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Editorial

In the rapidly evolving world of technology, innovation in automation, artificial intelligence, and formal verification is reshaping the landscape of both education and industry. Three distinct research papers shed light on groundbreaking advancements in these fields, each addressing a unique problem and proposing transformative solutions.

The first paper delves into the realm of education, focusing on automated grading systems. With the increasing demands on educators to evaluate students' work efficiently, particularly in technical subjects like SQL, this research proposes a model that not only grades assignments based on correctness but also provides partial grading and feedback. What stands out is the paper's thoughtful consideration of the student's learning stage, offering a tailored approach that accounts for the student's current understanding—whether at the introductory, intermediary, or advanced level. This nuanced model promises to reduce the burden on educators while enhancing the learning experience for students, offering them more targeted feedback. This shift towards automated, skill-level-sensitive grading is a step forward in leveraging technology to personalize education, saving time and improving the quality of feedback [1].

In the second paper, image classification technology, particularly in the gemstone and jewelry industry, takes center stage. The study introduces a CNN-based gemstone classification algorithm that integrates multiple image features, including color and spatial position. The innovation here lies in the use of deep multi-feature fusion, combining k-means++ clustering for color extraction and denoising convolutional neural networks for spatial analysis. The proposed method achieves a remarkable 9% improvement in classification accuracy over conventional CNN approaches. This research highlights the potential of combining various image processing techniques to enhance accuracy in critical fields, showcasing how machine learning can revolutionize industries reliant on visual data, providing more precise and efficient classification methods [2].

The third paper ventures into formal verification within silicon design verification platforms, addressing a crucial challenge in the hardware industry. The research explores Synopsys' VC Formal TM tool and its Sequential Equivalence (SEQ) App, which plays a pivotal role in verifying the equivalence between different RTL designs. Given the increasing complexity of silicon designs and the frequent need for feature modifications or bug fixes, ensuring functional verification sign-off has become a monumental task. This case study demonstrates how formal verification techniques can speed up convergence, reducing the time needed for exhaustive testing while maintaining the integrity of the design. It is a reminder of the importance of rigorous verification processes in the development of cutting-edge technology, particularly as silicon designs become more complex and nuanced [3].

These three research efforts illustrate the power of automation, artificial intelligence, and formal verification in addressing modern challenges across education, industry, and technology development. As these innovations continue to mature, they promise to bring greater efficiency, accuracy, and scalability to their respective fields, paving the way for a future where machines and algorithms work hand-in-hand with human expertise to drive progress.

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Dynamic and Partial Grading of SQL Queries

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ABSTRACT: Automated grading systems can help save a lot of time when evaluating students' assignments. In this paper we present our ongoing work for a model for generating correctness levels. We utilize this model to demonstrate how we can grade students SQL queries employing partial grading in order to allocate points to parts of the queries well written and to enable provision of feedback for the missing parts. Furthermore, we show how we can grade the queries taking into account the skill level of students at different stages of SQL learning process. We divide the stages into introductory, intermediary, and advanced stages and in each apply different type of grading that takes account the students' knowledge at that stage. We implemented this model in our class and graded 5 quizzes containing more than 25 different questions for 309 students. We discuss 3 examples for each stage and offer comprehensive examples of the model in action.

KEYWORDS: Correctness Levels, Software Correctness, Automated Grading, Assessment, Partial Marks, SQL Query Grading

1. Introduction

Partial grading in SQL software exercises is awarding a selected portion or a fraction of a whole grade. It involves giving points to parts whereby the student has done well or deducting points to parts missed. An advantage of partial grading is that we are able to acknowledge students' efforts by awarding points to the correct parts of a query. This helps in protecting their motivation to learn [1]. Furthermore, we are able to pinpoint the parts of a query the student has missed. This helps in providing constructive feedback to help the student improve on their work. Partial grading systems which are able to carry out this form of grading have been extensively researched [2, 3, 4, 5]. Nevertheless, these systems do not address different skill levels of students at various stages of the learning process. We propose a model in which students' skill levels are taken into consideration. We refer to this as *dynamic grading*.

There are three types of knowledge acquired by students in programming courses, syntactic, conceptual, and strategic [6]. In our project, we broadly classify these groups of knowledge into 2 types, syntactic and semantic [7, 8] as it makes it manageable to translate our grading model into a running program. Students learn well when taught syntax and semantic knowledge in parallel while syntax knowledge develops as a result on repetition [8]. Even though this is the case, novice students might struggle more with syntax during the introductory lessons than at the end [9]. Various methods have been proposed of how to teach SQL in various steps. Some research proposes teaching SQL in an increasing order of difficulty [10]. This order begins from teaching 'SELECT' syntax to recursive SQL at the end. Other research proposes teaching SQL in a series of steps involving building a query one clause at a time [11]. The first clause would be SELECT followed by FROM clause then WHERE clause and so on. A mental model in which learners learn SQL starting with remembering SQL concepts followed by comprehending the concepts with creating the queries at the end have been proposed as well [12]. In the various learning styles proposed, students are novice during the start of the class struggling with syntax and at the end have accumulated enough knowledge to write completely semantically correct queries. We considered to utilize these findings to grading as well. To this effect, our goals in this paper are to demonstrate how we can:

- Assign a discrete level that shows how correct a query is, in relation to an instructor's specifications.
- Factor in students' knowledge level when calculating grades.

Also, to demonstrate whether:

- It is possible for an automated grading tool to match the grades given by manual graders.
- If students consider an automated grading tool to be fair.

In this context, a fair grade is a grade that matches the one that would be given by an instructor. Furthermore, this grading capability should be applied consistently to other answers as well.

To factor in students' knowledge level, we divided a full programming course's time into three stages. introductory stage, intermediate stage, and the advanced stage. We used syntax, semantics, and results as features for evaluation. For each stage, these three features which we refer to as

properties were evaluated in parallel while varying their individual weight to the whole grade. At the introductory stage, syntax had more weight. Similarly, at the intermediate stage, semantics had more weight than the other properties and at the advanced stage, results had more weight.

To carry out partial grading, we used software correctness levels and to enable dynamic grading, we used varying weights for properties like syntax which addressed different skills levels as we will see in this paper. We graded more than 25 different SQL questions for 309 students using different configurations of dynamic grading and we shall discuss 3 of these questions.

1.1. Advantages of skill based grading

Grading students' work while considering whether they are novice or more advanced can have several advantages. This is in comparison with grading the work of students who are struggling with the new programming language and those who are already familiar with or mastered it the same way.

1. Personalization and differentiation. Grading students work while considering whether they are novice or advanced would be considered as a personalized and differentiated way. In this manner, novice students are not penalized for not meeting a higher standard as expected of the more advanced students.

2. Student motivation and engagement. By basing the grading on the student knowledge level, their motivation to continue learning and engaging would be protected. This is because, the students are able to view learning the new programming language as something within their capability.

3. Targeted feedback. Due to the differences between novice students and advanced ones, specific feedback can be constructed that caters to the differing needs of both. Novice students may be more interested in the language syntactic elements while advanced students being more interested in semantic elements.

2. Related work

Partial grading systems have enabled awarding partial points instead of strict 0 or 1 [2, 3, 4, 5]. Some systems are even capable of generating datasets for testing [13]. The limitation of these systems is that they employ inflexible strategies to grade the queries. Our model is able to dynamically grade queries based on the gradual learning process of students. Furthermore, it has the flexibility of adding or removing properties during grading depending on the goals of the instructor.

Correctness levels have been used before to grade SQL queries. Some research has used 8 different correctness levels to partially grade queries [14]. Specifically, Dekeyser et al. [14] use syntax, schema, results, and peer review to grade the queries whereby each code feature is evaluated as either correct or not. Of these 8 levels, 5 are automatically awarded by the system while the rest require manual input. Our model automatically awards 9 different levels using syntax, semantics, and results, evaluating each feature using three categories instead of two. Our model also allows more levels by having the flexibility of adding more properties and their outcomes.

Dynamic grading has been used in other areas apart from SQL. For example, in gradual programming whereby the students learn a programming language in well-defined steps instead of learning everything at once [15].

Binary grading offers only two possible outcomes: correct and incorrect, which does not consider partial correctness or incorrectness [16]. As a result, students may not receive points for partially correct submissions. Providing detailed feedback on the areas where students' understanding is lacking becomes impossible as well. This limitation of binary grading gives rise to the need for partial grading. Our model offers more possible outcomes to enable differentiation of errors.

There are differences between novice and expert programmers. As a result, various research has been proposed which highlights these differences. It has been proposed that expert programmers memorize source code better than novice programmers [17]. In the proposal, the researchers also argued that novices tend to memorize syntactic elements while expert programmers focus on the algorithm. Expert programmers can solve a problem by abstracting the algorithm while novices cannot [18]. As the expertise increases, novice programmers gradually shift from focusing on syntactic elements to the semantic ones [19]. This may indicate that novice programmers are more focused on the language syntax while experts focus on the semantics. Differences among novices and experts have been argued in other fields as well. For example, in physics, it has been proposed that experts might use abstraction to solve a problem while novices use the problem's literal features [20]. Naturally, computer science students as programmers might show this phenomenon. Even though they may not become full experts in the programming language during the course of the class, they are able to achieve competency [21]. Due to the differences between novice and advanced students, it has been proposed to make the introductory material simple and systematically expand as students' expertise increases [22]. For example, beginning with writing syntax, comprehending templates, writing code with templates and tracing [23]. Therefore, we considered and utilized these findings to implement our grading model in such a way that it can acknowledge and accommodate these differences.

Grading students work based on unit testing has also been used in other programming languages like Java [24, 25]. Unit testing [26] involves testing the smallest unit in a program or code that can be isolated. In most cases, the testing parameters are already known by the developers and the testers before runtime. Our syntax analysis is a form of unit testing whereby a student's query's syntax is verified based on the target SQL standard and other similar syntactically correct queries. However, neither the testing parameters for our semantic nor results analysis are known up until runtime whereby the system loads the model query and the student query. Also, it is challenging to exactly anticipate the correct semantics since queries written in different ways can have the same meaning. Furthermore, the binary nature

of unit testing makes it difficult to carry out partial grading. This means that, our unit tests have additional requirements compared to ordinary unit tests.

3. Software correctness levels

Software correctness in software exercises is the degree to which code written by students satisfy the specifications given by the instructor [27]. Software correctness levels describe this degree [28]. Software correctness in SQL is tested using various techniques. The most used is executing the query and checking the results [29, 30].

There are various properties that can be evaluated to check for code correctness. Some of these properties are: syntax, semantics, results, efficiency, style and performance. During this evaluation, we classify a property into various categories that describe the correctness of the property. In this research, we call such categories ***outcomes***. Examples of outcomes are fully correct, meaning the property completely satisfies the specifications and fully incorrect for otherwise.

Using these properties and their outcomes, we can create a matrix of all the outcomes arranged in such a way that the first row describes the lowest adherence of the properties to the specifications. The last row would describe the complete adherence of these properties to the given specifications. We show such matrices as tables: Table 1, Table 2 and Table 3.

The number of properties and outcomes to use depends on the grading goals and the programming language. Database managements systems feature query optimizations therefore in SQL we would not evaluate properties like efficiency [31]. In C++, style, complexity and efficiency have been used to evaluate students' code [32, 33, 34]. In this implementation we focus on three properties: syntax, semantics, and results. for these properties, we evaluate them into three outcomes: *correct, minor incorrect*(small mistakes like misspells of 2 characters and less) and *incorrect*. The meaning behind each outcome will be discussed in the method section.

3.1. Property weight

Teaching SQL in a computer science class is done in various stages [10]. One of the most important stages is teaching proper SQL syntax. In this stage, students are introduced to SQL, how it is written, the tools used and how to run commands. Another notable stage is using already learned SQL commands to carry out simple tasks. In this stage students learn how to take simple specifications and turn them into SQL commands that accomplish the given task. Various stages of learning have various goals. Naturally, this should translate to grading goals. Our goal is to modify how grading is done based on the learning stage.

Grading modification is enabled in our model by assigning different weights for the properties. For example, At the introductory stage, grading would weigh more on syntax. During the intermediate stage, grading would weigh more on semantics, as the instructor turns their attention to carrying out given tasks. Similarly, at an advanced stage, grading would weigh more on results.

3.1.1. Introductory stage grading

At the introductory stage, the instructor would focus on correct syntax. For a student to successfully pass this stage, they would need to be able to write well-formed SQL clauses with correct keywords. For any quizzes at this stage, the instructor would classify the student queries based on how well written the syntax was. At one extreme of this classification, there would be completely incorrect syntax and at the other end fully correct syntax. The instructor would then put a threshold for passing, whereby, students below this threshold would have to practice more on syntax. A 9-magnitude model weighing more on syntax is shown in Table 1. In this model, the instructor might put the threshold for passing at correctness level 6. Students who can pass this threshold would be able to write queries that can be parsed and well executed by the database management system. Even though in this stage we focus on correct SQL syntax, the other properties, *semantics* and *results* still matter.

