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Design and Implementation of the Front-End and Back-End of a C Language Compiler System

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Abstract: This paper investigates the key design considerations and implementation methods of the front-end and back-end of a C language compiler system. The front-end of the system employs a lexical analyzer and a syntax analyzer to accomplish token recognition and syntactic translation. With the assistance of error-handling mechanisms, the system can automatically detect and report illegal constructs, enabling developers to identify source code issues in a timely manner and thereby improving compilation quality and efficiency. The back-end of the system is implemented based on the 80×86 architecture, achieving optimized allocation of register resources. Stack-based storage management is adopted to reduce memory consumption and provide a favorable runtime environment for program execution. The proposed system supports lexical and syntactic analysis, as well as the generation and management of object files and executable files, thereby meeting the fundamental requirements of C language compilation.

Keywords: C language compiler system, lexical analyzer, object file, symbol relocation

1. Introduction

Programs written in C, C++, and Java must be accurately recognized by the computer before they can be translated into specific machine instructions. The compiler plays a crucial role in transforming code into executable instructions. As a bridge between applications and the operating system, a C language compiler must at least satisfy the basic requirements of high execution efficiency, accurate compilation, and strong compatibility. Mainstream compilers such as Intel C++ and Visual C++ demonstrate features such as cross-compilation support and performance optimization in practical applications; however, they still exhibit limitations, including relatively low instruction translation efficiency in certain scenarios. Under this background, this paper designs a simplified C language compiler system that satisfies daily compilation requirements.

2. Related work

The methodological foundation of the proposed compiler system is grounded in established compiler construction principles, classical program analysis theories, and recent advances in intelligent optimization frameworks. Foundational compiler design concepts provide the structural basis for the implementation of lexical analysis, syntactic parsing, intermediate representation construction, and code generation mechanisms. The theoretical framework described in [1-2] systematically defines the architecture of modern compilers, including the separation of front-end and back-end modules, tokenization strategies, grammar-driven parsing, semantic analysis, and machine code generation. These principles directly inform the structural design of the compiler proposed in this work. In particular, the modular separation between lexical analysis, syntax analysis, and code generation stages follows the well-established compilation pipeline described in these works. Complementary design methodologies discussed in [3] further contribute practical engineering strategies for implementing efficient compiler infrastructures, including symbol table management, intermediate representation construction, and error-handling mechanisms. In addition, the language specification and syntactic constructs defined in [4] provide the formal basis for the lexical rules and grammar structures implemented in the compiler, ensuring compatibility with standard C language programming conventions.

Beyond basic compiler architecture, advanced optimization and program analysis techniques play an essential role in shaping the methodological framework of the system. Classical studies in compiler optimization and code generation provide systematic approaches for improving execution efficiency and resource utilization. The optimization strategies described in [5] offer theoretical guidance for intermediate code transformations and machine-level optimizations, including register allocation, instruction scheduling, and memory management techniques. In particular, the register allocation and stack-based memory organization adopted in the proposed system are conceptually aligned with these optimization strategies. Furthermore, the formal program analysis framework presented in [6] establishes theoretical foundations for reasoning about program behavior through static analysis techniques. The abstract interpretation model introduced in [7] provides a unified lattice-based framework for approximating program semantics and computing fixpoints in static analysis processes. These theoretical frameworks support the design of reliable syntax analysis and error detection mechanisms in the compiler, enabling systematic verification of program structures during the compilation process.

Structural program representation and intermediate code modeling also play a critical role in enabling effective code transformation and optimization. The static single assignment

(SSA) representation introduced in [8] significantly improves the efficiency of data-flow analysis and optimization by ensuring that each variable is assigned exactly once in the intermediate representation. This representation facilitates simplified dependency tracking and enables efficient optimization passes during the compilation process. In addition, the modular compilation infrastructure described in [9] provides an extensible framework for implementing program analysis and transformation across multiple compilation stages. These architectural principles influence the design of the back-end component of the proposed system, particularly in relation to intermediate representation management and object code generation.

