Effective Feedback for Introductory CS Theory:  
A JFLAP Extension and Student Persistence

Ivona Bezáková∗ Kimberly Fluet† Edith Hemaspaandra∗
Hannah Miller‡ David E. Narváez‡

Abstract

Computing theory analyzes abstract computational models to rigorously study the computational
difficulty of various problems. Introductory computing theory can be challenging for undergraduate stu-
dents, and the main goal of our research is to help students learn these computational models. The most
common pedagogical tool for interacting with these models is the Java Formal Languages and Automata
Package (JFLAP). We developed a JFLAP server extension, which accepts homework submissions from
students, evaluates the submission as correct or incorrect, and provides a witness string when the sub-
mission is incorrect. Our extension currently provides witness feedback for deterministic finite automata,
nondeterministic finite automata, regular expressions, context-free grammars, and pushdown automata.

In Fall 2019, we ran a preliminary investigation on two sections (Control and Study) of the required
undergraduate course Introduction to Computer Science Theory. The Study section used our extension
for five targeted homework questions, and the Control section solved and submitted these problems using
traditional means. Our results show that on these five questions, the Study section performed better on
average than the Control section. Moreover, the Study section persisted in submitting attempts until
correct, and from this finding, our preliminary conclusion is that minimal (not detailed or grade-based)
witness feedback helps students to truly learn the concepts. We describe the results that support this
conclusion as well as a related hypothesis conjecturing that with witness feedback and unlimited number
of submissions, partial credit is both unnecessary and ineffective.

1 Introduction

Computing theory is difficult for beginner students since the concepts are abstract. In introductory theory
courses, students construct computational models such as deterministic finite automata, nondeterministic
finite automata, regular expressions, context-free grammars, and pushdown automata (DFAs, NFAs, RegExs,
CFGs, and PDAs, respectively). The most popular graphical interface for students to interact with these
concepts [8] is the Java Formal Languages and Automata Package (JFLAP) [19, 20, 21].

For our Automated Feedback in Undergraduate Computing Theory [3] research, we developed the Di-
dactic And Visual Interface for Development (DAVID) extension to JFLAP. The DAVID extension accepts
introductory computer science theory homework submissions from students and sends each submission to a
feedback server, which automatically checks a student’s submission against the instructor’s correct solution;
the server then provides immediate feedback to the student if the submission is correct or not. Figure 1
shows JFLAP with the DAVID extension.

In Fall 2019, we conducted a successful preliminary investigation of the beta version of the DAVID exten-
sion. In this investigation, we compared a Control section and a Study section of students in Introduction
to Computer Science Theory. The Study section was required to use the DAVID extension to submit five
targeted homework questions, and we considered these exploratory and deliberately broad research ques-
tions about students and instructors. Our preliminary research questions were deliberately broad to prevent
artificially limiting ourselves. We discuss our most interesting finding in Section 4.3.

∗Rochester Institute of Technology, Department of Computer Science, Rochester, New York, USA
†University of Rochester, Center for Professional Development and Education Reform, Rochester, New York, USA
‡Rochester Institute of Technology, Golisano College of Computing and Information Sciences, Rochester, New York, USA
RQ1 How do students use the DAVID extension? (Results in Section 4.1.)

RQ2 What were students’ experiences with the extension? (Results in Section 4.2.)

RQ3 How do instructors benefit from the extension? (Results in Section 4.3.)

A student’s submission to the DAVID extension is either incorrect or correct. If a student’s submission is incorrect, then the server provides immediate feedback to the student via a witness string, which is a string that the incorrect submission accepts (or rejects) but the correct solution should reject (or accept). For the models used in introductory theory, these witness strings are usually just a few symbols long. Naturally, if the submission is correct, then the extension reports a simple “Correct!” to the student. We call this feedback of a witness string witness feedback, and we found that when given only witness feedback, students tended to persist in submitting attempts until correct.

Our preliminary investigation had multiple promising outcomes, including verifying the set-up of the DAVID extension, learning what additional telemetry would be valuable for our full investigation, understanding the practical workflow to make the extension easy for instructors to use, and analyzing the collected data of homework submissions, student surveys, and students’ grades.

