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Usability of Error Messages for Introductory Students

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ABSTRACT

Error messages are an important tool programmers use to help find and fix mistakes or issues in their code. When an error message is unhelpful, it can be difficult to find the issue and may impose additional challenges in learning the language and concepts. Error messages are especially critical for introductory programmers in understanding problems with their code. Unfortunately, not all error messages in programming are beneficial for novice programmers. This paper discusses the general usability of error messages for introductory programmers, analyses of error messages in compilers and DrRacket, and two methodologies intended to improve error handling.

Keywords

Novice programmers, usability, error messages, usability studies, compiler errors, syntax errors

1. INTRODUCTION

One of the most important foundations of computer programming is the communication between the system and the user, specifically in the error messages produced by the system. These error messages are especially important for introductory-level computer science students to help them resolve issues in their program because the error messages are the primary source for understanding what is wrong. According to Marceau et al., “[students] lack the experience to decipher complicated or poorly-constructed feedback” [4]. The first rule of good message design is to be sure that the error does not add confusion [2]. Difficulties in understanding error messages can often lead the programmers to frustration because the error message is either too complicated to understand or led them down the wrong path [5], which can sometimes introduce new errors [1].

Various studies have been conducted on modern programming languages’ error messages to evaluate their effectiveness in helping novice programmers. The results have shown

that students struggle with various elements of error messages such as terminology and source highlighting [1, 7]. Several tools and heuristics are being developed to help address issues in error message usability. The goals of these methodologies are to help introductory programmers locate the issue in the program and guide the programmers to a solution. The purpose of this paper is to discuss analyses of error message design and its usability for introductory students in the scope of a class (meaning students’ interactions with programming in a lab setting and at home), and how these developed methodologies help improve the user experience with error messages.

This paper is divided into four sections. In Section 2 we provide background on usability studies, dynamic and static typing, compiler and runtime errors, and an overview of languages and tools used. In Section 3 we focus on analyses of the usability of error messages in development environments and compiler messages for introductory students and how those analyses were performed. In Section 4 we examine Marceau et al.’s recommendations for error message design [5] and then we explore Denny et al.’s syntax error enhancement tool [1].

2. BACKGROUND

In order to discuss the analyses of error messages, we need to understand several concepts related to error types and usability. These concepts include compiler errors, syntax errors, runtime errors, usability studies, and Human-Computer Interaction. We also introduce dynamically and statically typed languages and their differences. We then discuss the programming languages and tools used in the analysis of the error messages. We will focus on the Racket, C++, and Java programming languages and the integrated development environment (IDE) DrRacket.

2.1 Human-computer interaction and methods of usability analysis

The study of Human-Computer Interaction, or HCI, is focused on how computer technology is used, specifically on the interfaces between the user and the programs on the computer. As Traver notes, “HCI is a discipline that aims to provide user interfaces that make working with a computer a more productive, effective, and enjoyable task” [7]. Much of the research presented in this paper is viewed from an HCI perspective and emphasizes usability.

In order to analyze these messages from an HCI perspective and attain qualitative and quantitative information about their usability, a case study may be performed. A

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case study is a research method that closely studies a group of participants (in this paper, the participants are introductory students in the scope of the class) and collects data about participants interactions by observations and interviews. Many of the studies analyzed in this paper are using a case study design. Using the data obtained from these studies a t-test may be performed, which is a statistical examination of two data sets and finds if they are significantly different from each other. The significance in a t-test is determined by the calculated probability, or the p-value. The p-value is the estimated probability that there is no significant difference in the data sets. In this paper, a p-value < 0.05 will be considered significant.

2.2 Compiler and runtime errors

When writing code, a programmer may receive various error messages during different phases of the program, runtime and compile time. A compiler is a program that converts source code written in a programming language to a lower-level language understood by a processor or interpreter so that instructions can be executed. A compilation error is returned when the compiler fails to compile a piece of program source code. A program will not run if there is a compilation error because the compiler will not be able to create executable code to run if there are errors the compiler finds.

