Communicative role of trees in Algorithms and Data Structures Textbooks

Illustration Practices in Computer Science Textbooks

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Abstract. Tree-based illustrations are widely used in Algorithms and Data Structures (ADS) textbooks to communicate hierarchical relationships. This study investigates how tree-based illustrations are used and what communicative functions they serve across different topics and textbooks.
A comparative qualitative thematic analysis was conducted on three ADS textbooks. Illustrations of general trees, binary trees, binary search trees, AVL trees and heaps were analysed using a coding framework derived from Levin's functional taxonomy of illustrations, Mayer's multimedia learning theory and Duval's theory of semiotic representation. The analysis focused on signalling and register shift.
The results revealed two main patterns. First, signalling techniques such as highlighted paths, arrows and geometric shapes were frequently used to communicate algorithmic behaviour that is not directly visible in tree structures. These techniques often accompanied register shifts between visual and verbal representations. Second, the textbooks differ substantially in their visual conventions, reflecting different approaches to communicating information through illustrations.
The study concludes that tree-based illustrations function as communicative tools that support both structural and procedural understanding, while shaping how readers connect visual and verbal representations.

Keywords: Algorithms and Data Structures · tree-based illustrations · signalling

1 Introduction

Trees are among the most important data structures in computer science and are used in applications ranging from file systems to databases. Understanding these structures requires students to think about hierarchical relationships that are often presented through diagrams, code and verbal explanations. Prior research has shown that diagrams support reasoning and influence how mathematical ideas are conceptualized and communicated [6,7]. Much of this work has focused on well-established visual domains such as geometry, where the structure and interpretation of diagrams have received considerable attention [8,13].

Learning in Algorithms and Data Structures (ADS) often involves multiple forms of representation, such as text, code and diagrams. Research on multiple representations suggests that learning can benefit when learners coordinate information across different representations [1]. However, there has been little systematic analysis of how illustrations are used in ADS. While some studies have explored diagrammatic representations in programming contexts [19], relatively little attention has been paid to how textbook illustrations contribute to learning in ADS.

In particular, tree-based illustrations are fundamental in computer science, as they express hierarchical structures and operations such as traversal and balancing. However, they have not been extensively studied for their communicative role across learning materials.

To address this lack of systematic understanding, this paper aims to provide a structured analysis of how tree-based illustrations function across various textbooks, focusing on general trees, binary trees, binary search trees, AVL trees, heaps, and tree traversal algorithms. The aim is to systematically analyse how these illustrations are used and what communicative functions they serve in explaining key concepts, as a better understanding of these visualisations may contribute to improved learning in ADS. The research is guided by the following research questions:

- **RQ1:** How are tree-based representations used in illustrations, and what communicative functions do they serve, within selected topics in Algorithms and Data Structures textbooks?
- **RQ2:** How do the use and communicative role of tree-based illustrations vary across textbooks and topics?

By combining qualitative coding, thematic analysis and comparative analysis across multiple textbooks, this study contributes a structured understanding of the roles and variations of tree-based visualisations in ADS education. The analysis identified two recurring themes. First, signalling techniques such as highlighted lines or arrows are frequently used to communicate algorithmic processes not directly visible in tree structures. Second, substantial differences exist in the visual conventions used across textbooks, reflecting different approaches to communicating information.

2 Background

2.1 Related Work

Research on educational diagrams has shown that visual representations support reasoning and problem solving by making relationships explicit and reducing the cognitive effort required to identify relevant information [16]. In mathematics education, diagrams have been studied as representational tools that influence how concepts are communicated and understood [7,8].

Within computer science education, researchers have also examined how visual representations contribute to understanding computational concepts. For example, Mazumder et al. analysed variable, array and object diagrams in Java textbooks and investigated the extent to which such diagrams function as explanatory representations [19]. A related body of research focuses on algorithm visualisation. Hundhausen, Douglas and Stasko conducted a meta-study of algorithm visualisation effectiveness and found that the educational value of algorithm visualisations depends strongly on how learners engage with them, highlighting the role of visual representations in supporting algorithm learning [15].

Research has also examined visual representations for algorithm explanations. For linked data structures, abstract representations derived through shape analysis have been proposed to support explanation by highlighting the portions of a data structure that are relevant to an algorithm's upcoming actions and suppressing irrelevant detail [4]. More recently, Hayatpur et al. analysed programmer-produced data structure diagrams and identified three recurring visual abstraction strategies, namely simplification, revisualisation and annotation, that programmers use to communicate and reason about data structures and program state [12]. These studies highlight the importance of abstraction in visual representations of computational concepts, but focus primarily on algorithm execution and runtime representations rather than textbook illustrations.