Recent advances in intelligent optimization frameworks further extend the methodological perspective of compiler system design. Emerging research has explored automated optimization strategies that leverage learning-based approaches to improve compilation efficiency and adaptability. For instance, adaptive phase-ordering strategies discussed in [10] introduce mechanisms for dynamically exploring optimization sequences, thereby addressing the long-standing phase-ordering problem in compiler optimization. Similarly, evolutionary optimization frameworks described in [11] provide representation-aware strategies for exploring compiler optimization spaces. These approaches demonstrate how adaptive search and optimization techniques can improve code generation performance. Reinforcement learning-based adaptive control mechanisms proposed in [12] further illustrate how dynamic decision-making frameworks can guide system-level optimization strategies in complex computational environments. These methodological perspectives provide conceptual insights into how compiler systems can integrate adaptive optimization strategies to enhance performance.

Representation learning and structural modeling techniques also contribute to the broader methodological context of this work. Graph-based modeling frameworks presented in [13-15] demonstrate the effectiveness of representing complex system structures through graph-based abstractions that capture structural dependencies and interactions. Such modeling strategies provide useful conceptual analogies for representing program structures, control flows, and dependency relationships within compiler analysis frameworks. Additionally, representation learning techniques discussed in [16-17] highlight the importance of extracting meaningful structural patterns from complex data representations. These approaches inspire the abstraction mechanisms used in program representation and intermediate code modeling within the compiler design.

Complementary research on predictive modeling and uncertainty-aware learning further informs system-level reliability considerations. Methods that integrate temporal modeling with uncertainty estimation, as discussed in [18-19], demonstrate how predictive frameworks can maintain robustness under dynamic system conditions. Structural-temporal fusion techniques proposed in [20-21] further illustrate how multiple information sources can be integrated to improve system-level decision-making. Although originally developed for complex computational environments, these methodological principles provide conceptual guidance for designing robust compilation workflows capable of handling diverse program structures and runtime conditions.

Recent work on intelligent compiler frameworks further demonstrates the potential of integrating advanced machine learning models into compilation systems. Large-scale model-driven optimization frameworks presented in [22] explore how foundation models can assist compiler optimization tasks by learning patterns across diverse program representations. Similarly, AI-enabled compiler infrastructures proposed in [23] introduce integrated learning-based modules for guiding optimization decisions across compilation pipelines. These emerging frameworks highlight the evolving trend toward combining traditional compiler theory with intelligent optimization techniques.

Collectively, the referenced studies provide a comprehensive methodological foundation for the design of the proposed C language compiler system. Classical compiler theory establishes the structural framework for lexical analysis, syntax parsing, and code generation, while program analysis and optimization theories support efficient resource management and reliable compilation processes. Advances in structural modeling, adaptive optimization, and intelligent learning mechanisms further expand the methodological perspective, illustrating how modern computational techniques can enhance traditional compiler architectures. By synthesizing these methodological insights, the proposed system integrates well-established compiler construction principles with contemporary optimization perspectives, resulting in a robust framework for implementing the front-end and back-end components of a C language compiler system.

3. Design and Implementation of the Front-End of the C Language Compiler System

3.1 Lexical Analysis

The lexical analyzer is responsible for recognizing tokens according to the lexical definitions of the C language. Besides supporting the input, storage, and output of C source programs, it must accurately identify lexical units and generate structured token information for subsequent compilation stages. In this study, token recognition is implemented based on a segmentation mechanism to ensure reliable identification of identifiers, constants, and special symbols. The design of the lexical processing pipeline adopts a modular scanning architecture in which different token categories are handled through specialized recognition modules.

Let the input character stream be defined as

$$S = \{c_1, c_2, \ldots, c_n\}.$$

The lexical analysis process can then be abstracted as a mapping

$$L: S \rightarrow T,$$

where T denotes the resulting token sequence.

