University of Johannesburg

Masters Dissertation

A NEAT Inspired GEP Algorithm

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in the

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“*It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is most adaptable to change. In the struggle for survival, the fittest win out at the expense of their rivals because they succeed in adapting themselves best to their environment.*”

Charles Darwin

Acknowledgements

I would like to sincerely thank my supervisor, Prof Coulter, for his guidance and support throughout this research. His expertise and feedback were invaluable.

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1. Introduction

1.1 Background

The theory of evolution by natural selection, first introduced by Charles Darwin, has profoundly influenced our understanding of the life and adaption in the natural world. Darwin's insight that species evolved over generations through the survival and reproduction of individuals with advantageous traits has not only shaped the biological sciences, but has also inspired computational models that emulate these adaptive processes (Li et al. 2024). Over millions of years, evolution has given rise to complex biological systems, among which the human brain stands as one of the most intricate. Composed of billions of neurons, the brain processes information through electrochemical signaling across complex interconnected networks, enabling perception, reasoning, and decision-making (Engelbrecht 2007). These biological mechanisms have served as a blueprint for the development of artificial intelligent systems, particular in the field of evolutionary computation and neural networks.

In computer science, evolutionary algorithms simulate the process of natural selection to solve complex optimisation problems. These algorithms operate on populations of candidate solutions, applying genetic operators such as mutation, crossover, and selection to iteratively improve the problem's solution. In conjunction to the expanding field of evolutionary computing, artificial neural networks (ANNs) which are inspired by the structure and function of biological neurons have become foundational in machine learning.

These networks consist of interconnected nodes that process information in layers, enabling machines to learn from data and perform tasks such as classification, prediction, and control (Russell and Norvig 2016). The intersection of evolutionary algorithms and neural networks has given rise to the field of neuroevolution, which seeks to evolve both the structure and parameters of neural networks using evolutionary principles.

Among the many algorithms developed within the field of evolutionary computing and neuroevolution, Gene Expression Programming (GEP) and the NeuroEvolution of Augmenting Topologies (NEAT) stand out due to their unique and complementary approaches to evolving computational structures. Gene Expression Programming (GEP) is an evolutionary algorithm that evolves computer programs or symbolic expressions. It represents solutions as linear chromosomes, which are then expressed as expression trees through an effective genotype-to-phenotype mapping scheme. This approach allows the evolution of tree-like structures in a more robust and flexible manner than traditional genetic programming techniques (Ferreira 2006). NEAT, in contrast, focuses on evolving the topology and weights of neural networks. It introduces several key innovations, including historical markings (innovation numbers) to track structural changes, speciation to preserve diversity within the population, and incremental growth of network complexity to efficiently explore the search space. These features enable NEAT to evolve increasingly sophisticated neural architectures over time (Stanley and Miikkulainen 2002).

This dissertation introduces a novel hybrid algorithm, GEP-NEAT, which seeks to combine the structural expressiveness of GEP with the adaptive topology evolution of NEAT. The motivation for developing GEP-NEAT arises from specific limitations observed in both NEAT and GEP-based neural network approaches. While NEAT has demonstrated success in evolving neural network topologies, it suffers from computational inefficiencies, particularly due to the overhead introduced by topological sorting during network evaluation which becomes increasingly problematic as networks grow in complexity. On the other hand, GEP-NN, an approach that applies GEP to evolve neural networks, offers promising alternative by representing neural structures as expression trees, but it remains relatively underexplored in the literature and lacks the methodological maturity and empirical validation seen in other neuroevolutionary techniques. GEP-NEAT is proposed a response to these challenges, aiming to combine the structural flexibility of GEP with the evolutionary dynamics of NEAT. At the heart of GEP-NEAT is a new representation scheme in which innovation numbers are encoded as sub-tree configurations. This approach allows for a more expressive and hierarchical encoding of neural structures, facilitating the reuse of functional subcomponents and promoting the emergence of modular architectures. By integrating GEP's symbolic representation with NEAT's evolutionary dynamics, GEP-NEAT aims to provide a more powerful and flexible tool for evolving neural networks.