![Figure 1. JFLAP with the DAVID extension “Submit” option.](image)

2 Relevant Literature

Norton [17] studied near-linear time algorithms [16, 14] for DFA equivalence and wrote JFLAP-compatible code to prove DFA equivalence and to produce a witness string if two DFAs are not equivalent. Since CFG equivalence is an undecidable problem, Sorrell used CFGAnalyzer [2] to experimentally show that checking all strings up to length \( k = 10 \) suffices for typical homework assignments. Sorrell’s work included integrating the PicoSAT solver [5] into CFGAnalyzer; this work is the CFGSolver software [23] used by the DAVID extension. To be conservative, our extension checks all strings up to length \( k = 15 \) for strings generated by a CFG submission. We announced the setup of our preliminary investigation in [4].

Automata Tutor is an alternative feedback tool for computing theory. Version 2 [12] provides a graphical user interface with roughly the functionality of JFLAP as well as additional features related to checking equivalence for regular languages, including witness feedback and automated grading of DFAs [1, 11]. Presented in May 2020, Version 3 [10] has many added features, including those that we implemented on top of JFLAP.

While the tools are similar, the focus of the Automata Tutor study [10] and our investigation are very different. Automata Tutor focuses on automation, including partial grading. We focus on educational research, attempting to measure the educational benefits of the DAVID extension, which provides a witness string for incorrect solutions and does not venture into partial credit. In fact, the most interesting finding of our preliminary investigation is that the majority of students persisted in submitting attempts until the DAVID extension reported correct. We discuss the implications of the persistence result in Section 4.3, from which we hypothesize (Section 5.1) that witness feedback is the appropriate type of feedback (Section 5.2) and that partial credit is not needed in our setting (Section 5.3).
For this paper, we use the term feedback, which is defined as “information provided by an agent (e.g., teacher, peer, book, parent, experience) regarding aspects of one’s performance or understanding” [15]. In particular, we are interested in intermediate feedback (Section 5.2), which is a type of formative feedback [22].

3 Fall 2019 Preliminary Investigation

In Summer 2019, we developed the DAVID extension. In Fall 2019, we ran a preliminary investigation on approximately 65 students enrolled in Introduction to Computer Science Theory, and in Spring 2020, we analyzed the investigation results. These results and the implications for our future work are discussed in this paper.

For our Fall 2019 preliminary study with the DAVID extension, two synchronized sections of the Introduction to Computer Science Theory course shared the same instructor, course delivery style, homework assignments, similar midterm exams, and an identical final exam. The majority of students (> 80%) in both sections were majoring in Computer Science; the second-most popular major (< 15%) was Software Engineering.

For both sections, we collected homework and grade data, surveyed the students about their experiences in the course, and asked the Study section additional survey questions about their experiences with the DAVID extension, their perception of the extension, and their thoughts on automated feedback in general. We monitored how the Study students used the DAVID extension. We also interviewed the instructor. At the end of the course, there were 35 students in the Control section and 29 students in the Study section who gave consent for their data to be used in our investigation. There were eleven homework assignments for the semester with an average of five questions per homework.

Out of these eleven assignments, we compared the performance between the two sections on five targeted homework questions (one each on a DFA, NFA, RegEx, CFG, and PDA), which were identical between the sections. For these five targeted homework questions, the Control section submitted their homework solutions to these five questions using traditional means the Study section was required to use the DAVID extension. The text of the five targeted homework questions is below. The CFG question, which was especially challenging, had by far the most number of submissions to the DAVID extension.

4.1 Statistical analysis

For RQ1 (student use), for both the final exam grade and the overall course grade, the Study section scored lower than the Control section, and both lower scores were statistically significant (Table 2); these differences

5. PDA. Let \( L = \{w \in \{a, b\}^* \mid w \text{ has more } a \text{'s than } b \text{'s}\}. \) Draw the state diagram of a PDA that accepts the language \( L. \) Your PDA should not be overly complicated.