Table 1: Syntax has the most weight, next semantics and then results. inc. refers to incorrect.

Level	Syntax	Semantics	Results	Grade
1	incorrect	incorrect	incorrect	0
2	minor inc.	incorrect	incorrect	0.125
3	minor inc.	incorrect	minor inc.	0.25
4	minor inc.	minor inc.	correct	0.375
5	minor inc.	correct	correct	0.5
6	correct	incorrect	incorrect	0.625
7	correct	incorrect	minor inc.	0.75
8	correct	minor inc.	correct	0.875
9	correct	correct	correct	1

3.1.2. Intermediate stage grading

At an intermediate stage, the instructor would turn the students' attention to solving some tasks. At this point the students already know how to write correct SQL grammar. The instructor would teach how to turn given specifications into correct SQL queries that accomplish the task. For any given quiz at this stage, the instructor would want to check if the students are able to carry out some tasks using SQL. This would involve checking if the students' queries have the correct semantics. A 9-magnitude model focusing more on semantics is given in Table 2. In this model, the instructor might put a passing threshold at correctness level 6. This means that students with queries below this threshold might be struggling with how to turn some specifications into a semantically correct query.

3.1.3. Advanced stage grading

In the last stage, the students should already have mastered how to write correct SQL grammar. Furthermore, they should be able to turn given specifications into semantically correct SQL statements. At this point, the instructor might focus on making sure the students are able to write queries that return the expected results. This means, grading would weigh more on results. A 9-magnitude model weighing

more on results is shown in Table 3. Similarly, as the other stages, the instructor might put the threshold for passing at correctness level 6. Correct semantics imply correct results. Nevertheless, instead of focusing on semantics only, we check results because they give extra information about those queries without fully correct semantics. For example, if the reference correct query output is a subset of a student query, it means the student query may not have carried out correct filtering of results in the WHERE clause.

Table 2: Semantics has the most weight, next syntax and then results. inc. refers to incorrect.

Level	Semantics	Syntax	Results	Grade
1	incorrect	incorrect	incorrect	0
2	incorrect	minor inc.	incorrect	0.125
3	incorrect	minor inc.	minor inc.	0.25
4	incorrect	correct	incorrect	0.375
5	incorrect	correct	minor inc.	0.5
6	minor inc.	minor inc.	correct	0.625
7	minor inc.	correct	correct	0.75
8	correct	minor inc.	correct	0.875
9	correct	correct	correct	1

Table 3: Results has the most weight, next semantics and then syntax. inc. refers to incorrect.

Level	Results	Semantics	Syntax	Grade
1	incorrect	incorrect	incorrect	0
2	incorrect	incorrect	minor inc.	0.125
3	incorrect	incorrect	correct	0.25
4	minor inc.	incorrect	minor inc.	0.375
5	minor inc.	incorrect	correct	0.5
6	correct	minor inc.	minor inc.	0.625
7	correct	minor inc.	correct	0.75
8	correct	correct	minor inc.	0.875
9	correct	correct	correct	1

The instructor is free to use any threshold for passing that aligns with their goals. Notice how in all the different weights models, the students are still allowed to make minor mistakes without severe points reduction in their grades. This gives appreciation to their efforts in carrying out the tasks.

3.2. Grading

The final grade awarded to a query is calculated using the correctness level assigned as shown below:

$$g = \frac{l - min(l)}{max(l) - min(l)} \quad (1)$$

where g is the grade in the range 0 to 1, l is the correctness level, $min(l)$ is the minimum correctness level and $max(l)$ is the maximum correctness level of a specific model in use. The grade is linearly distributed along the possible correctness levels. This is an improvement to the earlier model which factored in the missing or impossible levels when calculating the grade [28].

3.3. Flexibility in adding or removing properties

Our software correctness model is made up of combinations of the chosen properties and their possible outcomes. The 9-magnitude model shown in Table 1, Table 2 and Table 3 comprises of properties *results*, *semantics* and *syntax* each with 3 possible outcomes: correct, minor incorrect and incorrect. This gives rise to 27 possible combinations of which 9 are usable in our implementation. Unusable combinations are for example, when both syntax and semantics are fully incorrect while the results, fully correct. The instructor is free to choose whichever properties or outcomes align with their teaching goals. For example, they can choose to carry out binary grading using only the results. In this case, property *results* would have 2 possible outcomes: correct and incorrect. This would translate in the correctness model having 2 levels: level 1 for an incorrect query and level 2 for a correct query. Using the same property, they might opt for a 3 magnitude correctness levels model. In this case, results would have 3 outcomes: *fully correct*, *minor incorrect* for results not filtered, i.e. correct results would be contained inside the query results and *fully incorrect*. Similarly, the instructor can choose syntax and semantics, or results and syntax with various outcomes.

As we see here, the number of properties or outcomes used to construct a correctness model for grading is not fixed. The instructor can add or remove properties and their outcomes as well. Adding properties or outcomes increases the size of the correctness model. This increases the number of correctness levels as well, which translates to higher grading sensitivity. On the other hand, using fewer properties or outcomes reduces the size of the correctness model. This reduces the number of correctness levels, which translates to lower grading sensitivity. In this paper, we demonstrate the power of a correctness model using 3 properties and 3 outcomes. Using 4 properties or outcomes and more or less is also possible in this model.

4. Grading process

Algorithm 1 shows the main algorithm for grading students queries using the correctness model discussed above. This was implemented in C++ under Linux with DuckDB [35] as the database management system.

4.1. Initialization

We begin by initializing parameters that will be used to instantiate the correctness model. This involves initializing the number of syntax, semantics and results outcomes that will be used on grading. We also initialize the 'property weight' variable. We assert that these variables are initialized to integers greater than 0 and a maximum of 3. This maximum is not fixed but can change by adding more properties or outcomes. A correctness model matrix is constructed using this initialization as shown in algorithm 2. This is a 2-dimensional array containing all the various combinations of the properties and their outcomes. We then remove unusable rows from the matrix.

Algorithm 1: Main Algorithm

```
Result: Grades
stx ← number of syntax outcomes;
sem ← number of semantics outcomes;
res ← number of results outcomes;
pw ← property weight;
// Ensure 1 ≤ stx ≤ 3, 1 ≤ sem ≤ 3, 1 ≤ res ≤ 3,
   1 ≤ pw ≤ 3
text_ed ← 3; // text edit distance
tree_ed ← 2; // tree edit distance
incorrect ← 0;
minor incorrect ← 1;
correct ← 2;
// See Algorithm 2
correctness_m ← create_matrix(stx, sem, res, pw);
// Put reference queries into data
   structure
ref ← reference queries;
// Load student queries
student ← student queries;
for n ∈ {ref} do
    n.AST ← reference query abstract syntax tree;
    // Run the query in DuckDB
    n.Output ← query result;
end
for n ∈ {student} do
    if n ≡ {} then
        // Empty
        n.PARSEABLE ← false;
        n.SYN ← incorrect;
    else
        Parse the query;
        if parseable then
            n.PARSEABLE ← true;
            n.AST ←
              student query abstract syntax tree;
            n.Output ← query result;
        end
        else
            n.PARSEABLE ← false;
            n.SYN ← incorrect;
        end
    end
end
foreach n ∈ {student} do
    // See Algorithm 3
    syntax_analysis(n, text_ed, syn);
    // See Algorithm 4, ref(1) denotes the
       first query
    results_analysis(n, ref(1), res);
    // See Algorithm 6
    semantics_analysis(n, ref, student, tree_ed, sem);
end
foreach n ∈ {student} do
    // See Algorithm 5
    get_correctness_level(n, correctness_m, stx, sem, res);

    get_grade(n);
end
```

Algorithm 2: Creating the correctness matrix

```
Result: Correctness matrix
Function create_matrix(stx, sem, res, pw):
    matrix ← vector of integers;
    if stx ≡ 1 and sem ≡ 1 and res ≡ 1 then
        // Binary grading
        Append 0,0,0 to matrix;
        Append 1,1,1 to matrix;
        return matrix;
    end
    if pw ≡ 1 then
        // Syntax most important
        for i = 0 to stx − 1 do
            for j = 0 to sem − 1 do
                for k = 0 to res − 1 do
                    Append k,j,i to matrix;
                end
            end
        end
    end
    else if pw ≡ 2 then
        // Semantics most important
        for j = 0 to stx − 1 do
            for i = 0 to sem − 1 do
                for k = 0 to res − 1 do
                    Append k,j,i to matrix;
                end
            end
        end
    end
    else if pw ≡ 3 then
        // Results most important
        for k = 0 to stx − 1 do
            for j = 0 to sem − 1 do
                for i = 0 to res − 1 do
                    Append k,j,i to matrix;
                end
            end
        end
    end
    // Remove the levels not possible from
       the matrix
    return matrix;
```

4.2. Pre-processing

Next, we carry out pre-processing of reference and student queries. For reference queries, we create abstract syntax trees for each and execute them, saving the output in a 2-dimensional array. We used the library, pg_query [36] to create abstract syntax trees. Student queries undergo the same procedure but first, we check if they are parseable. If a query is not parseable, we mark its syntax outcome as incorrect. Then, we carry out syntax, results and semantics analysis finalizing by calculating the correctness level for each query and the subsequent grade. These steps will be discussed next.

4.3. Syntax analysis

Syntax analysis is done first. Algorithm 3 shows how syntax analysis is accomplished. In this stage, all parseable queries are marked as having correct syntax. Next, we check how far the unparseable queries are from being parseable. To accomplish this, we carry out a comparison between unparseable queries with those that are parseable using text edit distance metric [37]. The parseable queries include both parseable reference and student queries. For those student queries with mistakes of 2 characters and below, we mark as having minor incorrect syntax and edit them. This enables further processing of the queries. For unparseable queries without close reference or correct student queries, we then check the SQL keywords in the query. We employ the same edit distance metric to check how much malformed the keywords are. We identify the SQL keywords using information from the parse tree.

Algorithm 3: Syntax analysis

```
Result: Syntax outcomes
Function syntax_analysis(query, text_ed, syn):
    if query.PARSEABLE ≡ true then
        query.SYN ← correct;
    end
    else
        mis ← misspelled SQL keywords characters;
        if mis < text_ed then
            if syn ≡ 3 then
                query.SYN ← minor incorrect;
                Edit query; // Correct the query
            end
            else
                query.SYN ← incorrect;
            end
        end
        else
            query.SYN ← incorrect;
        end
    end
```

4.4. Result analysis

Result analysis is done next. Algorithm 4 shows how results analysis is accomplished. In this stage, we compare the results of each student query with the results of the reference queries. If both outputs match, the student query is deemed as having correct results. For those queries with different output, we then check if the reference query output is a subset of the student query output. If so, we mark the student query as having minor incorrect results. The rest of cases are marked as having fully incorrect results.

4.5. Semantics analysis

The final analysis involves semantics. Algorithm 6 shows how semantics analysis is accomplished. In this stage we check if the student queries have the intended meaning. First, we mark as having correct semantics, those queries that had correct results in the previous step. Next, we mark unparseable queries as having fully incorrect semantics. This is because in this implementation we cannot verify the severity of the mistakes.

For the rest, we carry out parse tree edit distance comparisons using Shasha Zhang's algorithm [38]. This is accomplished by comparing parse trees of the student queries under processing and the reference queries together with the student queries with correct output. We further check the text edit distance for those queries found to have a tree edit distance of 1. If this text edit distance is 2 characters or less, the query is marked as containing minor incorrect semantics. The rest of the cases are marked as having fully incorrect semantics.

Algorithm 4: Result analysis

```
Result: Results outcomes
Function result_analysis(query, ref, res):
    if query.OUTPUT ≡ ref.OUTPUT then
        query.RES ← correct;
    end
    else if ref.OUTPUT ⊂ query.OUTPUT then
        if res ≡ 3 then
            query.RES ← minor incorrect;
        end
        else
            query.RES ← incorrect;
        end
    end
    else
        query.RES ← incorrect;
    end
```

Algorithm 5: Calculating correctness level

```
Result: Correctness level of a query
Function
 get_correctness_level(query, matrix, stx, sem, res):
    level ← 1;
    if stx ≡ 1 and sem ≡ 1 and res ≡ 1 then
        // Binary grading
        level ← query.RESULT  1;
        return level;
    end
    foreach m ∈ {matrix} do
        if m0 ≡ query.RES and m1 ≡ query.SEM and
          m2 ≡ query.SYN then
            break;
        end
        level ← level  1;
    end
    return level;
```

At this point, the student queries have been tagged with various outcomes for the properties. The outcomes of each query are compared with the outcomes in the correctness matrix. The correctness level of a query is the level with matching outcomes. The grades are calculated in the range 0 to 1, using Equation 1.

