclosed}\,R & \text{(Represents '(Balanced)')} \\
 & | & \textit{Pair Balanced} & \text{(Represents '( ) Balanced')} \\
 & | & L\,R & \text{(Represents '( )')} \\
\textit{Nested} & \to & \textit{Unclosed}\,R & \\
\textit{Unclosed} & \to & L\,\textit{Balanced} & \\
\textit{Pair} & \to & L\,R & \\
L & \to & (& \\
R & \to &) &
\end{array}
$$

3.3.2 The CYK Algorithm

The Cocke-Younger-Kasami (CYK) [16, 17] algorithm is a bottom-up parsing method that given a CFG G in CNF determines whether a string w belongs to a language $L(G)$. It operates via dynamic programming, constructing a triangular table where each cell $T[i, j]$ contains the set of non-terminals that can generate the substring of w starting at i and ending at j.

Definition 3.3 (CYK Table Construction)**.** For an input string $w = w_1 w_2 \dots w_n$:

1. **Base Case:** For each $i \in \{1, \dots, n\}$, $T[i, i] = \{A \in V \mid A \to w_i\}$.
2. **Recursive Step ($j > i$):** $T[i, j]$ contains A if there exists a rule $A \to BC$ and a split point k ($i \le k < j$) such that $B \in T[i, k]$ and $C \in T[k + 1, j]$.

The string is accepted if starting symbol $S \in T[1, n]$.

Example 3.3. *Table 3.1 illustrates the CYK Table construction to verify the acceptance of the string $w =$ ()() using the CNF grammar derived in Example 3.2. The top-right cell $T[1, 4]$ represents the entire string. It contains the Start symbol B (Balanced) because there is a rule 'Balanced $\to$ Pair Balanced' for a split point $k = 2$ where Pair $\in T[1, 2]$ and Balanced $\in T[3, 4]$.*

Similarly, the cell $T[1, 2]$ contains P (Pair) because there is a rule Pair $\to L\,R$ for a split point $k = 1$ ($L \in T[1, 1]$ and $R \in T[2, 2]$).

$w_1 =$ '(' $\{L\}$	$\{B, P\}$	$\emptyset$	**{B}**
	$w_2 =$ ')' {R}	$\emptyset$	$\emptyset$
		$w_3 =$ '(' {L}	{B,P}
			$w_4 =$ ')' {R}

TABLE 3.1: CYK Table for $w = ()()$. The cells $T[i, j]$ correspond to the substring starting at i and ending at j. The diagonal elements contain the input terminals and unary rules able to generate them. **Abbreviations:** B = Balanced, P = Pair

3.4 Explaining Context-Free Languages

This report describes ongoing work to explain decisions regarding membership in a Context-Free Grammar (CFG) G for an input $w \in \Sigma^*$. Similar to explaining Finite Automata decisions [19], this problem can be viewed as a classifier mapping input w to a class in $\mathcal{K} = \{\text{accept}, \text{reject}\}$. We propose two types of explanations: **Abductive Explanations** (AXps), which answer "Why does G accept/reject w?"; and **Contrastive Explanations** (CXps), which answer "How can w be modified to alter the response of G?".

In this work, the class of explanations languages is based on regular expressions formed by replacing some characters in w by Σ.

An **abductive explanation** relative to a word, is a set of indices such that, if they are fixed, the prediction is going to remain the same regardless of the other tokens. A **contrastive explanation** is a set of indices such that, if they were free, it would be possible to flip the prediction.

Typically, accepted words in Context-Free Languages are easy to modify to flip the prediction to **rejected**. Conversely, rejected words are often robustly wrong, requiring multiple coordinated changes (or single specific one) to repair the word.

The following example illustrates this behaviour.

Example 3.4 (Fragility of Acceptance)**.** *Consider the accepted word $w =$ `()()`. The validity relies on every token. Modifying any single index is sufficient to flip the prediction to **rejected**.*

Every single index constitutes a CXp:

- ***Index 1:** Changing '`(`' $\to$ '`)`' makes `))()` (Rejected: starts with closing).*
- ***Index 2:** Changing '`)`' $\to$ '`(`' makes `((()` (Rejected: unmatched open).*
- ***Index 3:** Changing '`(`' $\to$ '`)`' makes `()))` (Rejected: unmatched close).*
- ***Index 4:** Changing '`)`' $\to$ '`(`' makes `()((` (Rejected: unmatched open).*

Since every feature is critical, the AXp (the subset of features required to guarantee acceptance) is the entire word.