Beyond educational research, studies in information visualisation have examined how hierarchical structures and relationships can be represented through graph, tree, and node-link diagrams [14]. Such work highlights the role of visual representations in organising and communicating complex structural information. Despite these contributions, relatively little research has examined how tree-based illustrations function within ADS textbooks, particularly in terms of how they communicate procedural information and support understanding.

2.2 Framework

Research on diagrams in mathematics has already shown that visual representations do more than just illustrate written explanations. They can support reasoning by making information visually explicit and reducing the amount of search and computation required during problem solving [16]. Research on multiple representations further suggests that learning depends not only on the representations themselves, but also on how learners interact with and relate to multiple forms of information [1]. Together, these perspectives indicate that understanding is influenced by how visual and textual representations interact.

To better understand how illustrations support learning, multiple theoretical frameworks have been developed to classify and analyse their functions in educational contexts. One example is Joel R. Levin's *functional taxonomy of illustrations*, which aims to functionally classify the relation of illustrations to the text [5,17]. Levin makes a distinction between illustrations, depending on whether they are decorative, representative, organisational, interpretational (explanatory) or transformational. In contrast, Richard E. Mayer's *multimedia learning theory* focuses on cognitive integration of visual and verbal information, suggesting that effective learning depends not only on simply combining visual and verbal elements, but that the right contextual and spatial combination is required, otherwise split-attention effects may overload the learner's working memory [18]. This is especially important for investigating the quality of illustrations in textbooks. Furthermore, Raymond Duval's *theory of semiotic representation* emphasizes the importance of relationships between different forms of representation (registers) [10]. According to Duval, understanding depends on the student's ability to consciously switch between registers and create connections between them.

Together, these frameworks allow tree-based illustrations to be analysed in terms of their communicative function, instructional design and relationships to accompanying representations.

3 Methodology

This research employed a comparative qualitative thematic analysis to examine the use of illustrations in ADS textbooks. A qualitative approach was chosen, because the communicative role of textbook illustrations cannot be described simply with quantitative measures alone. The interpretation of illustrations depends on contextual and visual relationships between text and diagrams. Thematic analysis provides a method for identifying, analysing, and interpreting patterns of meaning within qualitative data [3]. This approach is suitable for RQ1 and RQ2, as both research questions focus on understanding how tree-based illustrations are used and how their communicative roles vary across textbooks and topics. The analysis involved iterative coding of illustrations and the subsequent development and refinement of themes through repeated comparison across textbooks. This process enabled recurring patterns in the communicative functions and visual characteristics of illustrations to be identified.

3.1 Material Selection

The study applies the framework to sections of three ADS textbooks used in higher education that represent different visual and didactic approaches. These include works by Goodrich et al. [11], Drozdek [9], and Akepogu and Palagiri [2]. The selected textbooks were chosen because they cover overlapping core tree-based topics while also representing different pedagogical and visual approaches. The analysis is restricted to core tree-based topics that appear across all selected textbooks, including general trees, binary trees, binary search trees (BST), AVL trees, and heap representations.

The analysed material consisted of Goodrich Chapters 7, 8.3, 10.1 and 10.2; Akepogu Chapters 9, 11.3 and 12; and Drozdek sections 6.1-6.9. This material was selected because it covered the tree-based topics in the study. For the purposes of this research, only illustrations labelled as figures were included in the analysis. Code blocks labelled as figures were excluded due to them not having illustrative elements, and rather just being text.

3.2 Analytical Framework

The research applies perspectives from Levin's functional taxonomy of illustrations, Mayer's multimedia learning theory and Duval's theory of semiotic representation. Rather than using these frameworks in their complete and independent form, this study combines selected dimensions into a compact analytical framework specifically adapted for ADS textbook analysis.

Levin's framework was included because it provides a way to classify the communicative function of illustrations. From this framework, representational, organisational and explanatory categories were included as dimensions in the coding scheme. Decorative and transformational dimensions were excluded as such illustrations did not occur in the analysed textbooks.