Algorithm 6: Semantics analysis

```
Result: Semantic outcomes
Function
 semantic_analysis(query, ref, student, tree_ed, sem):
    if query.RES ≡ correct then
        query.SEM ← correct;
    end
    else
        if query.PARSEABLE ≡ false then
            query.SEM ← incorrect;
        end
        else
            smallest ← 0;
            ted ← 0;
            foreach m ∈ {ref} do
                dist ←
                 query.AST and m.AST distance ;
                l_ted ←
                 query.QUERY and m.QUERY distance ;

                if dist ≤ smallest and l_ted ≤ ted then
                    smallest ← dist;
                    ted ← l_ted;
                end
            end
            foreach s ∈ {student} do
                if s.RES ≡ correct then
                    dist ←
                     query.AST and s.AST distance ;
                    l_ted ←
                     query.QUERY and s.QUERY distance;

                    if dist < smallest and l_ted ≤ ted
                     then
                        smallest ← dist;
                        ted ← l_ted;
                    end
                end
            end
            if smallest < tree_ed and ted < text_ed
             then
                if sem ≡ 3 then
                    query.SEM ← minor incorrect;
                end
                else
                    query.SEM ← incorrect;
                end
                query.RES ← correct;
            end
            else
                query.SEM ← incorrect;
            end
        end
    end
```

5. Implementation and findings

We experimented with the correctness model discussed above for an automated grading system of SQL exercises in a first year's course at a first year's BSc course, Information Modelling and Databases at Radboud University. During this study, the course had 309 students. For the year 2023, we used the model to grade 5 quizzes containing more than 25 different questions using the three different matrices. These are shown in a cumulative graph, Figure 1. From the graph, we see that the grading model can differentiate student answers among 9 different groups. We will discuss 3 results from this large sample.

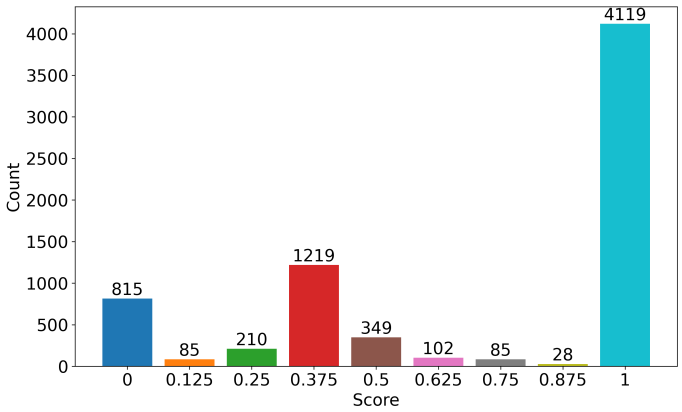

Figure 1: A bar graph showing the grades awarded to all 7012 answers across 25 different questions.

5.1. Introductory stage grading

The first question was graded as an introductory quiz. Syntax was prioritized more than the other properties. The grades awarded for this question are shown in Figure 2. The x-axis shows the grades given in the range 0 to 1. The y axis show the total number of queries given a certain grade.

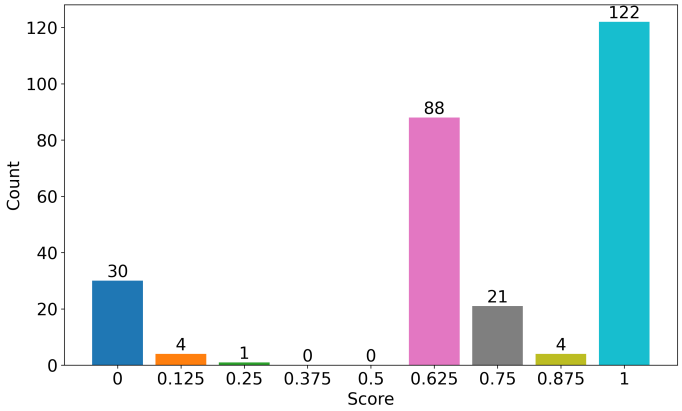

Figure 2: Grades calculated for the 1^{st} question using introductory grading.

We saw that most students were able to write correct SQL statements (122 students). This group of students could already write syntactically correct SQL that accomplished the given task. The second largest group could form correct syntax SQL queries but could not yet translate these into semantically correct queries (88 students). Taking 0.6 as the passing threshold (parseable queries), 35 students represented by 0, 0.125 and 0.25 grades failed the first question. The other 235 students passed. Grading the same question while prioritizing semantics would have produced

the results shown in Figure 3. In this grading, the number of students who passed would have reduced to 126. Lastly, grading the question while prioritizing results would have produced the results shown in Figure 4. In this case, the number of students who passed would have stayed the same as in previous case. However, the grades of those who failed would have reduced even further especially the large group of 88 answers. The reference correct query for this question is shown below.

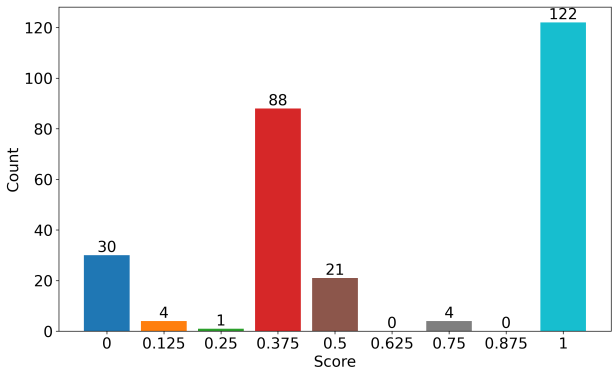

Figure 3: Grades calculated for the 1st question using intermediate grading.

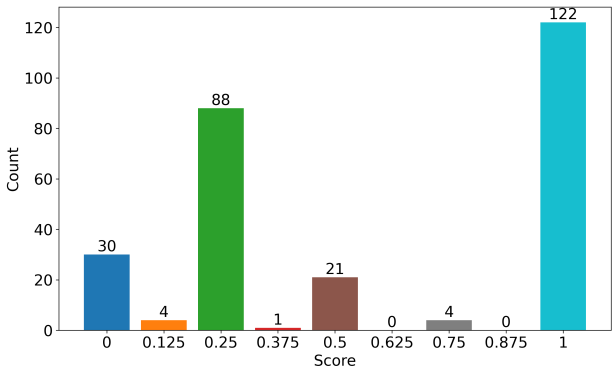

Figure 4: Grades calculated for the 1st question using advanced grading.

```
SELECT T.theme_id, T.name FROM Theme T, Teacher N
    WHERE N.name='Djoerd Hiemstra' AND
        T.teacher_id=N.teacher_id;
```

The student answers for this question fell into the following groups:

(1) 122 answers were fully correct.

```
--various query construction with the same meaning
SELECT theme_id, Theme.name FROM Teacher JOIN Theme
    USING (teacher_id) WHERE Teacher.name = 'Djoerd
    Hiemstra';
SELECT Theme.theme_id, Theme.name FROM Teacher JOIN
    Theme ON Teacher.teacher_id = Theme.teacher_id
    WHERE Teacher.name = 'Djoerd Hiemstra';
```

(2) 4 answers had minor incorrect semantics (tree edit distance of 1 and text edit distance of less than 3 from a reference query), and correct syntax and results.

```
-- mispelled the name 'Djoerd Hiemstra'
SELECT Theme.theme_id, Theme.name FROM Teacher,
    Theme  WHERE Teacher.name = 'Djoerd Hiemsta' AND
    Teacher.teacher_id = Theme.teacher_id;
```

(3) 21 answers had minor incorrect results (output of the reference correct query is a subset of the query's output), incorrect semantics and correct syntax.

```
--results were not well filtered
SELECT theme_id, Theme.name FROM Teacher, Theme
    WHERE Teacher.name = 'Djoerd Hiemstra';
```

(4) 88 answers managed only correct syntax.

```
--wrong columns selected and wrong filtering
SELECT * FROM Teacher, Theme WHERE Teacher.name =
    'Djoerd Hiemstra';
```

(5) 1 answer had minor incorrect syntax (text edit distance of less than 3 from a reference query) and results, and incorrect semantics.

```
--mispelled 'SELECT' and wrong filtering
SELECHT theme_id, Theme.name FROM Teacher, Theme
    WHERE Teacher.name = 'Djoerd Hiemstra';
```

(6) 4 answers had minor incorrect syntax, and fully incorrect results and semantics.

```
-- extra wrong character ';', wrong columsn selected
    and wrong filtering
SELECT * FROM Teacher A, Theme T; WHERE T.name =
    'Djoerd Hiemstra';
```

(7) 30 answers had fully incorrect properties.

```
SELECT name AND theme_id FROM Theme WHERE name =
    Djoerd Hiemstra
```

From the three graphs (Figure 2, Figure 3, and Figure 4), we see that the grouping stays the same. What changes is the grades awarded to the various groups seen. We also see that the grading progressed from lenient to stringent as we progress from grading using syntax, to semantics and finally results. For this reason, we focus on syntax to carry out introductory stage grading whereby we do not penalize novice students for not meeting higher standard as expected of the more advanced students. We strive to make an impression to the novice students that the new language presented is within their learning capability.

5.2. Intermediate stage grading

As the course progressed the next questions were graded as intermediate quizzes. In this subsection, we give an example of a question which was graded in this intermediate stage whereby, semantics were prioritized more than the other properties. The grades awarded for this question are shown in Figure 5. In the grades evaluated, we saw that almost the whole class (230/262) was able to write semantically fully correct queries. 18 students (0, 0.125 and 0.375 grades) got less than a half point therefore failed this exercise. The reference correct query for this question is shown below.

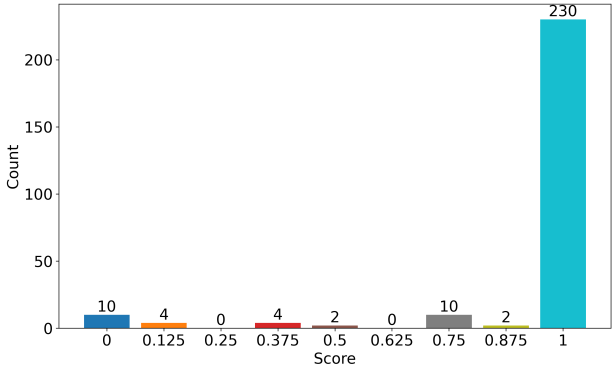

Figure 5: A bar graph showing the first question of the intermediate quiz. This was graded with more weight being on semantics.

```
SELECT DISTINCT album_title FROM Album WHERE
    type='compilation';
```

The student answers for this question fell into the following groups:

(1) 230 answers were fully correct.

```
--different phrasing but still correct
SELECT Album.album_title FROM Album WHERE
    Album.type='compilation';
```

(2) 2 answers answers had minor incorrect syntax, and correct semantics and results.

```
--extra ';' which made syntax minor incorrect
SELECT album_title; FROM Album; WHERE type =
    'compilation';
```

(3) 10 answers had minor incorrect semantics, and correct results and syntax.

```
-- missing enclosing ' for the word compilation
SELECT album_title FROM Album WHERE type =
    compilation
```

(4) 2 answers had minor incorrect results, fully incorrect semantics and correct syntax.

```
--selected more data than required. Correct results
    were a subset.
select album_title, type from album where type =
    'compilation'
```

(5) 4 answers had fully incorrect results and semantics, and fully correct syntax.

```
-- the query could be parsed even though the where
    clause was incorrect.
Select album_title from Album where album_name
```

(6) 4 answers had fully incorrect results and semantics, and minor incorrect syntax.

```
--had an extra '*' and the wrong column name
    'tracck_title'.
SELECT * track_title FROM Album WHERE
    type='compilation';
```

(7) 10 answers had fully incorrect properties.

```
sigma type='compilation'(Album) pi album_title
```

5.3. Advanced stage grading

As the course progressed to the final lessons, the questions given were graded as advanced quizzes. In this subsection, we give an example of a question which was graded in this advanced stage whereby, results were prioritized more than the other properties. The grades awarded for this question are shown in Figure 6. In these results, we saw that many students (110/164) managed to write fully correct queries. The second largest group (29/164) students wrote a fully incorrect query even though this group was small compared to those who wrote fully correct queries. The rest of the small groups were distributed among various scores. The reference correct query for this question is shown below.

```
SELECT name, hire_date FROM Employee WHERE salary
    BETWEEN 2500.00 AND 3500.00;
```

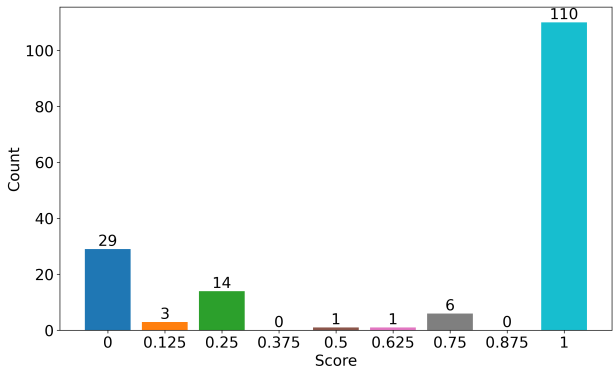

Figure 6: A bar graph showing one of the last questions of the advanced quiz. This was graded with more weight being on results.