4 Results

4.1 Statistical analysis

For RQ1 (student use), for both the final exam grade and the overall course grade, the Study section scored lower than the Control section, and both lower scores were statistically significant (Table 2); these differences
are not due to chance, which tells us that the two sections had different levels of academic strength. However, on the five targeted homework questions where the Study section used the DAVID extension for feedback, the Study section’s average grade was always higher than the Control section’s average grade (Figure 2).

Figure 2. Homework grade average and standard deviation for the five targeted homework questions. “C” is the Control section; “S” is the Study section. The y-axis limits are the same among the subplots.

The Study section strongly outperformed the Control section with respect to the percent of perfect homework grades for the targeted homework questions (Figure 3). (The Study section NFA percentage is low compared to the other questions because the NFA submissions through the DAVID extension are not checked for “sufficient” nondeterminism, which means that submissions counted as correct by the extension did not necessarily earn a perfect grade.) We saw high engagement with the extension from the Study students: on average, students submitted 9 times per homework question.

Figure 3. The percentage of students who earned a perfect grade on the five targeted questions from an experienced professor. “C” is the Control section; “S” is the Study section. The y-axis limits are the same among the subplots.

We used ANOVA with a threshold of $p < 0.050$ to compare the differences between the Control section and the Study section. Table 1 summarizes the statistical results. On three of the five targeted homework questions, the Study section’s higher score was statistically significant; for the other two targeted homework questions, there was no statistically significant difference between the sections. Because the Study section was academically less proficient than the Control section, it is particularly noteworthy that the Study section scored significantly higher than the Control section on the DFA, RegEx, and PDA questions.

|                                      | $p$ value | Significance                           |
|--------------------------------------|-----------|----------------------------------------|
| DFA                                  | 0.001     | Study scored higher than Control       |
| NFA                                  | –         | no statistical difference              |
| RegEx                                | 0.030     | Study scored higher than Control       |
| CFG                                  | –         | no statistical difference              |
| PDA                                  | 0.000     | Study scored higher than Control       |
| Final exam grade                     | 0.014     | Study scored lower than Control        |
| Course grade                         | 0.011     | Study scored lower than Control        |

Table 1. Statistical results. A dash indicates no statistically significant $p$ value. All analysis used a threshold of $p < 0.050$.

To determine the relative academic strength of the Control vs. Study sections, we used the final exam grade, the overall course grade, and the instructor’s perception. The final exam was identical for both
sections, and for the final exam grade, the Control section mean was 79.8% ± 17.0% for 35 students, and the Study section mean was 70.3% ± 12.9% for 29 students. This difference was statistically significant ($p = 0.014$) and therefore is not due to chance. For the overall course grade (Table 2), the Control section performed better than the Study section with respective means of 84.9% ± 9.9% and 78.0% ± 11.0%, which was statistically significant ($p = 0.011$).

|              | n  | µ    | σ  | min | 25% | 50% | 75% | max |
|--------------|----|------|----|-----|-----|-----|-----|-----|
| Control      | 35 | 84.9 | 9.9| 54.3| 80.0| 86.3| 92.9| 96.7|
| Study        | 29 | 78.0 | 11.0| 39.0| 76.0| 78.3| 86.4| 91.5|

Table 2. Overall course grades for both sections. The number of students is $n$, the mean grade is $µ$, and the standard deviation of the grades is $σ$.

Additionally, the course instructor said, “I do think it’s probably correct that just kind of as an average performance, the Control section was a little sharper [than the Study section].” This evidence of the final exam and the overall course grade as well as the instructor’s perception supports our claim that the Study section was academically less successful than the Control section. Therefore, the statistically significant higher scores by the Study section on three of the five targeted homework questions are even more striking since they outperformed the academically stronger Control section.

4.2 Survey responses

For RQ2 (student thoughts), we surveyed students in both sections twice about their experiences in the course. On each survey, the Study section responded positively about the DAVID extension. We share two representative free-text responses: on Survey 1 (after DFAs and NFAs), Student #21 said, “[The] DAVID extension is a very helpful tool. It helped me understand DFA and NFA better.” On Survey 2 (near the end of the course), Student #3 said, “I love the idea of the DAVID extension, but it could use improvement. Definitely don’t get rid of it.”