1.2 Structure

This dissertation begins with this introductory chapter, which outlines the research motivation, and key research questions. It also highlights the academic contributions of the work, including publications that have emerged from the research process. Following the introduction, a dedicated chapter is presented on the research methodology, which adopts a design science approach. This chapter details the methodological framework used to guide the development, implementation, and evaluation of the proposed algorithm.

The core of the dissertation presents a comprehensive literature review, divided into three chapters. The first of these explores the foundations of evolutionary computing, providing context for the broader field in which the work is situated. The focuses on neuroevolution, examining how evolutionary algorithms have been applied to the development of neural networks. The third chapter delves into gene expression programming, detailing its mechanisms, advantages, and relevance to the proposed approach.

After establishing the theoretical foundation, the dissertation introduces the GEP-NEAT algorithm in detail. This chapter covers the theoretical underpinnings of the algorithm, its practical implementation, and the experimental setup used to evaluate its performance. The results of these experiments are then presented and analysed, with a focus on assessing the algorithm's effectiveness, efficiency, and potential advantages over existing methods. The final chapter concludes the dissertation by summarising the key findings, discussing their implications, and outlining directions for future research.

1.3 Research Questions

The development of algorithms that evolve neural network architectures remains a dynamic and evolving area of research. While various approaches have been proposed to automate the design of neural networks through evolutionary computation, several open questions persist regarding the efficiency, expressiveness, and adaptability of these methods. This dissertation is driven by a set of research questions that aim to explore and address specific limitations in existing neuroevolutionary techniques, particularly GEP and NEAT.

The first research question investigates the structural limitations of current gene expression programming when applied to neural networks. Traditional neural networks typically include architectural features such as bias nodes and non-linear activation functions, which are essential for enhancing representational capacity. However, many implementations of gene expression programming for neural networks do not incorporate these features. This leads to the first question:

R1 *How can gene expression programming be extended to evolve neural networks that closely resemble traditional architectures, including the incorporation of bias nodes and activation functions?*

The second question addresses a known computational bottleneck in topology-based neuroevolutionary algorithms. Specifically, algorithms that evolve network structures often rely on topological sorting to ensure valid signal flow during evaluation. While effective, this process can become increasingly inefficient as networks grow in size and complexity. This raises the question:

R2 *Can the computational inefficiencies associated with topological sorting in neural network evaluation be mitigated through alternative representations or evaluation strategies?*

A third area of inquiry concerns the role of innovation numbers in NEAT. Traditionally, innovation numbers are used to track structural changes and align genomes during crossover, however, this usage is largely historical and does not contribute directly to the functional behavior of the algorithm. This lead to the question:

R3 *Is it possible to redefine innovation numbers in NEAT to represent meaningful and reusable structural components?*

Building on this idea, the fourth question explores the practical implications of such a redefinition. If innovation numbers can be used to encode modular structures, it is important to understand how this can be leverages to improve algorithmic performance. Thus, the next question is:

R4 *Provided that innovation numbers are redefined as reusable structural components, how can this representation be exploited to improve the performance, modularity, or evolutionary dynamics of the algorithm?*

The fifth question considers the broader hypothesis that combining distinct evolutionary strategies may lead to improved outcomes. Specifically, it examines whether integrating symbolic expression-based representations (GEP) with topological representations (NEAT) can result in a more effecting approach to evolving neural networks. This gives rise to the question:

R5 *Does the integration of symbolic-based representations (GEP) with topology-evolving strategies (NEAT) result in improved performance, scalability, or expressiveness compared to using either approach in isolation?*

Finally, the sixth question addresses a practical limitation in many symbolic neuroevolutionary systems, that is, the difficulty of evolving neural networks with multiple outputs. Many real-world tasks require networks to produce more than one output simultaneously, yet existing representations often struggle to accommodate this. This leads to the final question:

R6 *How can expression trees be adapted to support the evolution of neural networks with multiple outputs, and what are the implications for multi-output learning tasks?*

Together, these research questions form the foundation of this dissertation. They aim to explore the theoretical and practical challenges of evolving neural networks using symbolic and structural representations, and to investigate whether new approaches can overcome the limitations in existing methods.