The student answers for this question fell into the following groups:

(1) 110 answers were fully correct.

```
--different phrasing but still correct
SELECT name, hire_date  FROM Employee  WHERE salary
    >=2500 AND salary <= 3500;
```

(2) 6 answers had fully correct results and syntax but minor incorrect semantics.

```
-- had an extra 's' at the end of the string
    'Employee'
SELECT name, hire_date FROM Employees WHERE salary
    BETWEEN 2500 AND 3500;
```

(3) 1 answer had fully correct results but minor incorrect syntax and semantics.

```
-- incomplete where clause, missing second string,
    'salary' after AND
SELECT name , hire_date FROM Employee WHERE salary
    >= 2500 AND <= 3500;
```

This single query was incorrectly graded due to an error in the implementation which we rectified afterwards.

(4) 1 answer had fully correct syntax but minor incorrect results and fully incorrect semantics.

```
-- added another table at the FROM clause
SELECT name, hire_date  FROM Unit, Employee  WHERE
    salary > 2500  AND salary < 3500;
```

(5) 14 answers had fully correct syntax but fully incorrect results and semantics.

```
-- missing 'hire_date' column in SELECT clause
SELECT name FROM Employee WHERE salary>2500 AND
    salary<3500
```

(6) 3 answers had minor incorrect syntax and fully incorrect results and semantics.

```
--missing 'hire_data' in SELECT clause and 'salary'
    in WHERE clause
SELECT name  FROM Employee  WHERE salary IS BETWEEN
    2500 AND 3500
```

(7) 29 answers had fully incorrect semantics, results and syntax.

```
SELECT name, hire_date  FROM Employee, Unit   WHERE
    2500 < salary < 3500
```

5.4. Comparison with manual grading

To validate the capabilities of our implementation, we carried a comparison between the grades awarded for the end exam by the instructor, and those calculated by our automated grading system. The instructor evaluated the students not as novices but as learners already familiarized with SQL concepts and knowledge. Our grading system evaluated the queries as advanced quizzes to match the instructor's grading strategy using the model shown in Table 3. The correct answers to the questions are shown below.

```
1. SELECT A.name, COUNT(DISTINCT T.track_id) AS
    number FROM Artist A, Performs P, Track T WHERE
    A.artist_id = P.artist_id  AND P.track_id =
    T.track_id GROUP BY A.name HAVING COUNT(*) >= 3
    ORDER BY number DESC;
2. SELECT title, SUM(duration) FROM Album A, Track T
    WHERE A.album_id = T.album_id GROUP BY title;
3. SELECT song FROM Track T WHERE NOT EXISTS( SELECT
    * FROM Performs P WHERE P.track_id = T.track_id
    AND role='vocals') AND EXISTS( SELECT * FROM
    Performs P WHERE P.track_id = T.track_id);
4. SELECT song FROM Album A, Track T WHERE
    A.album_id=T.album_id AND A.title='Nevermind';
5. SELECT album_id  FROM Release WHERE
    country='Belgium';
6. SELECT DISTINCT artist_id FROM Performs WHERE
    role = 'guitarist';
7. SELECT name FROM Artist WHERE death_date IS NULL;
8. WITH RECURSIVE Subordinates(employee_nr) AS
    (SELECT 'U000001' UNION SELECT
    Employee.employee_nr FROM Employee, Subordinates
    WHERE Employee.manager_nr =
    Subordinates.employee_nr ) SELECT * FROM
    Subordinates;
```

In the comparison, we checked the difference to the grades given for each question using the equation shown below:

$$difference = our\_grade - instructor\_grade \quad (2)$$

The frequency of differences seen are summarized in Table 4. In the table, score diff. is the difference between the grade given by the automated grading system and by the instructor. Q1 to Q8 are the 8 questions. Each cell in the questions' columns contain the total number of queries with a given grade difference in that question. The total column show the total number of queries for a given difference in all the questions. These are further illustrated using violin plots in Figure 7. In the figure, Q1 to Q8 are the eight questions. Each question has its own violin plot. The score difference is the difference between the grade given by the automated grading system and by the instructor.

Table 4: The frequencies of differences. Q1 to Q8 are the 8 questions. Diff. is the difference value.

Score Diff.	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Total
-1.0	1	0	1	1	0	0	0	1	4
-0.875	0	0	0	0	1	0	0	0	1
-0.75	9	21	0	1	0	1	0	0	23
-0.6	1	0	0	0	0	0	0	0	1
-0.55	0	2	2	41	43	31	0	2	121
-0.5	3	0	0	0	0	0	0	0	3
-0.35	0	0	0	0	0	1	0	0	1
-0.25	47	0	0	0	1	0	0	0	48
-0.05	0	0	7	0	0	0	0	0	7
0.0	63	123	98	180	171	146	202	110	1093
0.125	14	1	0	1	0	0	3	8	27
0.2	0	0	0	1	0	0	0	0	1
0.25	108	103	96	22	30	50	26	115	550
0.375	0	0	1	0	0	0	0	0	1
0.5	1	0	48	3	2	23	1	3	81
0.625	0	0	0	1	0	0	0	0	1
0.75	0	2	0	2	6	2	22	0	34
1.0	0	0	0	1	0	0	0	0	1

We calculated the mean absolute difference (MAD) and the root mean square error (RMSE) between the two types of grading which was 0.16 and 0.07 respectively using Equation 3 and Equation 4.

$$MAD = \frac{1}{n}\Sigma_{i1}^{n}|x_i - y_i| \quad (3)$$

$$RMSE = \sqrt{\frac{1}{n}\Sigma_{i1}^{n}(x_i - y_i)^2} \quad (4)$$

Whereby n is the total number of differences, x is a grade given by our system and y is a grade given by the instructor. This difference between the two systems comes from the following main observations which are summarized below:

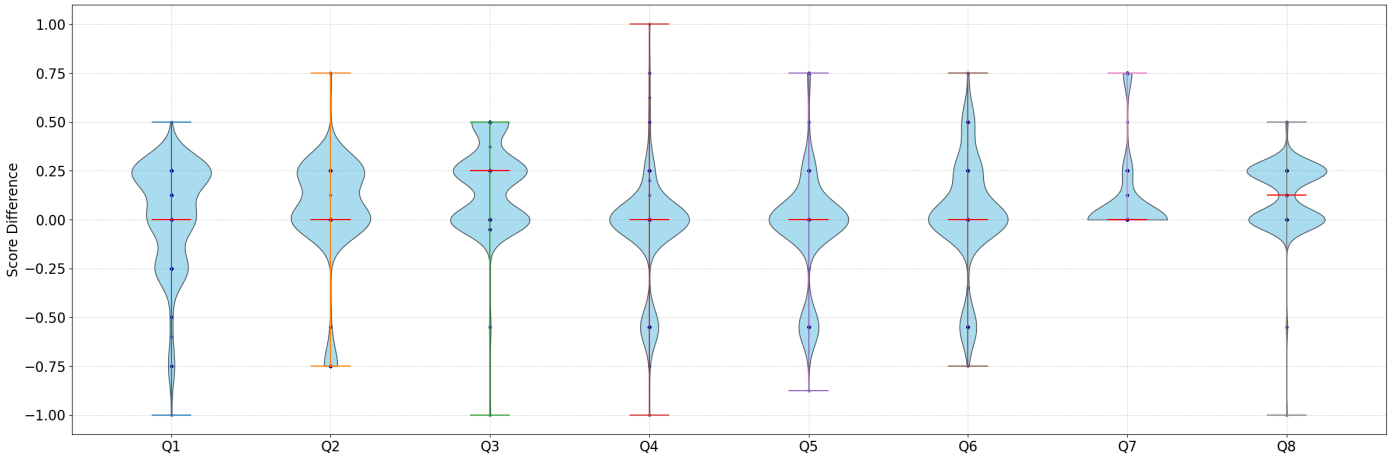

Figure 7: Grades differences between the instructor and our system. Q1 to Q8 are the 8 questions.

1. 1093 queries received the same score in both cases. These were fully correct queries and fully incorrect queries.

2. 550 queries received a 0.25 score higher in our automated grading system. These were incorrect queries that were at least parseable. Our grading acknowledged that even though these students did not learn correct SQL semantics, they were able to form correct SQL syntax.

3. 121 queries received a 0.55 score higher from the instructor. These were correct queries containing unexpected special characters, for example:

```
-- has an extra non-SQL characters Â‘
 SELECT T.song FROM Track T, Album A WHERE
     T.album_id = A.album_id AND A.title = Â
     ‘NevermindÂ‘ ;
```

```
--used non-SQL character ‘ instead of '
SELECT album_id FROM Release WHERE country
    = ‘Belgium‘;
```

```
--used non-SQL character ‘ instead of '
SELECT DISTINCT artist_id FROM Performs
    WHERE role = ‘guitarist‘;
```

   The instructor deducted a 0.2 from the score while our system struggled to correctly evaluate such queries.

4. 81 queries received a 0.5 score higher in our system. These were queries which were semantically incorrect with correct results as a subset of the queries' results.

5. 48 queries received a 0.25 score higher from the instructor. Most of these differences were from the first question. The instructor gave a 0.5 to those answers that demonstrated that the student clearly understood the semantics of the question but could not fully translate it to the complete query. For example:

```
SELECT name, COUNT(*) as count FROM Artist,
    Performs, Track WHERE Artist.artist_id
    = Performs.artist_id AND
    Performs.track_id = Track.track_id
    GROUP BY name HAVING count >= 3 ORDER
    BY count DESC;
```

   Our system failed to evaluate this and gave a 0.25.

6. 34 answers received a 0.75 score higher in our system. These were queries whose semantics were minor incorrect. For example, 17 queries contained:

```
SELECT name FROM Artist WHERE death_date =
    NULL;
```

   This query used a comparing operator for NULL instead of using IS NULL. The instructor observed that they were strict in this case.

7. 23 queries received a 0.75 higher score from the instructor. These were queries which were graded as fully correct by the instructor . Our system evaluated them as incorrect. For example:

```
SELECT A.title, SUM(T.duration) FROM Album
    A JOIN Track T ON A.album_id =
    T.album_id GROUP BY A.album_id;
```

   The query did not group by 'title' therefore it was considered as incorrect by our system.

As we seen in Figure 7, most differences between instructor's grading are within 0.25 score (horizontal bulges). We have highlighted the major differences seen above. In some cases, the instructor was strict as seen from the 34 queries in item 6 and item 4. In other cases, the instructor was lenient in grading as seen in queries in item 5 and item 7. In comparison, our grading was consistent across different queries. This consistency aided our system to allocate fair grades with some exceptions. These are cases whereby the system failed to capture special unexpected non-SQL characters as seen in item 3.

At the end of the experiment, we administered a questionnaire to the students. We let them know that the questionnaire was useful in that, we would use their answers

to improve the grading system. The students based their answers on the grades received since we carried out the grading using the system and sent them their results. This included some feedback text. For example, *SYNTAX: Correct! Well done. RESULTS: The output of the query is not correct. SEMANTICS: The query does not have correct semantics. This quiz was graded as an advanced quiz. We placed more weight on results, then semantics and finally syntax.* A group of 46 students present at the time participated in the questionnaire, in which we enquired about their opinion on the automatically given grades. For example, we asked them if they considered the grades received as fair or not. This was to verify that indeed the students found the grades given acceptable. The results are shown in Figure 8. We saw that 74% said the grades received were fair while the rest 26% considered the grades not completely fair. Some students observed our system being not completely fair in those cases our implementation failed to catch minor incorrect syntax, for example for those unparseable queries containing random characters that proved difficult to automatically identify and repair. We plan to work on this in our next implementation.

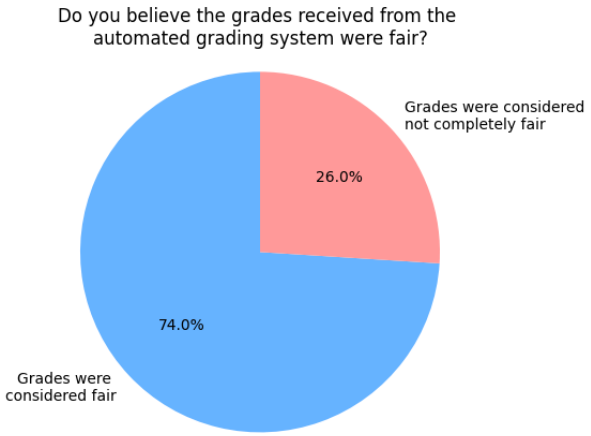

Figure 8: Survey about students' experience.