Mayer's multimedia learning theory was included to analyse aspects of instructional quality. From this framework, spatial contiguity, signalling and coherence were selected as dimensions because they directly affect how information is presented within textbook illustrations. These dimensions were particularly relevant for analysing the role of tree-based illustrations and comparing visual strategies across textbooks. Other principles of Mayer's framework were not included because they primarily concern multimedia environments, or temporal presentations, which are not applicable to static textbook illustrations.

Duval's theory of semiotic representation was included because it focuses on relationships between different forms of representation. Representation type and register shift were selected as dimensions to analyse how illustrations interact with text, code and other visual representations within ADS textbooks.

Together, these dimensions allow illustrations to be analysed from functional, cognitive, and representational perspectives with a single analytical approach.

3.3 Coding Scheme

The coding scheme was derived deductively from the analytical framework. The communicative function of each illustration was coded according to Levin's functional taxonomy. Illustrations were classified as **representational**, **organisational**, or **explanatory**.

The instructional quality of illustrations was evaluated using three principles derived from Mayer's multimedia learning theory, namely **spatial contiguity**, **signalling** and **coherence**. Signalling measured the extent to which visual cues directed the reader's attention toward relevant information. Examples mainly included arrows, highlighting and labels. Signalling was also coded on three levels, from none to strong.

– **None:** No visual elements beyond the basic tree representation direct attention to specific information.
– **Weak:** Minor visual cues organise the figure (e.g., subfigure labels, simple arrows between states).
– **Strong:** Visual cues explicitly communicate direction, sequence, algorithmic processes through elements such as arrows or highlighted paths.

Representation characteristics were analysed using concepts derived from Duval's theory of semiotic representation. The dominant **representation type** of each illustration, and the presence of **register shifts** were recorded. A register shift was present when the content of an illustration, and its related representations (such as text, code or other illustrations) did not match in content, or one introduced new information that is not present in the others. In cases where register shifts occurred, they were classified according to their complexity:

- **Single shift:** One relationship between representations, for example an illustration and accompanying text.
- **Complex shift:** Multiple relationships between representations, for example an illustration, accompanying text, and a block of code.

3.4 Coding Process

The coding process was conducted using Atlas.ti. To facilitate comparison between books and topics, different textbooks and topics were organised into separate files. Illustrations were coded sequentially across the topics. The coding process was based on the analytical framework described in Section 3.2.

Coding was conducted in multiple iterations. As new illustrations were encountered, the boundaries between codes were refined to reduce ambiguity and improve consistency. Previously analysed illustrations were then revised and recoded to ensure that the refined definitions were applied consistently throughout the dataset. Through repeated refinement and recoding, the coding scheme gradually achieved its final form.

Once coding was completed, the occurrence of codes was compared across books and topics to identify recurring patterns. Using thematic analysis, themes were developed by grouping related codes and observations that appeared repeatedly throughout the dataset. The resulting themes focused on broader communicative practices rather than individual coding categories.

4 Results

The analysis identified two recurring themes regarding the communicative role of tree-based illustrations. First, signalling techniques were frequently used to communicate algorithmic processes that are not directly visible in tree structures. Second, the analysed textbooks differed in visual conventions used to represent trees, reflecting different communicative priorities. The following subsections discuss these themes and how tree-based illustrations are used to communicate information in ADS.

4.1 Using signalling to represent algorithmic behaviour

Three distinct signalling strategies Tree diagrams naturally represent structural relationships, but not algorithmic steps. In most illustrations, algorithmic steps are explained either by having multiple subdiagrams that show successive states of an algorithm, or by using signalling techniques that highlight important elements within a single diagram. Across the dataset, signalling was frequently used to represent information that is not inherently visible in the tree structure itself, such as algorithmic steps or traversal paths.

Across the dataset, signalling was frequently used, appearing in 121 of 135 analysed illustrations. However, signalling was not used consistently across textbooks. Goodrich frequently relied on strong signalling through coloured highlighting and bold paths, while Akepogu more often used arrows to connect successive states of an algorithm. Drozdek employed a more varied set of signalling techniques, including geometric shapes, as well as arrows. These differences suggest that textbooks adopt different strategies for communicating algorithmic behaviour within tree representations.

Differences were also visible across topics. Traversal illustrations frequently used signalling to communicate order and direction, while illustrations of operations, such as insertion, deletion and balancing more commonly used signalling to highlight changes between states. Introductory tree-based illustrations generally relied less on signalling, because structural relationships were already visible in the representation itself.