The problem becomes significantly more interesting for rejected words.

Algorithm 1 ExtractCXp – a Single CXp Extraction

Input: Context-Free Grammar G, Candidate set $\mathcal{Y}$ (initially $\{1.. \ldots |w|\}$), word w
Output: Minimal CXp $\mathcal{Y}$

```
if not IsCXp(G, Y, w) then
    return ⊥
for all i ∈ Y do
    if IsCXp(G, Y \ {i}, w) then
        Y ← Y \ {i}
return Y
```

Example 3.5 (Robustness of Rejection)**.** *Consider the rejected word $w =$ `))))`. Changing a single index is insufficient to flip the prediction to* ***accepted****. There are only two Minimal CXps for this word:*

- *$CXp_1 = \{1, 2\}$: Generates* $\underline{\texttt{((}}\texttt{))}$.
- *$CXp_2 = \{1, 3\}$: Generates* $\underline{\texttt{(}}\texttt{)}\underline{\texttt{(}}\texttt{)}$.

From this, we can extract meaningful AXps that are sufficient to guarantee rejection:

- *$AXp_1 = \{1\}$: The first symbol '`)`' guarantees rejection regardless of the remaining suffix.*
- *$AXp_2 = \{2, 3\}$: The substring '`))`' at indices 2 and 3 guarantees rejection for any word of length 4.*

3.4.1 Extracting One Formal Explanation

To extract a CXp for a rejected word, we must first establish an efficient method to verify whether a candidate set of indices allows the word to be accepted. We achieve this by adapting the CYK parsing algorithm as described in Definition 3.4.

Definition 3.4 (CYK-based Verification of CXp)**.** For an input string $w = w_1 w_2 \ldots w_n$ and a grammar in Chomsky Normal Form, the CYK algorithm is modified to verify if an index set $S \subseteq \{1, \ldots, n\}$ is a CXp for a rejected word as follows:

1. **Base Case:** For each $i \in \{1, \ldots, n\}$:
   - If $i \in S$: $T[i, i] = \{A \in V \mid \exists \alpha \in \Sigma, A \to \alpha\}$ (all non-terminal symbols with at least one unary rule).
   - If $i \notin S$ (Fixed): $T[i, i] = \{A \in V \mid A \to w_i\}$ (as Standard CYK).
2. **Recursive Step ($j > i$):** Standard CYK update

The set S is a valid CXp if the start symbol belongs to $T[1, n]$.

$w_1 = \Sigma$ {L,R}	{B,P}	{L,U}	{**B**}
	$w_2 = \Sigma$ {L,R}	{B,P}	$\emptyset$
		$w_3 =$) {R}	$\emptyset$
			$w_4 =$ ')' {R}

Table 3.2: Modified CYK Table verifying `))))`. Indices 1 and 2 are treated as wildcards (Σ). **Abbreviations:** B = Balanced, P = Pair, U = Unclosed

Algorithm 1 extracts a minimal CXp using a greedy deletion strategy. Initially, $\mathcal{Y}$ includes all indices (effectively treating the whole word as wildcards). The algorithm iterates through the candidates, attempting to "recover" the original token w_i at each position. If the function IsCXp (Definition 3.4) confirms that the word can still be corrected *without* changing index i, then i is redundant and removed from the explanation, otherwise, i is part of the explanation. The result is a minimal CXp: removing any index from $\mathcal{Y}$ would find a pattern containing no valid strings in $L(G)$.

Abductive Explanations (AXps) are extracted similarly. Since AXps represent sufficient conditions for rejection, a set $\mathcal{X}$ is a valid AXp if treating indices in $\mathcal{X}$ as fixed (and all others as wildcards) as $\textsc{IsCXp}(G, \overline{\mathcal{X}}, w)$ and checking if the start symbol does not belong in $T[1, n]$.