5.5. Configuration variables

In our method, there are 6 configuration variables that affect the grading (number of syntax outcomes, number of semantics outcomes, number of results outcomes, property weight, text edit distance threshold and tree edit distance threshold). Changing these variables alters the grading in different ways. The first 3 variables affect the number of outcomes for the different properties. The fourth variable affects which property is focused more when grading. The fifth variable is the threshold value for syntax analysis edit distance calculation. Lastly, the sixth variable is the threshold for the semantics tree edit distance calculation. All these variables can be adjusted to change how grading is done. The threshold parameter for edit distances for syntax and semantics in this experiment were set to 2 and 1 respectively. In our next implementation we plan to study in detail how changing these variables will affect the grades awarded.

6. Discussion

During the introductory period of our course, one of the main goals was for the students to learn the correct SQL syntax and grammar. It was crucial for the students to be able to form SQL queries that can be parsed. In our first quiz, we tested whether the students had indeed understood how syntactically correct SQL queries are written. We graded the quiz focusing mostly on syntax with semantics and results being secondary. This grading model is shown in Table 1. Our results from Figure 2 showed that this goal was accomplished as most students (235/270) were able to form syntactically correct SQL queries. These students scored more than 0.6. Furthermore, a large number (122/270) were able to write semantically correct queries. This meant that the teaching could proceed onto the next stage, which is using SQL to accomplish the given tasks.

In the next stage of learning, the students could already write syntactically correct SQL queries. This was the intermediary stage, whereby the goal was using SQL to carry out the given tasks. The quizzes in this stage were graded focusing mostly on semantics while syntax and results were secondary. This grading model is shown in Table 2. In one of the questions, shown in Figure 5, most of the students (230/262) could translate SQL into statements that could accomplish the given task.

We graded the last quizzes for the course as advanced quizzes. At this stage the students could write the correct SQL grammar and write semantically correct queries. Therefore, when grading, we focused mostly on results while semantics and syntax were secondary. Many students were able to write queries with the correct results (110/164 students). The grading model used is shown in Table 3.

7. Conclusion

In this paper, we have demonstrated a model for generating discrete levels that enable effective partial grading of SQL queries. We call these discrete levels, software correctness levels that translate into partial grades. We have also demonstrated how we can be able to offer personalized and differentiated type of grading depending on the knowledge level of the students. This is in contrast to the previous research that utilize inflexible methods. we divided the learning process into 3 stages and applied specific types of grading to each stage. These stages were introductory, intermediate, and advanced. At each stage of our course, we were able to focus the grading on a specific goal which depended on the skills of the students. This is dynamic grading. Dynamic grading was enabled by weighing some properties like syntax more than others at specific points of the teaching process. Partial grading was enabled by individually evaluating different properties in such a way that their outcomes are categorized, for example in categories like correct, minor incorrect and fully incorrect. In our current implementation, we worked with the properties syntax, semantics, and results, and we generated corresponding correctness levels for those properties. In partial grading we utilized software correctness levels while in dynamic grading, we considered students' skills level. This helped

us to effectively provide partial grades that were dependent upon the skill or knowledge level of students at different stages of their learning process.

We observed that our grading model had some differences in the grades calculated from those awarded by the instructor. We evaluated these differences from SQL questions from an exam and observed a mean average difference of 0.16. We also administered a questionnaire to 46 students whereby 74% observed that our implementation of the model discussed was able to calculate grades they considered fair. Nevertheless, there were limitations which we plan to address in both the grading model and its implementation. For the implementation, we plan on improving on: handling unexpected special non-SQL characters, checking query results against more than 1 data schema, extending the supported queries to include, *Create*, *Delete*, *Insert* and *Update* and a clear separation between syntax and semantics analysis. The later limitation resulted in missing groups for example, [syntax: minor incorrect, result: correct]. For the model, we plan on adding another property or outcome for more sensitivity and to evaluate the optimum configuration for the minimum difference between the grades awarded by the system and the instructor. More thorough work is needed to present the full merits of the discussed model.

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MCNN+: Gemstone Image Classification Algorithm with Deep Multi-feature Fusion CNNs

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ABSTRACT: Accurate gemstone classification is critical to the gemstone and jewelry industry, and the good performance of convolutional neural networks in image processing has received wide attention in recent years. In order to better extract image content information and improve image classification accuracy, a CNNs gemstone image classification algorithm based on deep multi-feature fusion is proposed. The algorithm effectively deeply integrates a variety of features of the image, namely the main color features extracted by the k-means++ clustering algorithm and the spatial position features extracted by the denoising convolutional neural network. Experimental results show that the proposed method provides competitive results in gemstone image classification, and the classification accuracy is nearly 9% higher than that of CNN. By deeply integrating multiple features of the image, the algorithm can provide more comprehensive and significant useful information for subsequent image processing.

KEYWORDS: CNN, Multi-features, Image Classification, Gemstone, Data Fusion

1. Introduction

Gemology research [1], mainly including gemstone classification and identification of two areas, gemstone classification is the core of Gemology research is also the premise of gemstone identification, in the traditional classification of gemstone is mainly to the naked eye and gemstone microscope as the main tool, but with the progress of modern science and technology, synthetic gemstone technology is also constantly evolving, so that some of the optimized treatment of gemstone features and natural gemstone the difference is decreasing. Although complex instruments with strong spectral, fluorescence, or chemical analysis capabilities are increasingly being introduced into Gemology laboratories [2], identification is still difficult and time-consuming, and not all laboratories can specialize in precision instruments; Therefore, automatic technical recognition based only on images is attractive.

Computers and algorithms have come a long way in recent years, and image processing and computer vision tasks are common in many areas such as medical imaging, manufacturing, and security [3]. Image classification as one of the key technologies has also made great progress, mainly traditional methods and image classification methods based on deep learning. Traditional classification methods such as random forests, decision trees, and support vector machines all have a good classification effect on natural images. With the advent of big data and the rapid development of artificial intelligence, classification methods based on deep learning have become a hot topic in image classification research, and are applied to remote sensing images [4], medical images [5], and spectral images [6] and other fields. Although computer vision systems have widespread applications in many fields, there is only one study on the automatic recognition of gemstone images [7]. To date, to the author's knowledge, there have been reports. Unseen ruby, sapphire, and jadeite images are classified using artificial neural networks based on tonal channels in the HSV color space with 75-100% accuracy per class. It's important to note that rubies, sapphires, and emeralds are very unique in color and therefore relatively easy to distinguish, much easier than similarly colored gemstone such as topaz and aquamarine. Other computer vision studies in the context of Gemology focus on gemstone evaluation [8, 9, 10] and identification [11, 12]. The [13] is the first study to compare a computer vision-based approach with the image-based classification performance of trained Gemology on up to 68 types of gemstones. However, the method adopted is cumbersome and the classification accuracy needs to be improved.

In this paper, we propose a CNNs image classification algorithm based on deep multi-feature fusion for automatic image-based classification of gemstones. The work is first described in section 2 . Section 3 introduces the structure of the model we propose. The image dataset, experimental environment, and experimental results and discussion are detailed in section 4. Finally, further conclusions and ideas are presented in section 5.

2. Related Work

Accurate gemstone classification is critical to the gemstone and jewelry industry, as identification is an important first

step in evaluating any gemstone [14]. Currently, the identity of gemstone is determined by combining visual observation and spectral chemical analysis [15]. By carefully viewing the gemstone with the naked eye and a magnifying glass, Gemology can detect visual characteristics such as color, transparency, luster, fracture, cleavage, inclusions, polychromaticity, phenomena, and birefringence to facilitate the separation of the gemstone [16]. With the advent of new synthetic gemstone and treatment techniques, complex instruments with powerful spectral, fluorescence, or chemical analysis capabilities are increasingly being introduced into Gemology laboratories [15]. Such instruments include infrared spectrometers [16], Raman and luminescent spectrometers [1, 17, 18], ultraviolet-visible spectrometers [19], cathodoluminescence [20], etc.

In the geological sciences, computer vision algorithms have been developed for the study of mineral particles and rocks [20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30]. In [21], the author segmented microscopic flakes using edge detection and achieved up to 93.53% test accuracy when classifying 10 different minerals using artificial neural networks trained on extracted color and texture features. The accuracy of the report may be exaggerated because the same Biotite examples are used for training and testing. In [22], the author developed an artificial neural network that used the red-green-blue (RGB) values of the pixels in the thin slices as input to separate five minerals with 89.53% accuracy. In [23], the author segmented flakes using incremental clustering and mineral classification using cascading methods. Artificial neural networks were first used to distinguish 23 minerals and glass based on pixel color, and only minerals that appeared similar in planar polarized and cross-polarized light were passed to a second artificial neural network for simultaneous color and texture analysis. This results in an overall accuracy of 93.81%. In [24], the author demonstrated that simple machine learning algorithms—K-Nearest Neighbor and Decision Tree—were able to classify minerals in microscopic sheets with high average accuracy of 94.11-97.71% using two datasets for four and seventeen mineral types based on color and texture. In [25], microscopic images containing eight mineral types and backgrounds were segmented by simple linear iterative clustering and classified based on RGB, hue-saturation-value (HSV) color features , and CIELAB spaces using three machine learning algorithms, K-Nearest Neighbour, Random Forest, and Decision Tree. The random forest algorithm yields the highest accuracy of 82%. In [26], the author using inception-v3 features extracted from microscopic images, the classification of four minerals was studied using six different algorithms: logistic regression, support vector machine, random forest, K-nearest neighbor, multilayer perceptron, and naïve Bayes. The support vector machine is identified as the single algorithm that produces the highest accuracy (90.6%). The Stacking Support Vector Machine, Logistic Regression, and Multilayer Perceptron models further improved accuracy by 0.3%.

3. Model

In order to better read the image content information, the overall framework of the CNN network model of deep multi-feature fusion is shown in Figure 1.

The input image is first convoluted to obtain the denoising depth convolution feature, referred to as f_c. The position shape relationship information of the denoising space after the multilayer convolutional neural network. The convolutional layer contains multiple convolutional nuclei, each of which is capable of extracting shape-dependent features, and each neuron in the convolutional layer is connected to multiple neurons adjacent to the location of the previous layer, also known as the 'receptive field' [31], thus relying on the network to learn the contextual invariant features [32]: Shape and spatial position feature information, which is particularly useful for image classification. The main color features f_l of the input image are then extracted, using the k-means++ clustering algorithm. Then, cascading f_c and f_l, construct deep-in-depth features f_m.

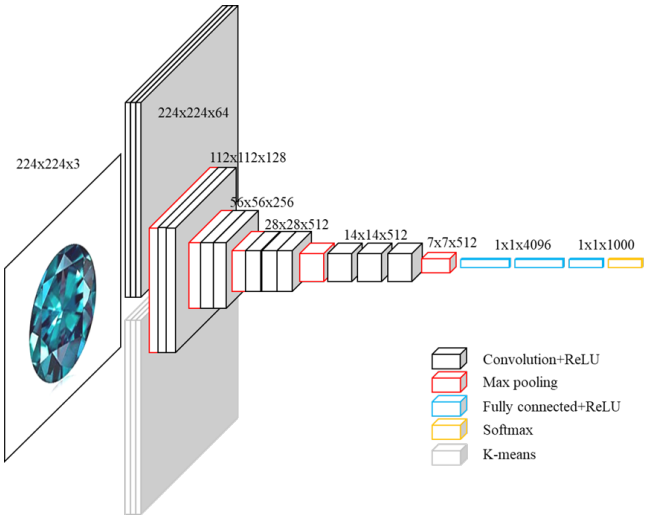

Figure 1: General framework of CNNs network model for deep multi-feature fusion

There are a total of four convolutional layers in the model frame. The first convolutional layer is called the data feature fusion layer, which fully fuses the denoising depth convolution and the main color feature. This is followed by a pooling layer whose role is to reduce network parameters and speed up fusion. The second convolutional layer is called the deep feature fusion layer, which undergoes further feature fusion, followed by a pooling layer. The third convolutional layer is called the feature abstraction representation layer, and the size of the convolutional kernel in this layer is changed from 5×5 in the first two convolutional layers to 3×3, which helps to eliminate noise in the feature and improve the abstract representation of the feature, followed by a pooling layer. The fourth convolutional layer, called the feature advanced presentation layer, helps eliminate redundant features and improve representative features, followed by a pooling layer. Three-layer fully connected layer for feature classification and parameter optimization during backpropagation. At the end of the network, the Softmax layer is used for classification. Softmax is a supervised learning method for multi-classification problems [33, 34] that provides important confidence levels for classification, where 0 indicates the lowest confidence and 1 indicates the highest.

3.1. The k-means++ clustering algorithm extracts the dominant color features

The k-means++ clustering algorithm is a 'hard clustering' algorithm, in which each sample in a dataset is scored 100% into a category. In contrast, 'soft clustering' can be understood as a certain probability that each sample is sorted into a certain category.

The original k-means algorithm initially randomly selects k points in the dataset as cluster centers, while k-means++ selects k cluster centers according to the following idea: assuming that n initial cluster centers have been selected.