We report the survey response percentages in Table 3 and Table 4, where the column names are “strongly agree + agree,” “neutral,” “disagree + strongly disagree.” Table 3 shows the Study section responses to the two survey questions below.

**Q1** The DAVID extension helped me solve the {DFA, NFA, RegEx, CFG, PDA} questions, and

**Q2** The DAVID extension helped me understand the {DFA, NFA, RegEx, CFG, PDA} questions.

From the survey responses, the Study students did feel helped by the DAVID extension (Table 3). For survey Q1 (DAVID extension helped the student solve), on the DFA, RegEx, and PDA questions where the Study section did better than the Control section, the majority of Study students strongly agreed or agreed that the extension helped them to solve that problem (54.9%, 60.7%, and 42.9%, respectively). For survey Q2 (DAVID extension helped the student understand), the majority of Study students strongly agreed or agreed that the extension helped them understand the concepts (41.9% for DFA and 46.4% for RegEx). For PDAs, the percentage of students who responded neutral (41.9%) was near equal to those who responded strongly agree or agree (39.3%); however, the percent of students who strongly agreed or agreed was more than double those that disagreed or strongly disagreed (17.8%).
Table 3. Study section survey responses. Bold percentages indicate the homework questions where the Study section performed statistically better than the Control section.

On the second survey, we also asked the Study students about resubmission and partial credit. The survey questions are below, and the Study students’ responses are in Table 4.

Q3 The DAVID extension should allow users to resubmit until correct.
Q4 Assignments submitted via the DAVID extension should be graded to allow partial credit.
Q5 Assignments submitted via the DAVID extension should be graded as correct/incorrect (i.e., without partial credit).

Students overwhelmingly agreed (> 95%) that the DAVID extension should allow users to resubmit until correct, and they also agreed that assignments should be graded to allow partial credit, but they disagreed that assignments should be graded as strictly correct or incorrect. In Section 4.3, we discuss the implications of these results for student learning and for optimum design of homework feedback.

Table 4. Survey response percentages from 28 students in the Study section about resubmission and partial credit. Bold shows the highest percentage response for each question.

4.3 The phenomenon of persistence

For RQ3 (instructor benefit), we saw that with the immediate feedback from the DAVID extension, more students in the Study section did eventually solve the homework problems correctly (Figure 3), which benefits an instructor because grading correct submissions is faster and easier than grading incorrect submissions. We have named this benefit of our extension grading triage.

Recall that the focus of our work is about developing a homework feedback server for students, and our work is not about automatic grading. In Figure 4, we see the percentage of students who continued to submit attempts until the extension reported “Correct.” We call this behavioral phenomenon persistence.

Figure 4. Persistence of the Study section until the DAVID extension reported “Correct.”

1In this figure, we omit the occasional student who did not get meaningful feedback because of syntax errors; for example, mismatched parentheses in regular expressions did not display an error message to the student.
Since the DAVID extension does not grade submissions, a student’s homework grade must be manually assigned by an instructor (or a TA). While grading homework which has received feedback from the DAVID extension, an instructor can easily look at the corresponding output from the DAVID extension. For incorrect submissions, the witness string feedback is a valuable resource to help an instructor see the error in the submission. Furthermore, even for correct submissions, this grading triage benefit is useful for regular expressions and CFGs, where manual verification of a correct solution can be complicated.

In fact, this behavior is voluntary persistence since students knew they would get partial credit for incorrect solutions, and yet students still persisted until getting a correct answer from the extension. Figure 5 shows a single student’s persistence with our extension for the DFA homework question in Section 3. We expect that persistence will be even higher if there is no partial credit. In Section 5, we discuss the phenomenon of voluntary persistence as a key insight for intermediate feedback on incorrect submissions (Section 5.2) and for partial credit (Section 5.3).

Figure 5. One student’s 26 unique submissions for a DFA for the homework question: “Draw a DFA that accepts the language of all strings over \{a, b\} that contain at least 2 b’s and do not contain the substring bb.” The thin gray lines are fewer similar submissions, and the gray lines are many similar submissions. The thick, dark gray line is the correct final submission.