3.4.2 Prioritizing Explanations

While the extraction of Minimal CXps provides a set of valid corrections, it often produces multiple candidates. For the rejected word $w =$ `))))`, we identified two minimal sets: $\text{CXp}_1 = \{1, 2\}$ (suggesting `(())`) and $\text{CXp}_2 = \{1, 3\}$ (suggesting `()()`).

A ranking approach is *Feature Attribution*, which counts the frequency of an index across all minimal explanations. In our case:

- **Index 1:** Frequency 1.0.
- **Index 2:** Frequency 0.5.
- **Indix 3:** Frequency 0.5.

However, symbolic frequency ignores the how likely is resulting correction. In domains like programming, certain structures (e.g., deeply nested brackets vs. sequential pairs) have different probabilities. To refine our suggestions, we use **Probabilistic Context-Free Grammars (PCFGs)**[20].

Example 3.6 (Rule Counting)**.** *Consider a training dataset $D = \{$`()()()`, `(())()`, `()(())`$\}$. Figure 3.2 shows the derivation trees, and Table 3.3 the rule counting to estimate the probability of each production rule (B denotes the non-terminal Balanced).*

Rule	**Count**	**Probability (P)**
$B \to L\ R$	4	$4/9 = 44.\overline{4}$
$B \to \text{Pair } B$	3	$3/9 = 33.\overline{3}$
$B \to \text{Nested } B$	1	$1/9 = 11.\overline{1}$
$B \to \text{Unclosed } R$	1	$1/9 = 11.\overline{1}$

Table 3.3: Probability distribution derived from D.

3.4.2.1 Ranking Explanations via PCFGs

To select the best correction, we calculate the probability of generating suggested correction given a fixed length constraint. For our running example to explain the rejected

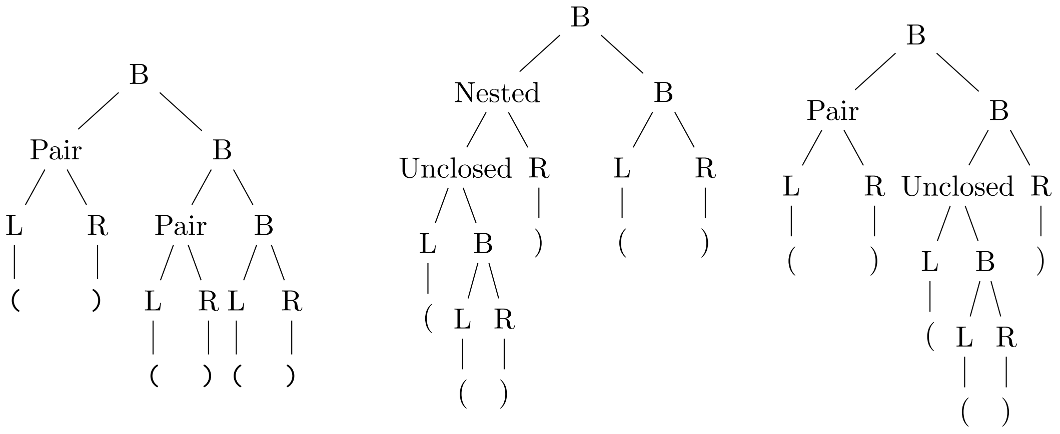

FIGURE 3.1: Parse trees for words `()()()`, `(())()`, `()(())`.