The k-means++ clustering algorithm [35] is described as follows:

1. Randomly select a sample from the dataset as the initial cluster center c_i.
2. First calculate the shortest distance between each sample and the current existing cluster center (that is, the distance from the nearest cluster center), expressed in terms of representation $D(x)$; The probability that each sample will be chosen as the next cluster center is then calculated $\frac{(D(x))^2}{\sum_{x \in X}(D(x))^2}$. Finally, the next cluster center is selected according to the roulette method.
3. Repeat Step 2 until a common cluster center k is selected.
4. For each sample $x_(i)$ in the dataset, calculate its distance to a cluster center k and divide it into classes corresponding to the cluster center with the smallest distance.
5. For each category $c_(i)$, recalculate its cluster center $c_i = \frac{1}{|c_i|} \sum_{x \in c_i} X$ (i.e. the centroid of all samples belonging to that class).
6. Repeat Steps 4 and Step 5 until the position of the cluster center no longer changes.

3.2. Deep multi-feature fusion

Convolutional layers, nonlinearly activated transformations, and pooled layers are the three basic components of CNNs. By superimposing multiple convolutional layers with nonlinear operations and multiple pooling layers, a deep CNNs can be formed, which extract input features in layers, with invariance and robustness [36]. With specific architectures, such as local connections and shared weights, CNNs tend to have good generalization capabilities. Convolutional layers with nonlinear operations [32] are as follows (1):

$$x_j^l = f\left(\sum_{i=1}^{M} x_i^{l-1} * k_{ij}^l + b_j^l\right) \tag{1}$$

Where the matrix x_i^{l-1} is the ith feature map of the $l-1$ layer, x_j^l is the jth feature map of the current layer l, and M is the number of input feature maps. k_l^{ij} and b_j^l are randomly initialized and set to zero, then fine-tuned precisely by backpropagation. $f(\cdot)$ is a nonlinear activation function, and $*$ is a convolution operation.

The denoising depth convolution features f_c of the network structure output and the main color features extracted by the k-means++ clustering algorithm f_l are constructed according to the cascading and features of (2) to construct the deep integration features f_m.

$$f_m = \alpha f_c + \beta f_l \tag{2}$$

Due to the high characteristic dimensions and limited training samples, overfitting is a serious problem that can occur. To solve this problem, the Dropout [37] method was used, which is a method of randomly deleting neurons during learning in Figure 2. During training, every time the data is passed, the neurons in the hidden layer are randomly selected, and then deleted, and the deleted neurons no longer transmit signals; During the test, although all neuronal signals are transmitted, the output of each neuron is multiplied by the deletion ratio at the time of training before the output. Therefore, the deleted neurons are not involved in forward transmission and are no longer used in the backward propagation process. At different training stages, deep networks form different neural networks by randomly discarding neurons. The Dropout method prevents complex co-adaptations, and neurons can learn more correct features.

Figure 2: MCNN+ configuration

4. Experiment

4.1. Datasets

To verify the model orientation in this paper, a dataset of gemstone images obtained from [38] was selected for analysis. The dataset contains more than 3,200 images of different gemstone. The images are divided into 87 categories, which have been divided into training data and test data. Some of these examples are shown in Figure 3. Images are obtained under very different lighting and background color conditions. A total of 2800 images were used for training and 400 images were reserved for testing. For each class, there are 24-44 training images and 4-5 test images available.

The Epoch of the CNNs network model with deep multi-feature fusion is set to 50, the number of iterations is 8, and the batch size is 1000 images. The convolutional kernel size of the first convolutional layer is 5 *5, and the filter is 32; The convolutional kernel size of the second convolutional layer is 5*5, and the filter is 64; The convolutional kernel size of the third and fourth convolutional layers is 3*3, and the filter is 128. The convolution step is set to 1 and the fill is set to 0. The pooling layer step size is set to 2, and the pooling window size is 2*2. Finally, the Softmax layer has 10 neural units, indicating that the images are divided into 10 classes.

Figure 3: Partial image of the gemstone image dataset

The optimal solution is obtained by minimizing the loss function. This study uses the cross-entropy error function [14] as the loss function, which is expressed as (3):

$$Q = -\frac{1}{N}\sum_{n=1}^{N}\left((y)_n (log)_2 ((o)_n) + (\tilde{y})_n (log)_2 \left(\tilde{o_n}\right)\right) \quad (3)$$

Where the $\tilde{y_n} = 1 - y_n, \tilde{o_n} = 1 - o_n$, Nnumber of samples is trained for batch processing, y is the true label value for each sample, and o is the actual output value of the network.

To optimize the loss function, an optimization method is required, and the Adam optimizer is used for the experiment [15]. Combine the advantages of two optimization algorithms, AdaGrad and RMSProp. Considering the first-order moment estimation (the mean of the gradient) and the second-order moment estimation (the undercentric variance of the gradient) of the gradient, the update step is calculated.

4.2. *Experimental results and analysis*

4.2.1. *Evaluation function*

To evaluate the performance of the algorithm, this paper uses a training validation test scheme in which 80% of the data is used as the training set and 20% as the test set. The test accuracy rate is used to evaluate the performance of the model and is expressed as (4):

$$Accuracy = \frac{R}{T} \quad (4)$$

where: R is the sample with the correct classification and T is the total sample.

4.2.2. *Experimental results*

In this study, a convolutional neural network that deeply integrates the main color features with position and shape-related features, referred to as MCNN+. The model training results of MCNN+ are shown in the following Figure 4 and Figure 5. As can be seen from the Figure 4, the model gradually reaches a steady state after iterative training. One of the best classifications has an accuracy rate of 82%.

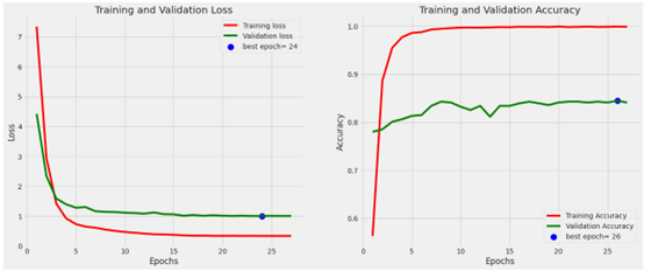

Figure 4: Model training results

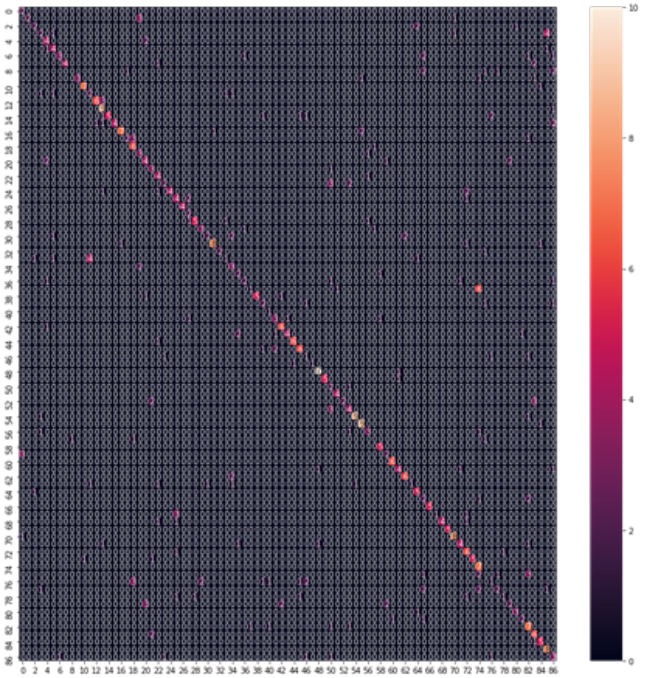

Figure 5: Confusion matrix for model classification

4.2.3. *Model Comparison*

We also compares the MCNN+ model with several machine learning models and deep learning models, as shown in the following Table 1.

Table 1: Comparison of different model results

Methods	Accuracy
CNN	0.721
Random Forest	0.694
Logistic Regression	0.687
SVM	0.669
Naive Bayes	0.627
InGG16	0.732
ResNet50	0.746
MCNN+	0.810

As can be seen from the table, the model in this paper can achieve the best classification results when classifying the gemstone image data set. And it can be improved by nearly 9% compared to the CNN model.

5. Conclusion

In this study, we proposed a CNN gemstone image classification algorithm with deep multi-feature fusion, which effectively integrates the main color characteristics of gemstone images with the spatial position and shape characteristics extracted by convolutional neural networks. This approach addresses the limitation of traditional CNN models, which primarily focus on spatial position information and are less sensitive to color information. Experimental results demonstrate that MCNN+ not only significantly improves image classification performance but also exhibits greater stability and robustness. Additionally, our experiments show that different weight values in the MCNN+ network models have varying effects on experimental performance.

In future research, we aim to implement adaptive weight mechanisms to further enhance the model's performance. Additionally, we plan to explore the integration of other feature extraction techniques, such as texture and edge detection, to enrich the feature set used for classification. We will also investigate the application of this model to other types of images and domains to test its versatility and generalizability. Finally, leveraging advanced techniques like transfer learning and self-supervised learning could further optimize the model and reduce the reliance on large labeled datasets.

Conflict of Interest The authors declare no conflict of interest.

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A Case Study on Formal Sequential Equivalence Checking based Hierarchical Flow Setup towards Faster Convergence of Complex SOC Designs

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ABSTRACT: Functional Verification Sign-Off is the crux of the design verification problem faced by latest Silicon Designs on the Simulation/Stimulus Driven and the Formal Verification Platforms. Formal Verification Convergence is a custom specific criterion depending on the success, failure, exhaustiveness and reachability of the verification goals generated and validated by the Formal Tool. One of the key techniques in Formal Verification is the ability to mathematically prove the equivalence between two different versions of the same RTL Designs. Those RTL Design versions may differ in terms of Feature addition/removal or Bug Fixes or Low Power Capability or specific requirements. Synopsys VC Formal ™ tool provides this formal verification technique using a built-in Formal Application known as 'Sequential Equivalence (SEQ)' App. This Case Study outlines various approaches in deploying Formal SEQ App and an approach towards Faster Convergence.

KEYWORDS: Register Transfer Logic (RTL), Functional Verification, Formal Verification, Sequential Equivalence (SEQ), Sequential Equivalence Check (SEC), Synopsys VC Formal ™ tool, Formal Convergence, Universal Verification Methodology (UVM), Portable Stimulus Standard (PSS), Artificial Intelligence (AI), Machine Learning (ML). Object Oriented Programming (OOPs), Factory Pattern, Design Under Test (DUT), System On Chip (SOC), Synopsys SolvNet Plus ™, Specification (SPEC), Implementation (IMPL), Return Of Investment (ROI)

1. Introduction

Complex & Computationally Intensive SOC Designs drive the functional verification complexity much beyond the realm of conventional verification techniques. Further the functional verification complexity is compounded by the shorter time-to-market requirements & performance intensive applications of the latest Silicon Designs [1].

Semiconductor & EDA Industries in collaboration with Research Community pushing the functional verification capabilities to address the ever-increasing design complexity. Those functional verification capabilities are improved through advent of language Capabilities like OOPs, Software Inspired capabilities like factory pattern, verification standards like UVM & PSS. Noticeably these exciting interventions are mostly centered on the heavily leveraged & standardized simulation driven dynamic verification platform.

2. Formal Verification

Formal Verification has been around for few decades co-existing with simulation driven dynamic verification platform. Concurrent and Exponential growth of AI/ML driven EDA Tool mathematical proofing capabilities, Hardware Computing Resources & Silicon Design Complexities bringing forth the Formal Verification towards addressing the verification gap (Figure 1).

Advanced Silicon Solutions for Artificial Intelligence, Machine Learning, Real Time Data Processing & High-Performance Computing are driving the Silicon Design Complexity that can be effectively handled by Mathematical Proofing techniques than Simulation driven verification techniques [2], [3], [4], [5]. Hence, it's time for Formal Verification to be understood, leveraged & deployed for Silicon Design Verification.

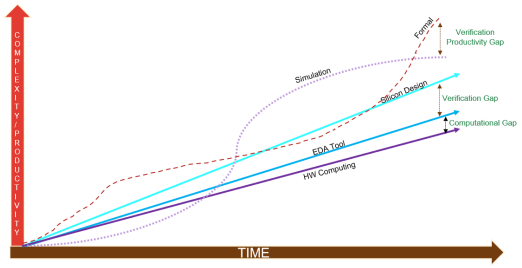

Figure 1: Exponential Growth of EDA Tool Capabilities, Hardware Computing and Silicon Design Complexity with Verification Productivity Gap

3. Formal Convergence is a Challenge

Formal Verification Convergence is defined by the ability to mathematically prove the absence of bugs in the Design Under Test (DUT) based on the Formal Constraints, Checks & Verification Setup [6]. Formal Convergence as a criterion is characterized by the success, failure & inconclusiveness of the formal properties in each Formal Application Mode. Similar to Simulation's Verification SignOff Criteria, the Formal Convergence depends on multitude of factors like DUT Complexity, Formal Constraints Complexity, Formal Checks & much more (Figure 2).