5 Discussion

5.1 Hypotheses for our full investigation

For our exploratory and preliminary Fall 2019 investigation, our research questions were deliberately broad so that we could find interesting directions for our future work. Our most interesting result was student persistence: with only the short witness string as feedback, students persisted in submitting attempts until the DAVID extension reported “Correct” (Figure 4). Our preliminary investigation led us to these hypotheses for our full investigation.

H1 In our setting, witness feedback is the appropriate type of feedback.

H2 In our setting, partial credit is not needed.

5.2 The case for witness feedback

Witness feedback is the minimal reasonable feedback. The educational literature calls this minimal intervention, which has been found to promote better learning than more detailed feedback [24]. Minimal reasonable feedback convincingly shows that the submission is wrong, but the feedback does not give any hints for fixing the submission. Creighton et al. say, “If feedback attempts to provide too much guidance, there is nothing left for the student to do or learn” [9]. Similar ideas are also in [13, 18].
Witness feedback, which is very minimal, gives the student a reason why a submission is wrong, but the witness feedback does not tell the student how to correct the mistakes. Thus, witness feedback will not lead a student to the correct solution; instead, the student must think independently. In fact, this sort of minimal witness feedback mimics the feedback that an instructor or a tutor would give to a student seeking help by providing a short witness string showing where the student’s attempt is incorrect. Feedback of a single, short witness string requires the student to actively learn in order to solve the question.

One problem with allowing students to submit as many times as they like is that students may try to random-walk to the correct solution. Because the witness does not give information about how to change the submission, the potential of randomly converging on the correct solution is not an issue. For example, Figure 5 shows a student who clearly has the right idea and is refining the solution based on the minimal feedback of the DAVID extension.

However, when giving more detailed feedback, encouraging “random walks to a solution” can be an issue. In addition, there is a real risk of “over helping” and leading the student to the solution step-by-step in such a way that the student contributes very little (even though the student may not realize this). Finally, more detailed feedback may encourage students to make local fixes that create more and more bloated submissions.

As a related but distinct point, giving more detailed feedback is hard. For example, if there is more than one way to approach a problem, feedback can easily steer students into a direction that does not correlate to the student’s approach. For a simple, standard example, there are two ways to approach designing a CFG for the language \( \{a^ib^k \mid i \neq k\} \). The first one is to cross off \( a \)'s and \( b \)'s until you are left with just \( a \)'s or just \( b \)'s. This corresponds to a CFG with the following rules.

\[
S \rightarrow aSb \mid A \mid B \\
A \rightarrow aA \mid a \\
B \rightarrow bB \mid b
\]

The second one is to view this language as the union of two cases: “\( i < k \)” and “\( i > k \).” This corresponds to a CFG with the following rules.

\[
S \rightarrow A \mid B \\
A \rightarrow aAb \mid aA \mid a \\
B \rightarrow aBb \mid bB \mid b
\]

Telling a student who is following the first approach to “think of the language as a union” is not helpful at best. Of course, an instructor could add both approaches to a feedback system, and for regular expressions, Automata Tutor uses this technique of adding multiple “reasonable” approaches to the grading system. In general, it will be hard for an instructor to come up with all reasonable approaches, and it seems impossible to do this with an automated program.

### 5.3 The case against partial credit

Our investigation focuses on automated feedback for intermediate student submissions. Of course, grading is a form of feedback as well. Automata Tutor uses the current grade as (part of) the feedback on intermediate student submissions. Automated grading is a very interesting topic in its own right, particularly given the large numbers of CS majors.

For incorrect attempts, using partial grade credit as feedback in addition to the witness suffers from the problems described in Section 5.2. If students are chasing more partial credit, then they may be randomly trying to converge on the wrong thing (more points) rather than the right thing (the correct language). In [7], Cain and Babar paraphrase (Skinner 2014), saying, “Attaching marks to an assessment task means that, from the student’s perspective, the task will play a summative role and feedback is not seen as formative.” They continue, “Interestingly, it has been reported that students pay more careful attention to feedback when there are no associated marks [6] or put another way ‘marks’ reduced student attention to formative feedback.” In other words, it is difficult to design a good scoring system that really drives to the correct solution.