1.4 Publications Resulting from this Work

A peer-reviewed conference paper derived from this research was published in the proceedings of the **8th International Conference on Information Science and Systems**

(ICISS 2025). As an established forum in its eight iteration, ICISS maintains rigorous academic standards through its double-blind peer review process, where both author and reviewer identities are concealed to remove bias and ensure impartial evaluation based solely on scholarly merit. The conference brings together leading researchers across ten interdisciplinary tracks spanning artificial intelligence, data science, and information systems.

The accepted paper, which contributes to the Machine Learning and Artificial Intelligence track, presents the algorithm GEP-NEAT with its innovation number novelty, showcasing the ability to solve the XOR and Cart Pole problem effectively. ICISS 2025 facilitated valuable scholarly exchange through keynote presentations by field leaders, technical workshops, and interdisciplinary discussion bridging academic and real-world application. The conference proceedings are to be published into **Communications in Computer and Information Sicence (Electronic ISSN: 1865-0937 & Print ISSN: 1865-0929)** as a proceedings book volume and indexed by EI Compendex, Scopus, INSPEC, SCImago and other databases.

2. Research Methodology

Hello World

3. Sectioning Examples

3.1 Section Title

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3.1.1 Subsection Title

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Unnumbered Section

Unnumbered Subsection

Unnumbered Subsubsection

4. In-text Element Examples

4.1 Referencing Publications

This statement requires citation Jones and Smith 2022; this one is more specific Smith and Jones 2021, page 162.

4.2 Link Examples

This is a URL link: LaTeX Templates. This is an email link: example@example.com. This is a monospaced URL link: `https://www.LaTeXTemplates.com`.

4.3 Lists

Lists are useful to present information in a concise and/or ordered way.

4.3.1 Numbered List

1. First numbered item
    a. First indented numbered item
    b. Second indented numbered item
        i. First second-level indented numbered item
2. Second numbered item
3. Third numbered item

4.3.2 Bullet Point List

- First bullet point item
  - First indented bullet point item
  - Second indented bullet point item
    - First second-level indented bullet point item
- Second bullet point item
- Third bullet point item

4.3.3 Descriptions and Definitions

Name Description

Word Definition

Comment Elaboration

4.4 International Support

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4.5 Ligatures

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Part Two Title

5. Mathematics

5.1 Theorems

5.1.1 Several equations

This is a theorem consisting of several equations.

Theorem 5.1 — Name of the theorem. In $E = \mathbb{R}^n$ all norms are equivalent. It has the properties:

$$\big| ||\mathbf{x}|| - ||\mathbf{y}|| \big| \leq ||\mathbf{x} - \mathbf{y}|| \tag{5.1}$$

$$|| \sum_{i=1}^{n} \mathbf{x}_i || \leq \sum_{i=1}^{n} ||\mathbf{x}_i|| \quad \text{where } n \text{ is a finite integer} \tag{5.2}$$

5.1.2 Single Line

This is a theorem consisting of just one line.

Theorem 5.2 A set $\mathscr{D}(G)$ in dense in $L^2(G)$, $|\cdot|_0$.

5.2 Definitions

A definition can be mathematical or it could define a concept.

Definition 5.1 — Definition name. Given a vector space E, a norm on E is an application, denoted $||\cdot||$, E in $\mathbb{R}^+ = [0, +\infty[$ such that:

$$||\mathbf{x}|| = 0 \Rightarrow \mathbf{x} = \mathbf{0} \tag{5.3}$$

$$||\lambda \mathbf{x}|| = |\lambda| \cdot ||\mathbf{x}|| \tag{5.4}$$

$$||\mathbf{x} + \mathbf{y}|| \leq ||\mathbf{x}|| + ||\mathbf{y}|| \tag{5.5}$$

5.3 Notations

▪ **Notation 5.1** Given an open subset G of $\mathbb{R}^n$, the set of functions φ are:

1. Bounded support G;
2. Infinitely differentiable;

a vector space is denoted by $\mathscr{D}(G)$.