Figure 2 : Formal Convergence Dependency

Formal Convergence is the single most complex & demanding activity [5] in the Formal Verification Flow (Figure 3). In this paper, we will discuss the Formal Convergence of Sequential Equivalence Checking Mode of the Formal Verification Platforms using Synopsys VC Formal ™ Tool.

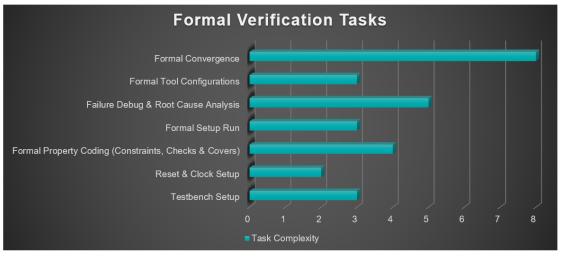

Figure 3 : Formal Verification Tasks with their Complexity

4. Sequential Equivalence Checking Mode (SEQ/SEC)

In SEQ Mode, the Formal Engine checks the functional behavior at all the output ports across two releases or versions of the same Design Under Test (DUT). Formal Engine utilizes both the state-matching and non-state matching algorithms to prove those DUT releases/versions are functionally equivalent [7]. In addition to output port checks, the SEQ mode also performs internal sequential difference checks to ensure the DUT similarity within Design States.

Synopsys VC Formal ™ tool auto generates these output port checks for the given DUT (referred as SEQ_TOP). This SEQ mode reduces the verification turn-around time (TAT) and improves productivity by providing an approach to exhaustively verify the modified/implemented Design feature. This avoids the need to redo the verification of the entire design. Towards Formally verify the Clock Gating logic in our complex SOC design, we have developed Formal SEQ Verification Setup using Synopsys VC Formal ™ tool. The two versions of the DUT are referred to as SPEC and IMPL in the SEQ mode nomenclature. Here specification-SPEC refers to the complex SOC design blocks without Clock Gating feature disabled and implementation-IMPL refers to complex SOC design blocks with Clock Gating feature enabled (Figure 4).

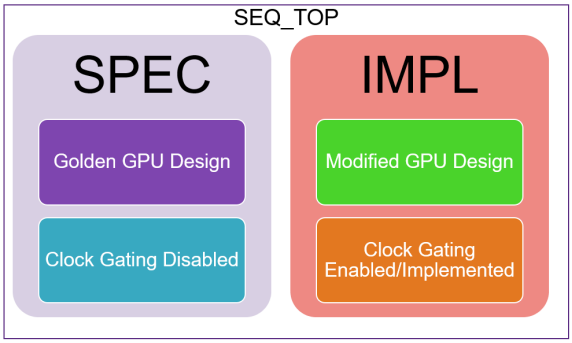

Figure 4 : SPEC & IMPL Versions of the DUT in this Case Study

5. SEQ Conventional Flow

In the conventional Flow of SEQ Mode, the Formal Engine checks the functional behavior at all the output ports of the top-level block across two versions of the same DUT (e.g., RTL Model A & RTL Model B as shown in Figure 5. Formal Engine proves or disproves the functional equivalence of the output ports of the top-level block in the SPEC & IMPL DUTs adhering to the defined Formal Input Constraints.

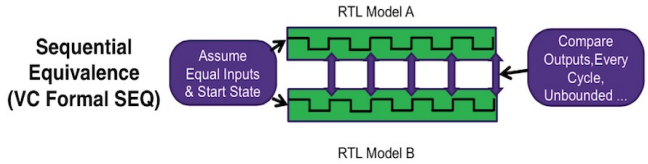

Figure 5 : Formal SEQ Verification

Though Formal Engine highlights internal sequential mismatches among with sub-blocks in the given DUT, there is NO output port level checks on the internal sub-blocks. Therefore, the Design Complexity of the entire DUT along with Formal Input Constraints plays a key role in the Formal Convergence.

6. SEQ Hierarchical Flow

Towards verifying the sub-block in each Top-Level Block without the need to develop Formal verification Setup, Synopsys VC Formal™ tool provides an approach known as 'SEQ Hierarchical Verification Flow'. In this approach, we will be verifying the sub-block of a given Top-Level Block with complete reuse of the Formal Verification Setup & Input Constraints in the SEQ Mode as shown in the Figure 6. For the merit of this paper, we are utilizing the configuration#1 of the SEQ Hierarchical verification Flow defined in the Synopsys SolvNet Plus™ documentation [8]. Please refer to the SolvNet Plus ™ documentation [9] for more details on the same.

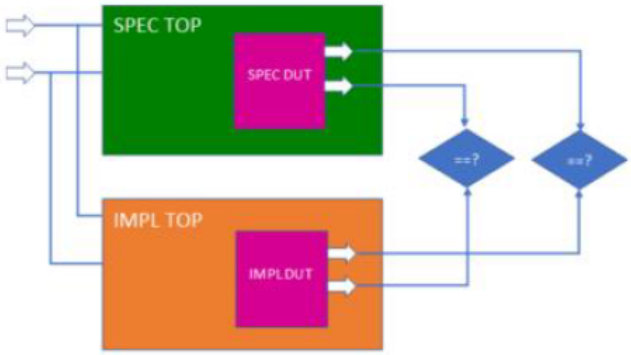

Figure 6 : Formal SEQ Conventional Verification Flow

7. Value Addition by SEQ Hierarchical Flow

It is imperative to understand the value of sub-block or unit, or IP level verification compared to the Top/System/SOC level verification in the Simulation Stimuli driven verification platform for obvious reasons. Similarly, there exists great potential & ROI in verifying the Sub-blocks in Formal Verification provided the reusability of Top-Level Verification Setup & Constraints. Further the SEQ Hierarchical Verification Flow provides the much-needed boost to achieve Formal Verification Convergence at a much-desired rate. Figure 7 highlights the key value addition of Sub-block Verification in the SEQ Mode.

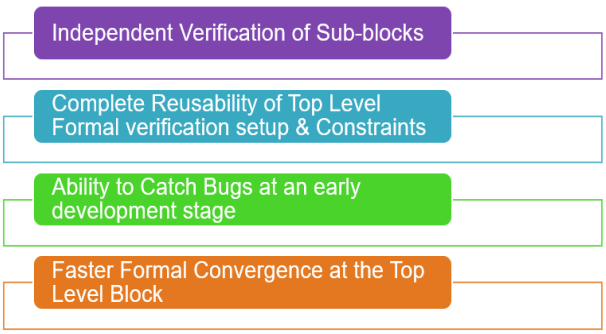

Figure 7 : Benefits of Formal SEQ Hierarchical Verification Flow

8. Case Study

In this paper, we will be discussing the Formal SEQ Verification of Two Subsystem Level Top Blocks 'A' & 'B'. These Blocks are few among the many subsystems with different functional capabilities & design complexities in the complex SOC (Figure 8).

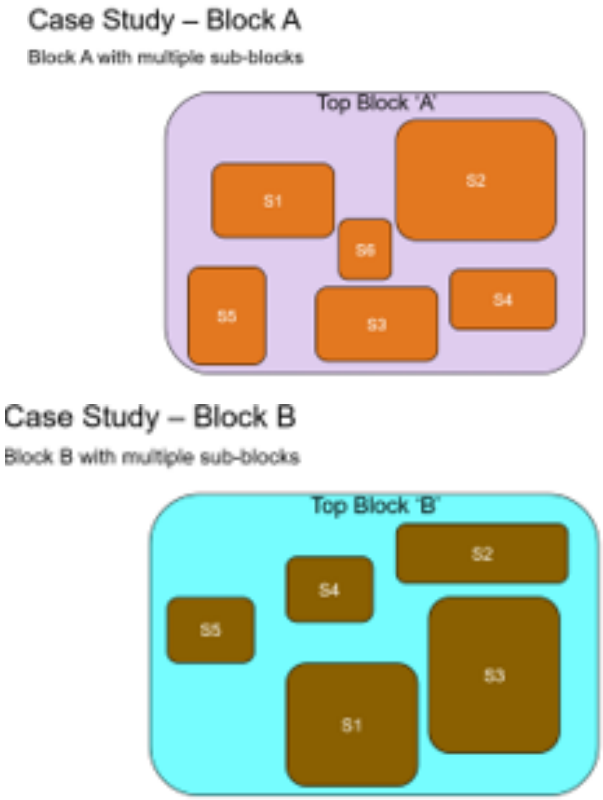

Figure 8 : Block Diagram of Top-Level Blocks 'A' & 'B'

Refer below Table 1 for a high-level relative comparison of Blocks 'A' & 'B'.

Table 1 : Relative Comparison of Case Study Blocks 'A' & 'B'

DUT	Block 'A'	Block 'B'
Design Complexity	High	Medium
Number of Sub blocks (first level)	6	5
Number of input ports	~250	~150
Number of output ports	~750	~450
Multipliers	Yes	Yes
Counters	Yes	Yes
Arithmetic Units	Yes	Yes

8.1. Block 'A' – SEQ Conventional Setup

As Shown in the Figure 9, the Formal Engine drives the input ports of both the SPEC & IMPL (Top level block 'A') based on the Formal Input Constraints and generates the auto checks to compare the output ports of the SPEC

& IMPL (Top level block 'A'). Here the Formal Convergence of the auto checks on the output ports is impacted by the Design Complexity of the entire DUT – Top Level Block 'A' and its Sub-blocks. Owing to the Complex nature of the SOC Design & large Cone of Influence (COI), we have achieved <80% Formal Convergence in our Case Study for Clock Gating Verification of Top-Level Block 'A'.

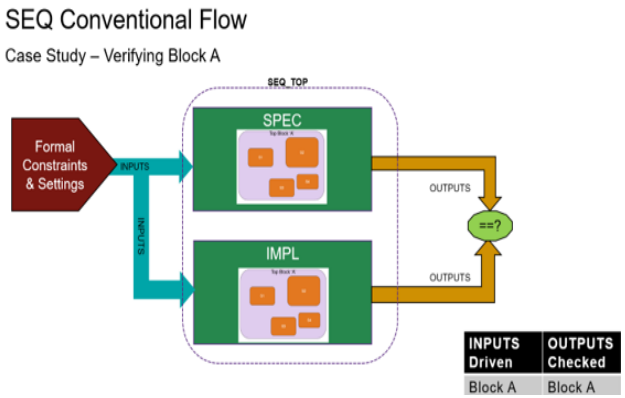

Figure 9 : Case Study - SEQ Conventional Flow of Block 'A'

Despite various efforts to improve Formal Convergence by Formal Techniques (like Black Boxing, Abstractions, Design reductions, Enhances Engine & Effort level and much more), our verification returns were stagnated with the unrelenting Formal Convergence at level of < 80% for this Top-Level Block 'A'. Hence, we have decided to deploy SEQ Hierarchical Flow to achieve the Formal Convergence of this Top-Level Block 'A'.

8.2. Block 'A' – SEQ Hierarchical Setups

In the SEQ Hierarchical Verification Flow (Figure 10, Figure 11 & Figure 12) of Block 'A', the Formal Engine drives the input ports of both the SPEC & IMPL (Top level block 'A') based on the Formal Input Constraints identical to the SEQ Conventional Verification Flow.

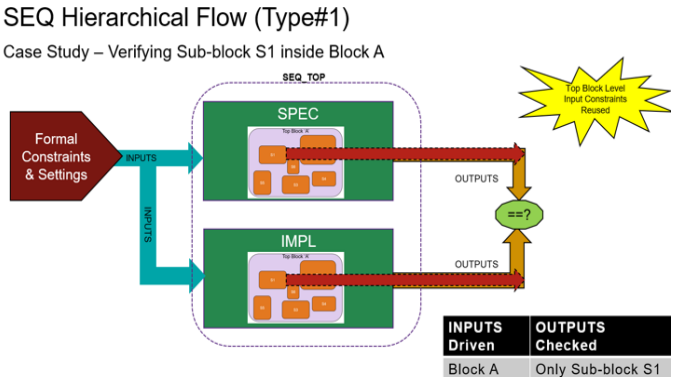

Figure 10 : SEQ Hierarchical Flow of Block 'A' - Sub-block 'S1'

But the Formal Engine generates auto checks to compare the output ports of the targeted Sub-block within the SPEC & IMPL blocks (Top level block 'A'). Multiple types of SEQ Hierarchical Verification Flow Testbenches were developed specific to each Sub-block which were chosen on selection criteria (refer next section).