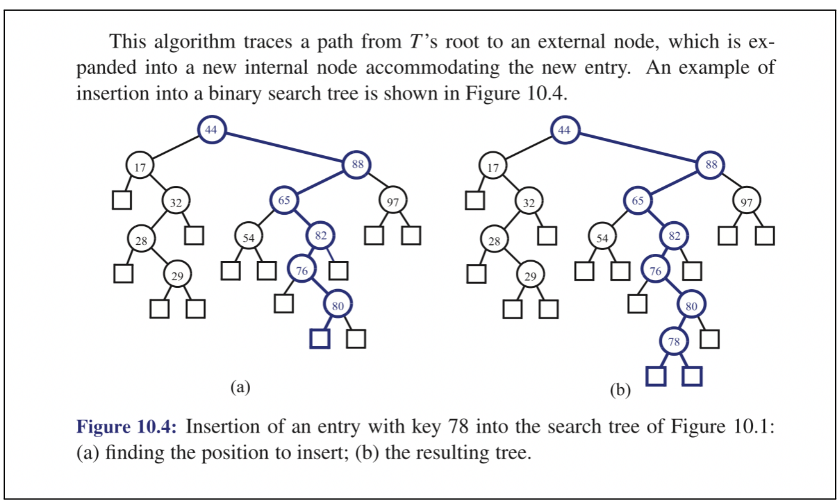
This algorithm traces a path from T's root to an external node, which is expanded into a new internal node accommodating the new entry. An example of insertion into a binary search tree is shown in Figure 10.4.

Figure 10.4: Insertion of an entry with key 78 into the search tree of Figure 10.1: (a) finding the position to insert; (b) the resulting tree.

Fig. 1. Example of strong signalling from Goodrich [11]

As visible in Fig. 1, the highlighted line brings attention to where the new node was added, and how its insertion position was found. The use of a different colour (dark blue) and bold lines make the recognition of this path, and the entries on the path instantaneous. The accompanying text discusses the insertion algorithm in general terms, however it does not explain the specific steps to reach the insertion point. In this case, the image provides this information visually.

Without highlighting, it would not be immediately apparent how the insertion point was reached, or what differences exist between the two illustrations. This shows one strategy for using signalling, where the illustration itself carries part of the procedural information.

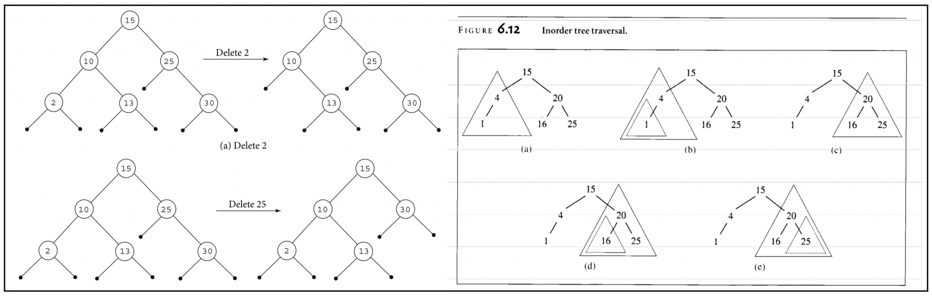

Fig. 2. Example of weak signalling from Akepogu (left) [2] and strong signalling from Drozdek (right) [9]

In the case of the left panel of Fig. 2, the signalling is less prominent. While the text above the arrow specifies which entry was deleted and guides the reader from one state of the tree to the next, it does not explain how the operation was performed. Instead, the accompanying text provides a detailed explanation as to where, why and how the deletion occurs, and what consequences it had. In this case, the illustration serves primarily as a visual reference for the explanation that is already present in the text.

A third signalling technique can also be observed in Drozdek. In the right panel of Fig. 2, geometric shapes are used to highlight the current state of the algorithm and to indicate which parts of the tree are currently relevant. Rather than showing a traversal path, the shapes help the reader identify the algorithm's current focus. Although this is visually different from the previous examples, its purpose remains similar, to direct attention towards information that would otherwise be difficult to identify within the tree structure alone.