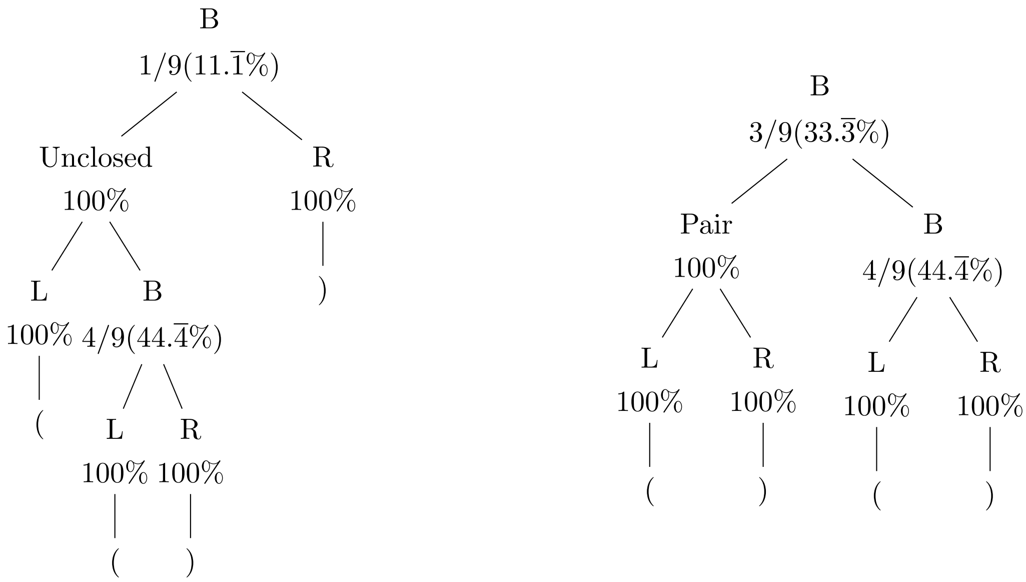

FIGURE 3.2: Parse trees for words `(())` and `()()`.

word w = `))))` we consider the set of all valid words in the language of length 4 $L_4 = \{\texttt{()()}, \texttt{(())}\}$.

The total probability for valid words of length 4 is:

$$P(L_4) = P(\texttt{()()}) + P(\texttt{(())}) \tag{3.3}$$

Using the estimated rule probabilities, we compute the likelihood of the corrections suggested by our CXps (shown in Figure 3.2):

- $\mathrm{CXp}_1 \rightarrow \texttt{(())}$: $P(\texttt{(())}) = \frac{1}{9} \times \frac{4}{9} \approx 0.049$
- $\mathrm{CXp}_2 \rightarrow \texttt{()()}$: $P(\texttt{()()}) = \frac{3}{9} \times \frac{4}{9} \approx 0.148$

We define the *Relative Likelihood Score* for a CXp suggesting correction w' as:

$$Score(w') = P(w')/P(L_{|w|}) \tag{3.4}$$

$$Score(\mathrm{CXp}_1) = \frac{0.049}{0.148 + 0.049} \approx \mathbf{0.25} \quad \text{vs} \quad Score(\mathrm{CXp}_2) \approx \mathbf{0.75}$$

Under this PCFG, the correction `()()` (suggested by CXp_2) is more likely than `(())` (suggested by CXp_1). This allows the explainer to prioritize the most statistically probable fix.

3.5 Conclusion

We present a polynomial-time algorithm for extracting Abductive and Contrastive Explanations relying on linear calls to a CYK based algorithm. Additionally, incorporating training data, this approach can prioritize the most relevant contrastive explanations. Future work will focus on benchmarks to evaluate the scalability and and a propose to understand how can we prioritize abductive explanations.

Chapter 4

Future Plan

In my third year, I plan to finalize the validation and theoretical details for Formal Explanations for Pushdown Automata. Then, I will address Research Problem 3, investigating formal explanations for models with sthocastic behaviour.

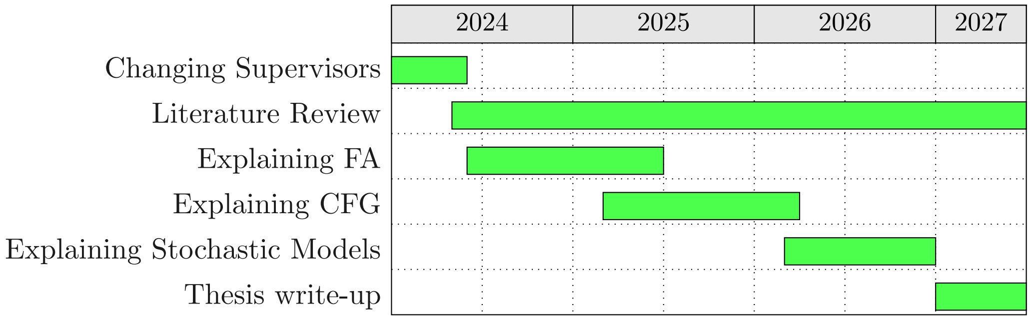

FIGURE 4.1: Timeline to completion of the PhD project

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