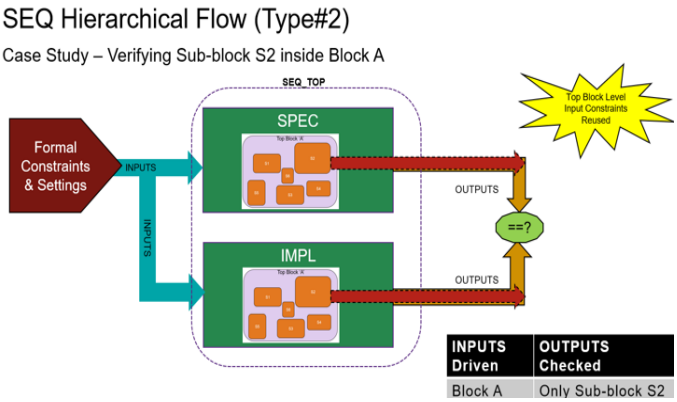

Figure 11: SEQ Hierarchical Flow of Block 'A' - Sub-block 'S2'

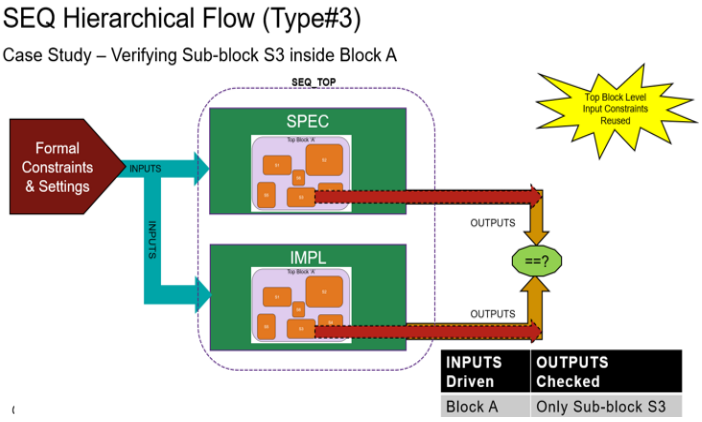

Figure 12: SEQ Hierarchical Flow of Block 'A' - Sub-block 'S3'

For this case study, we have selected three sub-blocks (S1, S2 & S3) from Top Level Block 'A' for SEQ Hierarchical Verification Flow setups as show in the Figure 10, Figure 11 & Figure 12. Here the Formal Convergence of these newly generated auto checks on the sub-block output ports can be achieved much faster due to the limited nature of the Design Complexity & Cone Of Influence (COI) on these output checks.

8.3. Block 'A' – SEQ Conventional Setup with verified Sub-blocks Clock Gating Disabled

After successful verification closure of Sub-blocks S1, S2 & S3 using the SEQ Hierarchical Verification Flow of Top-Level Block 'A', we have created another version of the SEQ Conventional Flow setup the Top-Level Block 'A' with Clock Gating Disabled only those three verified sub-blocks (refer Figure 13). Thereby leveraging the Formal Verification Closure of those three sub-blocks within the Top-Level Block 'A' as well as reducing the Design Complexity & COI Effects on the Top-Level Output Port Checks of the Block 'A'.

Now we have achieved a better & faster Formal Convergence of >09% on the Top-Level Block 'A' with the

same Formal Verification Setup & Constraints except for Clock Gating disabled sub-blocks within the DUT. This clearly proves the effectiveness of the SEQ Hierarchical Verification Flow on the selective Sub-Blocks (S1, S2 & S3) of the Top-Level Block 'A' to achieve faster Formal Convergence.

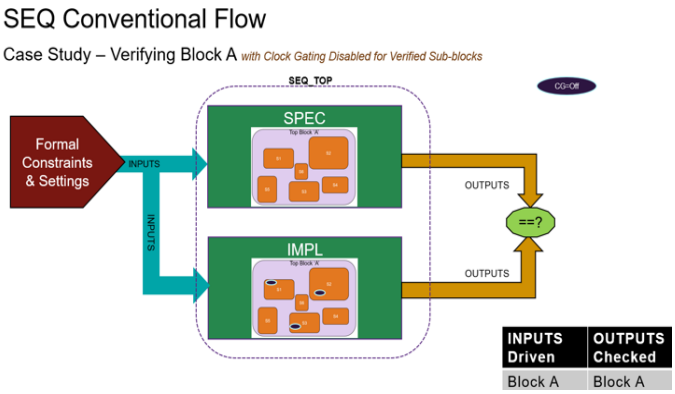

Figure 13: SEQ Conventional Flow of Block 'A' with verified Sub-blocks Clock Gating Disabled

8.4. Sub-block Selection Criteria

Even though the Sub-block SEQ verification setup can be developed quickly with reusable components from Top Level SEQ verification setup, it is ineffective to perform Sub-block verification on all the first level sub-blocks within a Top-Level Block. Henceforth we have devised a selection criterion to choose a sub-block for SEQ Hierarchical Verification Flow. Please note this selection criteria may be effective specifically for this case study.

Factors involved in the selection criterion of a sub-block are: (not limited to)

1. Number of Inconclusive Top Level Block Checks impacted by the COI of this sub-block
2. Placement of this sub-block within the Logic Levels of the Top-Level Block
3. Proximity of this Sub-block to the Input/Output Ports of the Top-Level Block
4. Fan-in & Fan-out nature of this sub-block
5. Design Complexity of this sub-block

8.5. Block 'B' – SEQ Verification Setups

Considering that the verification setups of Top-Level Block 'B' is like the Top-Level Block 'A' as discussed in the previous sections, we are omitting the details on Top Level Block 'B' SEQ Verification Setup in this paper.

8.6. SEQ Verification Metrics Table

Based on this case study execution of Formal SEQ Verification on Top Level Blocks 'A' & 'B', we have captured the key metrics from the Synopsys VC Formal™ Tool execution. These metrics were gathered from various Formal runs with unchanged Formal Verification setup (except SEQ Flow change), Input Constraints, Design Versions of IMPL/SPEC, Tool Settings like Engine Selection, Number of Workers and so.

Table 2: SEQ Metrics of Block 'A'

Case Study – Block A

DUT	Formal SEQ	SEQ Goals Count	Goals Converged (%)	Run Time
Top Block - A	Conventional	738	536 (72%)	150hrs
Sub-block- S1	Hierarchical	437	437 (100%)	91hrs
Sub-block- S2	Hierarchical	140	140 (100%)	34hrs
Sub-block- S3	Hierarchical	290	290 (100%)	51hrs
Top Block - A	Conventional (with Clock Gating disabled for verified sub-blocks – S1, S2 & S3)	738	695 (94%)	108hrs

Table 3: SEQ Metrics of Block 'B'

Case Study – Block B

DUT	Formal SEQ	SEQ Goals Count	Goals Converged (%)	Run Time
Top Block - B	Conventional	452	97(21.46%)	96hrs
Sub-block- S1	Hierarchical	410	409(99.75%)	21hrs
Sub-block- S2	Hierarchical	107	107(100%)	11hrs
Top Block - B	Conventional (with Clock Gating disabled for verified sub-blocks S1 & S2)	452	443(98.08%)	53hrs

9. SEQ Verification Formal Convergence Rate

We have analyzed the Rate of Convergence for all the SEQ Verification Flow Setups discussed in this case study on Top Level Blocks 'A' & 'B'.

9.1. Block 'A' SEQ Verification Formal Convergence Rate

In this case study, we were able to achieve Formal Convergence at a faster rate for Top Level Block 'A' with clock gating disabled on verified sub-blocks (S1, S2 & S3) in comparison to the SEQ Conventional Verification Flow of Top-Level Block 'A' (refer Figure 14)

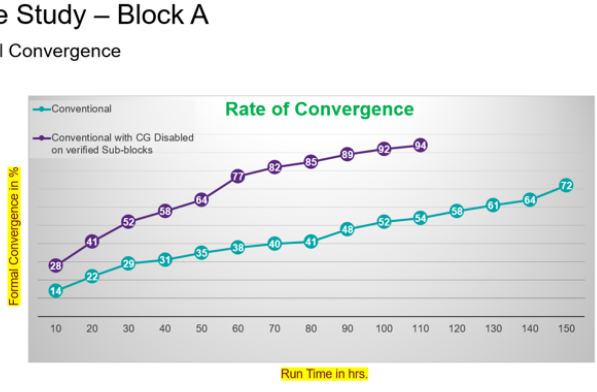

Figure 14 : Formal Convergence Rate of Block 'A'

9.2. Block 'B' SEQ Verification Formal Convergence Rate

In this case study, we were able to achieve Formal Convergence at a faster rate for Top Level Block 'B' with clock gating disabled on verified sub-blocks (S1 & S2) in comparison to the SEQ Conventional Verification Flow of Top-Level Block 'B' (refer Figure 15)

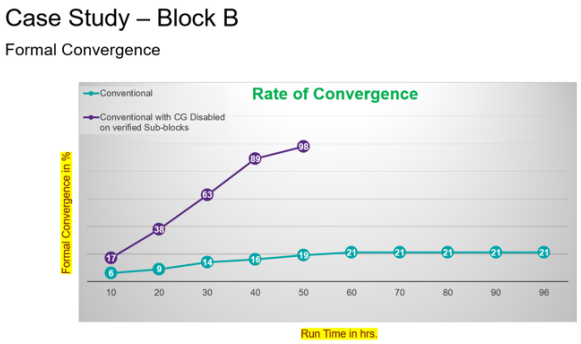

Figure 15 : Formal Convergence Rate of Block 'B'

10. Conclusions

This case study explored the Formal SEQ Verification setups with conventional and hierarchical flows on the Top-Level Blocks 'A' & 'B'. Further we have devised an added ability to disable clock gating for verified sub-blocks using SEQ Hierarchical flow in the Top-Level Block SEQ Conventional Flow.

Table 4 : Relative Comparison of SEQ Flows'

Feature	Conventional	Hierarchical
Testbench Top	Single	Multiple
Constraints Reuse	No	Yes
Independent Sub-block Verification Support	No	Yes
Efforts required for Convergence	High	Medium
Rate of Convergence	Average	Faster

In Table 4, we have highlighted the key comparative features of the SEQ Conventional and Hierarchical Flows.

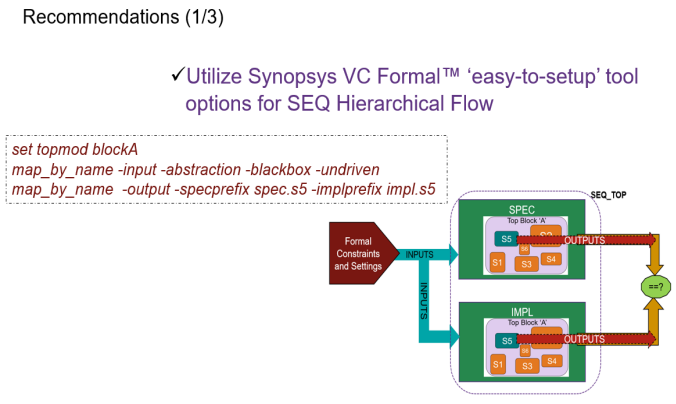

Figure 166: Recommendation#1 on SEQ Hierarchical Flow

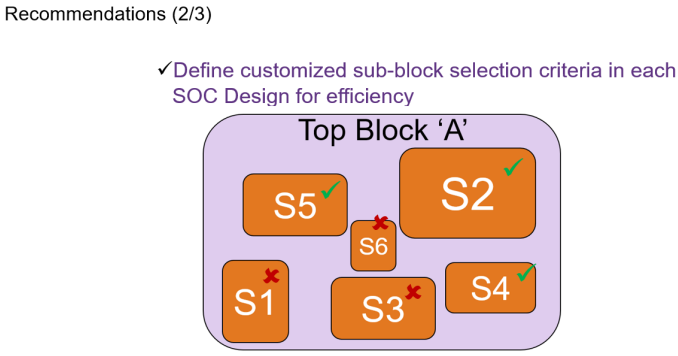

Figure 177: Recommendation#2 on SEQ Hierarchical Flow

Consequently, we were able to achieve faster convergence between the Top-Level blocks in the Formal SEQ Conventional Flow. Figure 16, Figure 17 & Figure 18 illustrates the recommendations on SEQ Hierarchical Flow from this Case Study.

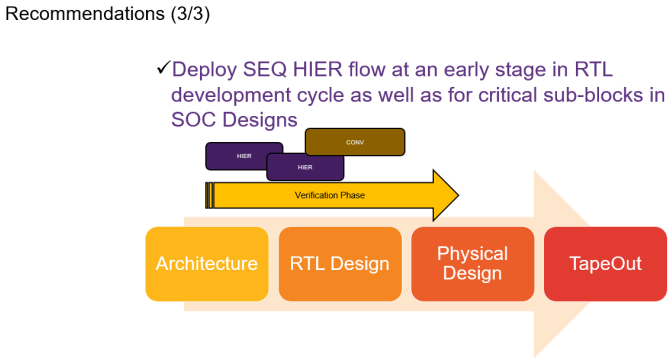

Figure 188: Recommendation#3 on SEQ Hierarchical Flow

Hence, we recommend the Formal SEQ Hierarchical flow on the Designs that need convergence improvements beyond the known formal convergence techniques.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgment

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