These three signalling strategies appear to reflect different communicative goals. Highlighted paths were primarily used to communicate the specific route followed by an algorithm, arrows between successive tree states were used to indicate transitions and guide the reader through a sequence of operations, while geometric highlighting was used to draw attention to the parts of the tree currently relevant to the algorithm. Although all three techniques direct attention, they differ in the type of information they communicate. Highlighted paths and traversal arrows make algorithmic behaviour explicit within the illustration itself, allowing readers to follow a process directly from the visual representation. In contrast, arrows between successive states primarily organise a sequence of diagrams and often rely on accompanying text to explain the underlying operation. Geometric highlighting occupies an intermediate position, as it identifies algorithmically relevant regions of the tree without explicitly communicating a sequence of actions.

Tree-based illustrations naturally communicate hierarchical and structural information, such as parent-child relationships, but they are less suited to representing temporal sequences of actions. Algorithms consist of sequences of steps, a before state and an after state, and multiple states in between that are difficult to communicate through a static diagram alone. The most direct way of representing an algorithm is often through multiple illustrations that show successive states. However, signalling techniques can reduce the need for additional diagrams by making procedural information explicit within a single representation. In cases such as the Euler Tour illustration in the bottom-left panel of Fig. 3, signalling can even be used to represent an entire process within one figure. In this sense, signalling transforms a structural representation into a process-oriented one. As a result, part of the explanatory burden shifted from the accompanying text to the illustration itself, allowing procedural information to be communicated visually rather than verbally.

Three purposes of arrows Across the dataset, arrows were primarily used for three purposes: to show the path followed by an algorithm, to indicate transitions between states of an algorithm, and to direct attention to specific features of an illustration. Although these uses share a common visual form, they communicate different kinds of information. The Euler Tour illustration shown in the bottom-left panel of Fig. 3 provides an example of the first of these uses, where arrows indicate the route taken by an algorithm.

Unlike the arrows in the left panel of Fig. 2, which primarily connect successive states, these arrows in the bottom-left panel of Fig. 3 communicate direction and order. The tree structure itself already shows hierarchical relationships between nodes, but it does not indicate how the algorithm moves through those relationships. The arrows therefore introduce information that is not already present in the diagram.

The different uses of arrows show that signalling techniques do not have fixed meanings, instead their communicative role depends on how they are used in the illustration. The same arrow can communicate direction, sequence or emphasis, allowing authors to adapt a familiar symbol to different explanatory needs.

Signalling, explanatory burden and register shift The dimension of register shift captures the degree of difference in information portrayed by an illustration and its surrounding text. The relationship between register shift and signalling appears to depend on how explanatory information is distributed between text and illustration. In cases where illustrations are expected to communicate procedural information independently, stronger signalling often appears to guide interpretation and direct the reader towards the relevant elements of the figure. Conversely, when procedural details are explained explicitly through text, signalling can play a more limited role because less information needs to be extracted from the visual representation itself.

The relationship between register shift and signalling can be observed in the comparison between Fig. 1 and the left panel of Fig. 2. In Fig. 1, strong signalling communicates information that is not explicitly described in the surrounding text, requiring readers to extract information directly from the visual representation and increasing the informational contribution of the illustration relative to the accompanying text. In contrast, the left panel of Fig. 2 relies more heavily on textual explanation, while the illustration primarily serves as a visual reference, reducing the informational difference between the two representations. These examples suggest that signalling influences how explanatory information is distributed across representations and therefore may affect the degree of register shift between illustrations and text. Strong signalling appears particularly useful when readers must reconstruct procedural information directly from the illustration, whereas weaker signalling may be sufficient when procedural details are already explained through text. In such cases, signalling can guide attention to relevant elements without duplicating information already available in another representation.

These observations discussed above suggest a relationship between signalling and register shift. While both signalling and register shift were analysed independently, both concepts frequently appeared together within the analysed material. Table 1 presents the co-occurrence between signalling and register shift complexity.

Table 1. Co-occurrence of signalling and register shift.

Signalling/Register Shift	No Shift	Single Shift	Complex Shift
None	6	6	2
Weak	**33**	18	5
Strong	11	**37**	**17**

Illustrations coded as having no register shift were often associated with weak signalling, occurring 33 times out of 50 illustrations. In contrast, illustrations with single or complex shifts were often associated with strong signalling, accounting for 37 out of 61 and 17 out of 24 illustrations respectively. The proportion of strongly signalled illustrations therefore increases with register shift complexity.

This pattern suggests a possible association between the complexity of relationships across representations and the strength of signalling techniques employed within illustrations. This relationship was observed across multiple topics and textbooks, suggesting that it reflects a broader pattern rather than a topic-specific phenomenon.