5.4 Remarks

This is an example of a remark.

R The concepts presented here are now in conventional employment in mathematics. Vector spaces are taken over the field $\mathbb{K} = \mathbb{R}$, however, established properties are easily extended to $\mathbb{K} = \mathbb{C}$.

5.5 Corollaries

Corollary 5.1 — Corollary name. The concepts presented here are now in conventional employment in mathematics. Vector spaces are taken over the field $\mathbb{K} = \mathbb{R}$, however, established properties are easily extended to $\mathbb{K} = \mathbb{C}$.

5.6 Propositions

5.6.1 Several equations

Proposition 5.1 — Proposition name. It has the properties:

$$\big| ||\mathbf{x}|| - ||\mathbf{y}|| \big| \leq ||\mathbf{x} - \mathbf{y}|| \tag{5.6}$$

$$|| \sum_{i=1}^{n} \mathbf{x}_i || \leq \sum_{i=1}^{n} ||\mathbf{x}_i|| \quad \text{where } n \text{ is a finite integer} \tag{5.7}$$

5.6.2 Single Line

Proposition 5.2 Let $f, g \in L^2(G)$; if $\forall \varphi \in \mathscr{D}(G)$, $(f, \varphi)_0 = (g, \varphi)_0$ then $f = g$.

5.7 Examples

5.7.1 Equation Example

▪ **Example 5.1** Let $G = \{x \in \mathbb{R}^2 : |x| < 3\}$ and denoted by: $x^0 = (1,1)$; consider the function:

$$f(x) = \begin{cases} e^{|x|} & \text{si } |x - x^0| \leq 1/2 \\ 0 & \text{si } |x - x^0| > 1/2 \end{cases} \tag{5.8}$$

The function f has bounded support, we can take $A = \{x \in \mathbb{R}^2 : |x - x^0| \leq 1/2 + \varepsilon\}$ for all $\varepsilon \in]0; 5/2 - \sqrt{2}[$. ▪

5.7.2 Text Example

▪ **Example 5.2 — Example name.** Aliquam arcu turpis, ultrices sed luctus ac, vehicula id metus. Morbi eu feugiat velit, et tempus augue. Proin ac mattis tortor. Donec tincidunt, ante rhoncus luctus semper, arcu lorem lobortis justo, nec convallis ante quam quis lectus. Aenean tincidunt sodales massa, et hendrerit tellus mattis ac. Sed non pretium nibh. Donec cursus maximus luctus. Vivamus lobortis eros et massa porta porttitor. ▪

5.8 Exercises

Exercise 5.1 This is a good place to ask a question to test learning progress or further cement ideas into students' minds. ▪

5.9 Problems

Problem 5.1 What is the average airspeed velocity of an unladen swallow?

5.10 Vocabulary

Define a word to improve a students' vocabulary.

▪ **Vocabulary 5.1 — Word.** Definition of word.

6. Presenting Information and Results with a Long Chapter Title

6.1 Table

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Treatments	**Response 1**	**Response 2**
Treatment 1	0.0003262	0.562
Treatment 2	0.0015681	0.910
Treatment 3	0.0009271	0.296

Table 6.1: Table caption.

Referencing Table 6.1 in-text using its label.

6.2 Figure

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Treatments	Response 1	Response 2
Treatment 1	0.0003262	0.562
Treatment 2	0.0015681	0.910
Treatment 3	0.0009271	0.296

Table 6.2: Floating table.

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Figure 6.1: Figure caption.

Referencing Figure 6.1 in-text using its label.

Figure 6.2: Floating figure.

Bibliography

Articles

Jones, A. B. and J. M. Smith (Mar. 2022). “Article Title”. In: *Journal title* 13.52, pages 123–456. DOI: 10.1038/s41586-021-03616-x (cited on page 23).

Stanley, Kenneth O and Risto Miikkulainen (2002). “Evolving neural networks through augmenting topologies”. In: *Evolutionary computation* 10.2, pages 99–127 (cited on page 12).

Books

Engelbrecht, Andries P (2007). *Computational intelligence: an introduction*. John Wiley & Sons (cited on page 11).