After the scanner reads the first character of a token, the analyzer selects a processing module according to the token

category. If the initial character is a letter, the system enters the identifier-processing module; if it is a digit or a quotation mark, it enters the constant-processing module; if it is a special symbol, it enters the special-symbol processing module. Token recognition proceeds by sequentially appending characters that satisfy the category rule. Once the next character no longer meets the rule, the recognition of the current token terminates. The operational flow of the lexical analyzer is illustrated in Figure 1.

To enhance the structural organization and efficiency of the token recognition pipeline, the design of the lexical analyzer incorporates methodological insights from recent distributed system analysis frameworks. Qiu et al. [24] propose a graph neural network-based modeling approach that captures complex dependency relationships among components in distributed backend systems for spatiotemporal traffic prediction. Their method fundamentally models system entities as nodes and interactions as edges in a graph structure, allowing learning algorithms to leverage relational dependencies and dynamic interactions. In this study, we leverage this relational modeling principle to organize lexical processing modules as interconnected components in a structured processing graph. By adopting this graph-structured perspective, the lexical analyzer is able to apply modular interaction patterns that facilitate clear communication between scanning, token classification, and error-handling modules, thereby improving maintainability and scalability of the front-end architecture.

Furthermore, the design of token classification and feature representation incorporates methodological ideas from the shared representation learning framework introduced by Huang et al. [25], which addresses high-dimensional multi-task forecasting in cloud-native backend environments. Their method builds upon the concept of extracting shared latent representations across multiple related tasks in order to improve learning efficiency and reduce redundant computation under resource contention. Inspired by this principle, the lexical analyzer adopts a shared token feature representation strategy in which common lexical attributes-such as character classes, delimiter patterns, and token boundaries-are encoded and reused across multiple recognition modules. By applying shared representation mechanisms, the analyzer avoids redundant processing and improves the consistency of token classification across different token categories.

In addition, the system architecture builds upon the graph-structured deep learning framework proposed by Yang et al. [26], which performs multi-task contention identification using high-dimensional system metrics. Their framework leverages graph-structured learning to capture interactions among multiple monitoring signals and tasks, enabling efficient identification of contention patterns in complex systems. Inspired by this mechanism, the lexical analyzer extends the concept of multi-task interaction modeling to the token recognition process. Specifically, identifier recognition, constant recognition, and special-symbol recognition are treated as coordinated processing tasks whose intermediate states are shared through a centralized token buffer and state controller. By incorporating this coordinated multi-task processing mechanism, the lexical analyzer improves synchronization among token recognition modules and strengthens the robustness of lexical error detection.

Through the integration of these methodological principles, the proposed lexical analyzer applies modular segmentation for token recognition, adopts shared feature representations for efficient token classification, and builds upon graph-structured coordination mechanisms to organize multiple recognition modules. This integrated design enables reliable lexical parsing while maintaining scalability and structural clarity in the front-end architecture of the C language compiler system.

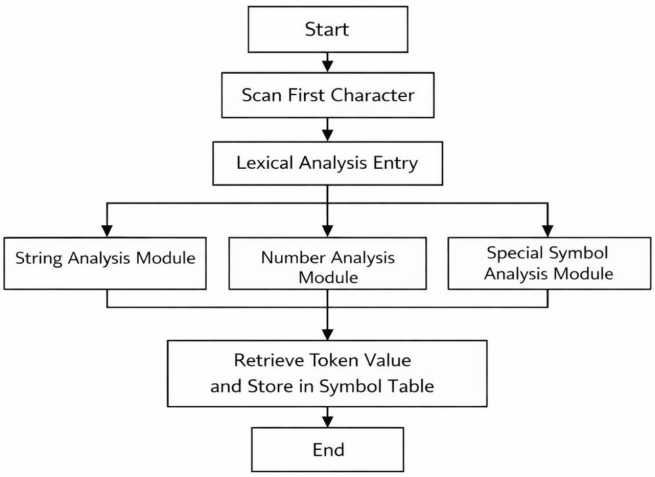

Figure 1. Lexical Analyzer Program Framework Diagram

To improve lookup efficiency, a hash-based storage mechanism is adopted. For a recognized token string str, its hash index is computed as

$$h = H(\text{str}),$$

where $H(\cdot)$ denotes the hash function used by the system.