This pattern does not suggest that one approach is superior to the other, rather it indicates that explanatory information can be distributed differently across visual and textual representations depending on the communicative goals of the illustration. Register shifts therefore appear not necessarily to be the result of missing information, but rather to be deliberate decisions about which representation is best suited to communicate a particular aspect of the concept. Structural relationships are often communicated visually, while reasoning is either added through signalling or explained through text.

4.2 How different books visualise trees differently

While all three books cover the same tree-based topics, they do not employ the same visual notations to represent trees. Instead, each textbook develops its own language consisting of different shapes and conventions. These conventions remain relatively consistent in the same book, but might differ slightly between different sections. The observed differences suggest that tree-based illustrations are adapted to emphasize particular properties of the concepts being taught, rather than being a plain representation of data.

Among the analysed textbooks, Goodrich employs the most systematic visual vocabulary. Example trees belonging to different categories are represented using different visual conventions, but each convention remains consistent across the examples. This is visible in the top row of Fig. 3, where trees representing books use ellipses for their nodes, and trees representing file systems use a folder for their nodes. General trees, BSTs, and AVL trees often distinguish between internal and external nodes, which they represent as circles and squares respectively, like in the bottom-left panel of Fig. 3. This changes when heaps are introduced, as they no longer show external nodes, as visible in the bottom-right panel of Fig. 3.

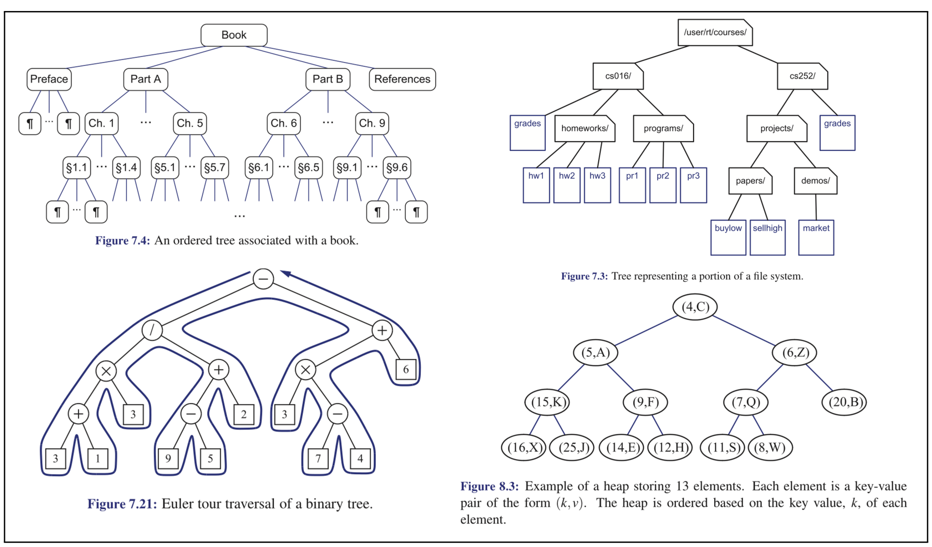

Fig. 3. Example of tree-based illustrations from Goodrich [11]

The disappearance of external nodes from heap representations may be a consequence of the concepts the different topics aim to communicate. In binary search trees, insertions terminate at external nodes, while AVL trees define balance and height using paths ending at external nodes. Therefore, external nodes play an important role in their algorithms, and are thus explicitly represented. In contrast, heap representations focus primarily on heap operations, where the location of external nodes does not contribute significantly to understanding these concepts. Their omission therefore decreases the illustration's visual complexity, without removing essential information. Rather than using a single representation, Goodrich adapts the notation to the current topic.

Although Goodrich maintains a high consistency in visual notations, the meaning assigned to certain symbols changes across topics. In expression trees, square nodes represent external nodes that contain meaningful values. In binary search trees and AVL trees, the same shape is used for external nodes that represent the absence of children. This suggests that maintaining a consistent visual notation is sometimes prioritised over assigning a single meaning to a symbol. While the square shape remains unchanged, its interpretation depends on the topic being discussed.