Ferreira, Cândida (2006). *Gene expression programming: mathematical modeling by an artificial intelligence*. Volume 21. Springer (cited on page 12).

Russell, Stuart J and Peter Norvig (2016). *Artificial intelligence: a modern approach*. Pearson (cited on page 12).

Smith, J. M. and A. B. Jones (2021). *Book Title*. 7th. Publisher (cited on page 23).

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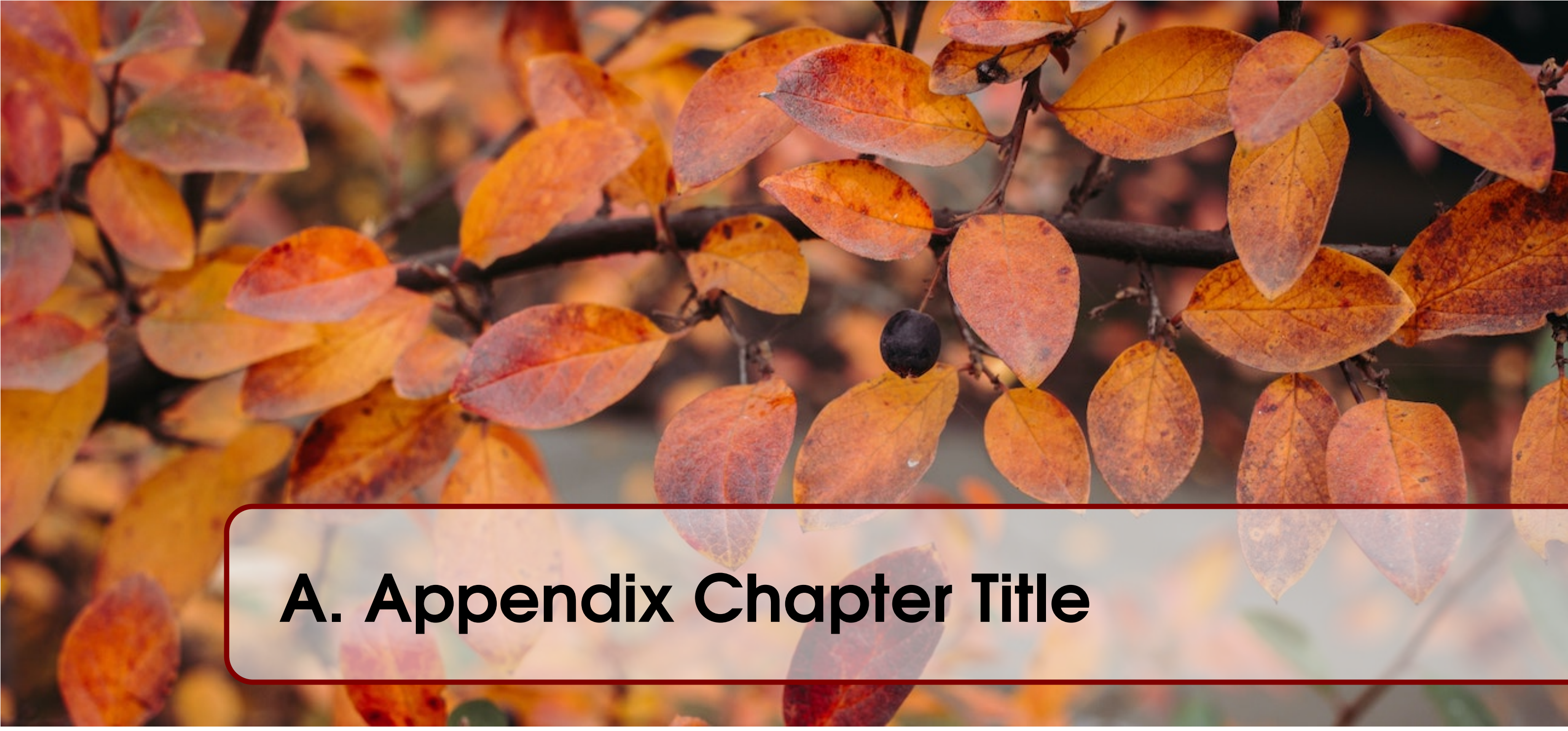