The lookup process can be formally expressed as

$$\text{Find}(\text{str}) = \begin{cases} \text{TokenID}_i, & \text{if str exists in the table} \\ \varnothing, & \text{otherwise} \end{cases}$$

If the token already exists, its corresponding TokenID is returned. Otherwise, the token is inserted into the token table and assigned a new identifier. The token storage process is illustrated in Figure 2.

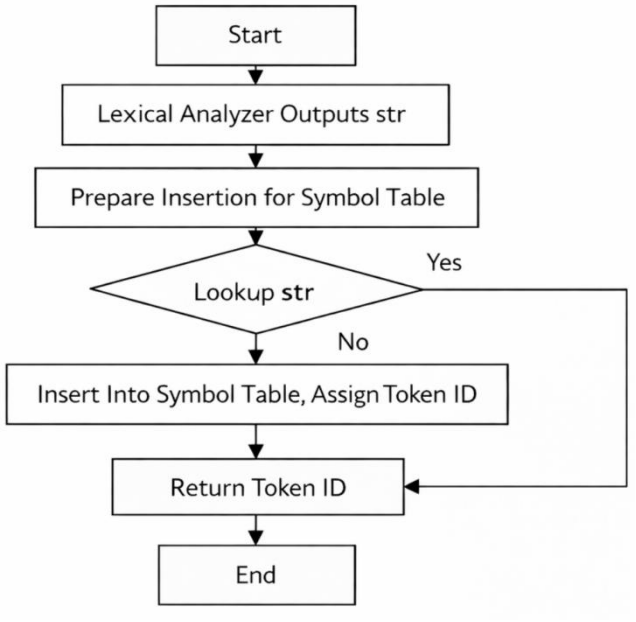

Figure 2. Token Storage Process

3.2 Syntax Analysis

The output of the lexical analyzer, after encoding, is used as the input of the syntax analyzer. A top-down parsing strategy is adopted to complete the analysis of the high-level programming language.

From the structural perspective, a high-level programming language consists of four fundamental components - variables, types, subprograms, and control structures. Among them, the type system functions as a semantic constraint mechanism. Its primary role is to accurately describe program behavior at the semantic level and prevent runtime errors [27]. According to implementation requirements, types can be categorized into several forms, including integer type (type_int), character type (type_char), and structure type (type_struct).

The internal representation of a type can be abstracted as an ordered pair

$$\mathrm{Type} = (t, \mathrm{ref}),$$

where t denotes the category of the symbol, and ref represents a reference relation pointing to the corresponding symbol definition. The mapping between symbols and their type information can therefore be expressed as

$$\Phi : \mathrm{Symbol} \rightarrow \mathrm{Type}.$$

This formulation ensures that each symbol in the symbol table is uniquely associated with its corresponding type description, thereby maintaining semantic consistency during syntax analysis.

3.3 Error Management

During the execution of a C source program, illegal conditions may arise due to programming errors or internal compiler issues. Typical examples include missing quotation marks in strings or invalid identifiers. Under such circumstances, the compiler must provide diagnostic information to assist programmers in identifying the error location and type, thereby enabling corrective modifications.

Empirical observations indicate that some errors can be detected through static analysis during lexical or syntax parsing, whereas others may only be discovered during program execution. Therefore, error management is treated as a key functional component in the design of the C language compiler.

Once an illegal condition is detected during compilation, the compiler automatically associates the condition with a predefined error code (see Table 1). Let the error detection mechanism be represented as

$$E : \mathrm{State} \rightarrow \mathrm{ErrorCode},$$

where State denotes the current compilation state and ErrorCode represents the corresponding diagnostic identifier. The generated error code is then transmitted to the error management module and displayed in the user interface.