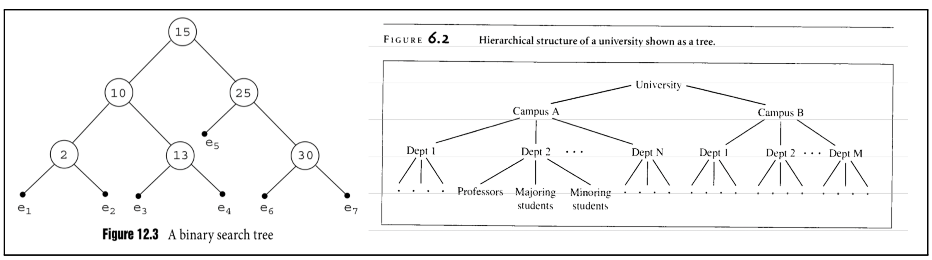

Fig. 4. Example of tree-based illustration from Akepogu (left) [2] and Drozdek (right) [9]

Akepogu employs a similar approach as well. For general trees, heaps and AVL trees, simple circular nodes are used. Binary trees expand on this, by introducing small black dots to represent external nodes, as visible in the left panel of Fig. 4. The textbook explicitly explains these external nodes as the representation of null pointers. Unlike Goodrich, where these appeared as squares, Akepogu chooses a notation that is more visually distinct, clearly separating values from symbolic elements.

A small number of BST illustrations also replace entire subtrees with triangles. Instead of representing a node, they indicate that a subtree exists but that its contents are irrelevant to the operation being explained. This allows the figure to focus on the important part of the algorithm, while reducing visual complexity.

Drozdek adopts a completely different visual vocabulary. Many tree-based illustrations contain little to no explicit node representations. Instead of enclosing values with circles or squares, values are positioned directly within the tree structure, with no visual highlight, as visible in the right panel of Fig. 4. This minimalist style produces simpler representations and places greater emphasis on structural relationships than on visual distinctions between different node types. Unlike Goodrich and Akepogu, who frequently distinguish different categories of nodes through visual notation, Drozdek generally relies on the arrangement of branches and labels to communicate structure. The reader is then expected to interpret the structure directly, rather than relying on visual cues to distinguish between different types of nodes.

Although the analysed topics cover the same tree-based concepts, they do not converge on a single way of representing them. This suggests that the differences are not driven by the underlying data structures themselves, but by different decisions regarding what information should be communicated through the illustrations. While all three books rely on the same basic tree structure, they differ both in the amount of additional information they choose to encode visually and how that information is presented. The illustrations therefore appear to reflect different assumptions regarding what information readers should be able to identify directly from the illustration.

These choices may further influence how later concepts are explained. Once a textbook has introduced a visual convention, following illustrations can build upon it, and reuse the same symbols. Goodrich frequently develops and reuses a richer visual vocabulary, whereas Drozdek tends to rely on a more minimalist representation. Akepogu occupies a middle position, maintaining a relatively simple notation, while introducing additional symbols, when they contribute to understanding a concept. In Goodrich, symbols introduced in earlier illustrations can be recognised immediately in later ones, allowing additional information to be communicated without introducing new notation. Drozdek's approach relies less on multiple visual conventions, instead maintaining a simpler representation that remains largely unchanged across topics.

The comparison across textbooks suggests that representational choices are related to the kinds of information communicated through the illustrations. Across the analysed topics, additional notation was introduced when the basic tree structure alone was insufficient to express a concept, while other elements were omitted when they were not relevant to the explanation. Although all three textbooks rely on the same underlying tree structures, they differ in both the amount of information they encode visually and the visual techniques used to represent it. Different authors make different choices regarding what information remains visible, is abstracted, omitted, or delegated to accompanying text.

5 Discussion

The findings suggest that tree-based illustrations serve more purposes than just depicting data structures. Across all analysed textbooks, trees were used to depict hierarchical relations, as well as to communicate procedural information associated with algorithms. This directly addresses RQ1, which asked how tree-based illustrations are used and what communicative functions they serve. While tree-based illustrations naturally communicate structural relationships, the analysis showed that signalling techniques often extend these illustrations by making algorithmic processes visible. Highlighted paths, arrows and geometric shapes were repeatedly used to communicate information that is not inherently encoded in the tree structure itself, such as traversal order, insertion path or changes between algorithmic states. This suggests that signalling is not merely used to emphasise existing information, but can also make procedural information explicit that would otherwise not be directly visible in the tree representation.

The results also indicate that illustrations and accompanying text operate as complementary representations, rather than independent sources of information. In some cases, the illustration carried part of the explanatory burden, by visualising procedural information, while in other cases, the accompanying text provided most of the explanation, and the illustration primarily served as a reference. This observation is consistent with Duval's notion that understanding depends on relationships between different representational registers, and suggests that explanatory information is distributed differently across visual and textual representations [10].