Automated partial credit has other problems and drawbacks. One obvious problem is that different instructors may want to assign different amounts of partial credit; although in practice, instructors would
probably accept “reasonable” partial credit (for example, no grade “inversions,” meaning that better solutions should not get less credit).

However, it is hard if not impossible to automatically assign reasonable partial credit. For example, in Automata Tutor, the fraction of points assigned for a CFG is computed as an estimate of \[ |A \cap B| \over |A \cup B| \], where \( A \) is the language generated by the submitted CFG and \( B \) is the correct language. If we consider a simple language like \( \{ a^{2i}b^i \mid i \geq 1 \} \) with the standard solution

\[ S \rightarrow aaSb \mid aab, \]

then the four solutions in Table 5, which are all fairly close, get no credit at all! This is not meant to be negative about Automata Tutor; any language-based partial credit metric will have similar problems.

| CFG          | language                        |
|--------------|---------------------------------|
| \( S \rightarrow aSbb \mid abb \) | \( \{ a^ib^{2i} \mid i \geq 1 \} \) |
| \( S \rightarrow bbSa \mid bba \) | \( \{ b^ia^{2i} \mid i \geq 1 \} \) |
| \( S \rightarrow aSb \mid ab \)  | \( \{ a^{i}b^{i} \mid i \geq 1 \} \) |
| \( S \rightarrow aaSb \mid ab \)  | \( \{ a^{2i+1}b^{i+1} \mid i \geq 0 \} \) |

Table 5. Solutions that are close to the rule \( S \rightarrow aaSb \mid aab \), but do not intersect with that language at all.

Indeed, Automata Tutor [10] for RegExs looks at the distance from a few “sensible” RegExs supplied by the instructor (if the submission is correct, the student always gets full credit), stating that “... This is preferable to comparing the languages, because a small careless mistake in the RE [RegEx] can have a large impact on the language.” We agree (and of course the same argument holds for CFGs as well), but it may be hard for an instructor to list all “sensible” RegExs, particularly for complicated RegExs. For a simple example, if a student writes

\[ a^* + b^* + (a + b)^* \]

instead of

\[ (a + b)^+ \]

(where * is the Kleene star, the infix operator + is the union operator, and the raised + is the Kleene plus), then the student will lose a lot of points, even though the submission is only missing the empty string.

On a final note, students and instructors may feel that not giving partial credit is overly harsh. Indeed, when we asked our students on the survey (Table 4), they were overwhelmingly (> 95%) in favor of the DAVID extension giving partial credit. However, there are other ways to give students partial credit. For example, we can give five CFG questions and ask the students to submit four, which is a stress-decreasing approach that works well in many situations, including exams. With our approach of minimal reasonable feedback, not only will the students have an unlimited number of retries with immediate witness feedback, but also they can seek help from the instructor or tutors.

6 Conclusion

The DAVID extension is successfully providing feedback for DFAs, NFAs, RegExs, CFGs, and PDAs. We have promising initial results: the Study section performed better on the five targeted homework questions than the Control section (Figure 2). The Study students persisted (Figure 4) from which we conjecture that witness feedback is the right feedback.

Our future work will continue the educational focus of RQ1 (student use), RQ2 (student thoughts), and RQ3 (instructor benefit). Since our Fall 2019 investigation was preliminary and our extension targeted < 10% of all homework questions in the course, we did not see (and did not expect to see) knowledge transfer as measured by the students’ performance on related but unfamiliar questions on exams. In our full investigation where students will use our extension on more homework questions, we expect to see knowledge transfer.
We are most excited about our unexpected result of student persistence. We believe that as students persist in solving problems via our extension (RQ1), students will learn the material (RQ2), which benefits not only the students but also their instructors (RQ3). From our finding of student persistence, we will examine our additional hypotheses about witness feedback and partial credit as discussed in Section 5.1:

H1 In our setting, witness feedback is the appropriate type of feedback.
H2 In our setting, partial credit is not needed.

As we prepare for our full investigation, we look forward to studying our preliminary conclusion that minimal witness feedback is both necessary and sufficient for students to learn effectively.

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