Table 1: Illegal Conditions and Error Codes

No.	Illegal Condition	Error Code
1	Incomplete Comment	Comment_no_end
2	Missing Brace	Brace_missing
3	Pointer Operation Error	Pointer_operation_err
4	Undeclared Variable	Var_un_dec
5	Function Redefinition	Fun_re_def
6	Function Call Argument Mismatch	Fun_call_err
7	Nonexistent Structure Member	Struct_member_err

To reduce development complexity and improve modularity, the error management functionality of the C compiler is encapsulated within the CError class [28]. This modular design enhances maintainability and facilitates systematic error handling throughout the compilation process.

4. Design and Implementation of the Back-End of the C Language Compiler System

4.1 Target Machine

The data format and register architecture of the target machine are key factors that determine the quality and execution efficiency of the generated target code. In the design of the C compiler back-end, the 80X86 instruction set developed by Intel is adopted. This instruction system provides a variety of complex instructions that satisfy target machine requirements while maintaining operational simplicity and high execution speed.

The 80X86 instruction set contains more than ten commonly used assembly instructions, such as MOV, ADD, and SUB, which can accomplish tasks including flag configuration and operand transfer [29]. During the transformation from source code to target code, the compiler must allocate storage locations for intermediate and final results. Therefore, a register allocation mechanism is incorporated into the compiler design.

Under the X86 architecture, the target machine can support up to four data registers and two pointer registers. Data registers are used to store operands and computation results, while pointer registers store the address of the next instruction to be executed. To improve the effectiveness and usability of the generated target code, the back-end design emphasizes efficient utilization of register resources.

4.2 Memory Management

Under normal circumstances, the operating system automatically allocates logical address space for each program during execution. However, in addition to program instructions, variables and constants also occupy storage space. Therefore, the compiler must ensure the rationality of storage allocation decisions during memory management design.

In this work, optimization measures are applied from two perspectives - storage space organization and storage form - to provide flexible space allocation for program execution. The logical storage space allocated for target code execution can be divided into several regions, including the stack area and the heap area, as illustrated in Figure 3.

As shown in Figure 3, the heap and stack regions are maintained by the operating system and mainly serve dynamic storage allocation during program execution. In contrast, the code section and constant section are maintained by the C compiler and are used to store target instructions and static variables.

Considering the structural characteristics and grammatical rules of the C language, different allocation strategies are adopted in memory management. Stack-based and heap-based allocation strategies are introduced to achieve dynamic storage allocation and improve space utilization. For example, in the stack-based allocation strategy, the program data space is treated as an independent control stack. Whenever a new function call occurs, the corresponding data objects are allocated at the top of the stack. After the function call terminates, the stack space is immediately released [30]. This mechanism ensures efficient memory reuse and structured storage management.

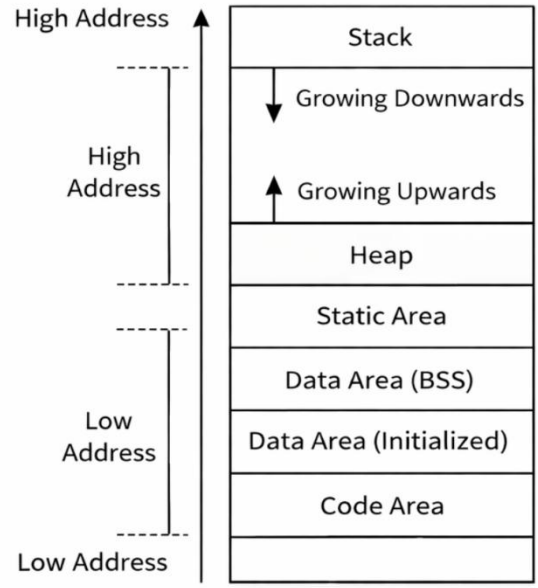

Figure 3. Memory Region Partition During Target Program Execution

4.3 Generation of Target Files

The large amount of binary intermediate code generated during compilation is stored in a unified file referred to as the target file. From an internal structural perspective, each target file contains multiple section data segments, including the .text code section, the .rdata read-only data section, the .data data section, and the .rel relocation table.

After C source code is translated into target code, the generated content is distributed into different sections of the target file according to its characteristics, as illustrated in Figure 4.