A. Appendix Chapter Title

A.1 Appendix Section Title

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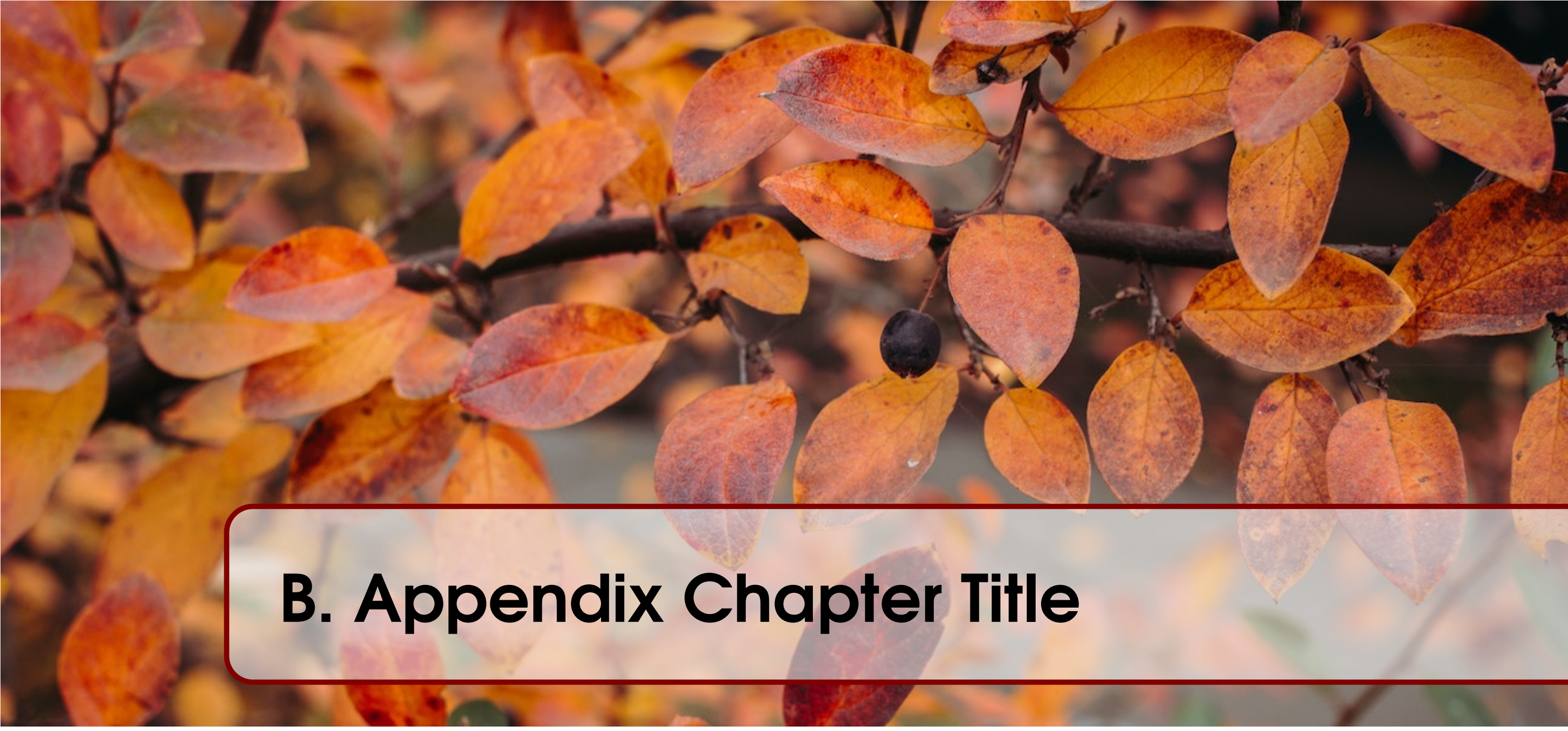

B. Appendix Chapter Title

B.1 Appendix Section Title

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