The analysis addresses RQ2 further by highlighting substantial variation between textbooks. RQ2 asked how the use and communicative role of illustrations vary across textbooks and topics, and while all three books covered the same topics, they often employed different visual conventions and signalling strategies. Goodrich frequently used varied visual notation and strong signalling to communicate algorithmic behaviour. Drozdek relied on a more minimalist style, focusing on structural relationships and delegating explanations to the accompanying text, while Akepogu introduced additional notation only when it contributed directly to understanding the concept. These differences suggest that there is no single accepted visual language for trees in ADS education. Instead, the findings suggest that the same tree-based concepts can be communicated through multiple visual conventions, each making different aspects of the structure more immediately visible.

The findings also have implications for educational illustration design. The co-occurrence analysis revealed a clear association between register-shift complexity and signalling strength. One possible interpretation is that signalling may help readers identify relationships that are distributed across multiple representations. As information becomes increasingly divided between text and illustrations, additional visual guidance may be required to make these relationships visible. While the present study cannot establish a causal relationship, the observed pattern suggests a potentially important connection between Duval's concept of register shift and Mayer's concept of signalling. While the two frameworks were developed independently, the findings suggest that they may describe related aspects of how educational illustrations communicate information.

Several limitations should be acknowledged. First, the study examined only three textbooks, which greatly limits the generalisability of the findings. Second, the analysis focused exclusively on tree-based topics, and therefore does not necessarily reflect illustration practices used for other ADS concepts. Third, the coding was conducted by a single researcher, meaning the analysis may contain subjective interpretations, despite the iterative refinement of the coding scheme.

Future research could address these limitations by extending the analysis to a larger set of textbooks and additional ADS topics. Empirical studies involving students could also examine how different signalling strategies and visual conventions influence comprehension and learning outcomes. Such work would provide insight into whether the communicative differences identified in this study also lead to measurable differences in educational effectiveness. Future research could also investigate the relationship between signalling and register shift more directly, to determine whether the connection observed in this study extends to other educational domains and illustrations.

6 Conclusion

This research examined how tree-based illustrations are used in ADS textbooks and what communicative functions they serve. Using a qualitative analysis of three ADS textbooks, illustrations were analysed through a framework combining elements of Levin's functional taxonomy, Mayer's multimedia learning theory and Duval's theory of semiotic representation. The goal was to understand how tree-based visualisations contribute to explaining core ADS topics.

The analysis identified two main findings. Firstly, signalling techniques play a central role in communicating algorithmic behaviour that is not directly visible in tree structures. Highlighted paths, arrows and geometric shapes were frequently used to represent traversal routes, state transitions, and algorithmically relevant elements. These signalling techniques frequently co-occurred with register shifts, suggesting a relationship between signalling and the distribution of explanatory information across visual and verbal representations.

Secondly, substantial variation exists in how textbooks visually represent trees. Although the underlying concepts are similar, different authors make different choices regarding what information should be presented directly through the illustration and what information should be delegated to the related text.

Overall, the findings show that tree-based illustrations serve as more than simple representations of data structures. They function as communicative tools that support the explanation of algorithms and direct attention to relevant information. By systematically analysing these visualisations across multiple textbooks, this study contributes to a better understanding of the role of illustrations in Algorithms and Data Structures.

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7 Responsible Research

7.1 Positionality Statement

This research was conducted by a computer science student with prior knowledge of Algorithms and Data Structures and educational visualisations. As the study relied on qualitative analysis, some degree of subjective interpretation was unavoidable.

7.2 Other concerns

The research follows the principles of the Netherlands Code of Conduct for Research Integrity. Sources and reproduced figures were properly cited, the methodology was described transparently, and limitations that may affect the interpretation of the findings were explicitly discussed.

To support reproducibility, the textbook selection criteria, analytical framework, coding dimensions and coding procedures are described in sufficient detail for another researcher to repeat the study. While exact replication may be influenced by the interpretive nature of qualitative research, the methodology is documented transparently to allow comparison of findings and application of the framework to other educational materials.

The research did not involve human participants or personal data and therefore raised no privacy concerns. Generative AI tools were used to support editing and refinement of the human-written text. All initial writing, coding, data analysis, interpretation of results and conclusions were performed by the author.