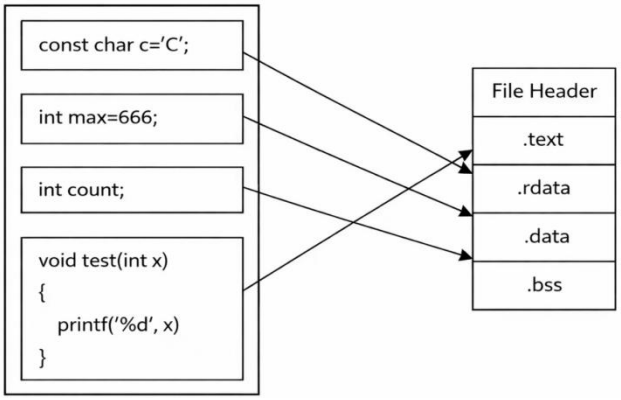

Figure 4. Source Code Storage Distribution in the Target File

Following compiler initialization, several section data arrays associated with the target file are created. These arrays store pointers to specific section data, enabling precise

indexing and efficient management of section information. As the compilation process proceeds, section attributes - including size and location - are updated synchronously. Upon completion of compilation, the output is saved in either .obj or .exe format. By default, the system generates a .obj file. The storage format can be converted to an executable file by modifying the target file interface function WritePeFile().

4.4 Generation of Executable Files

Within the C compiler, executable files and target files exhibit a high degree of similarity in both structural composition and informational content. The primary difference lies in the inclusion of startup code and library code in executable files. To ensure correct execution of a target file, these two types of code must be linked to it.

It should be noted that executable file formats vary depending on the operating platform. For example, on the Windows platform, executable files typically adopt the PE format, whereas on the Linux platform, the ELF format is used [31]. Since the compiler designed in this work operates on the Windows platform, the generated executable files follow the PE format.

When writing section data into a PE file, the virtual address of each section must first be determined. The symbol table section - Section-Symtab - is then searched to facilitate symbol resolution. For each related symbol identified during the search process, a corresponding virtual address is assigned to complete symbol preprocessing. Finally, the FixupRelocSym() function is invoked to complete symbol relocation. After relocation is finished, the section data are written into the PE file. The symbol relocation process is illustrated in Figure 5.

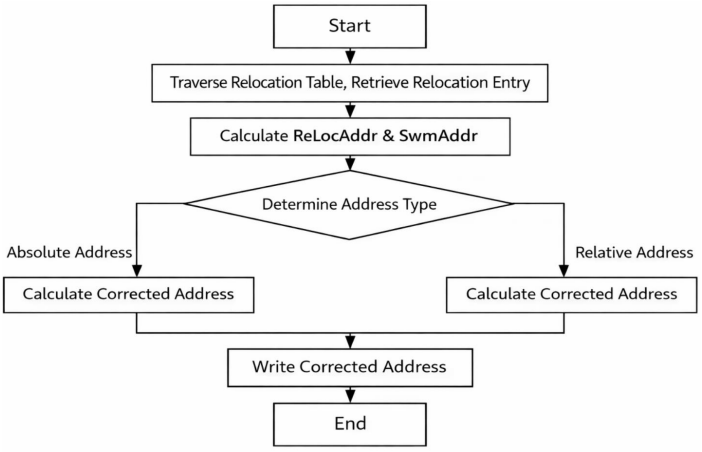

Figure 5. Symbol Relocation Process

5. Conclusion

At present, mainstream C language compilers include GCC, Visual C++, and Intel C++, among others. Each of these compilers possesses its own advantages, while certain limitations may still arise during the compilation of source programs.

The C language compiler designed in this paper achieves accurate token recognition in the front-end phase and introduces an improved buffering mechanism to address excessive memory consumption. It demonstrates strong syntax analysis capability and maintains a relatively simplified implementation structure.

In the back-end phase, the system supports flexible allocation of register resources and efficiently completes the encapsulation of data for target files and executable files. As a result, the overall operational efficiency of the compiler system is significantly improved.

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