We also discuss several examples of syntax errors in this paper. A syntax error is a type of compilation error that occurs when the code does not conform to the syntactical order expected by the parser. The parser is a program (usually part of a compiler) that receives input as source code and builds it into a structural representation of the input while checking for correct syntax of the input. As Kummerfeld and Kay note, “The usability of compiler errors is important because syntax error correction is the first step in the debugging process. It is not possible to continue program development until the code compiles. This means it is a crucial part of the error correction process.” [3]

Below is an example of a compiler error in Java. Here, the programmer is defining `seven` to be `2 + 5`, but forgot to close the parenthesis. The compiler caught the syntax error, so the program did not execute.

```
int seven = (2 + 5;
```

```
error: ')' expected
```

A runtime error is an error detected when the program has successfully compiled, but fails at the execution time. Runtime errors often indicate problems in the logic of the program, such as running out of memory, and can be harder to find and debug. Below is an example of a runtime error in Java. Here, the user wanted to print out a part of the string, “hello” but had the wrong bounds in the substring command (which returns a substring of a string from the start of the index up to but not including the end of the index). The error is telling the programmer that the wrong bounds are given and are out of the range of the string “hello”. The programmer should have given the bounds (3,5) in order for the program to successfully execute.

```
String string = "hello";
System.out.print(string.substring(3,6));
```

```
java.lang.StringIndexOutOfBoundsException:
String index out of range: 6
```

2.3 Statically and dynamically typed

While we do not mention these concepts in any study, it is important to note how some languages differ in error handling. In statically typed languages, type checking is done at compile-time and objects are bound to types. This means that when programming in statically typed languages, a programmer will need to pay attention to how a variable’s type is cast. However, statically typed languages provide benefits such as earlier detection of programming mistakes.

A dynamically typed language means a type is interpreted at runtime rather than compile time and variables in the language are not bound to types. Since the runtime system of a dynamically typed language deduces type and type conversions, a programmer does not have to worry about type declaration while writing code.

As dynamically and statically typed languages differ in how types are handled, something can be legal in dynamically typed and illegal in statically typed language. Consider the following example:

```
personName = "Francis"
personName = 7
```

This sequence of statements is illegal in a statically typed language since we are binding a string to `personName`, then an integer to `personName`. This statement would then throw an error during compile time. This is a legal statement in a dynamically typed language, however, since variables do not have types in dynamic languages. Note that this statement would not work in a purely function language, or a functional language that does not allow side effects, as you can not change the value of a variable.

2.4 Overview of programming languages and tools analyzed

In section 3, we discuss a study performed by Marceau et al. that analyzes the error messages in the DrRacket integrated development environment [4]. An integrated development environment, or IDE, is an application that has packaged several programs typically consisting of a text editor, compiler, and various debugging tools. An IDE is important for introductory programming classes because it offers useful error reporting not seen in the language and can help a student debug their programs more easily. For example, an IDE may be able to highlight the offending line of code when the program fails or display custom error messages.

Racket is a member of the Lisp family of programming languages designed for programmers of various levels and is especially useful for introductory-level programmers. Racket is a functional language, which means it uses a programming style of building elements of programs while retaining immutable data structures and without directly manipulating memory or changing state. Functional languages generally work well in teaching programming concepts to students since functional approaches emphasize core computer science concepts such as recursion. Racket is a dynamically typed language, so the type errors are handled at runtime.

An IDE commonly used in first computer science courses is DrRacket. DrRacket is an IDE meant for writing programs in Racket and is commonly geared toward introductory students. DrRacket offers libraries for students to program at various levels and several debugging features such as text highlighting and custom error messages.

Lab Number	#1			#2			#3			#4			#5			#6		
	%error	%bad	#bad	%error	%bad	#bad	%error	%bad	#bad	%error	%bad	#bad	%error	%bad	#bad	%error	%bad	#bad
arg. count	5%	48%	0.22	17%	27%	0.74	14%	17%	0.33	13%	20%	0.24	35%	21%	0.74	12%	31%	0.36
parens matching	28%	24%	0.58	12%	14%	0.27	17%	0%	0.00	14%	0%	0.00	13%	0%	0.00	10%	15%	0.15
runtime cond	3%	0%	0.00	3%	100%	0.49	4%	20%	0.12	6%	72%	0.40	8%	78%	0.62	1%	100%	0.06
runtime type	2%	100%	0.15	8%	73%	0.91	16%	40%	0.93	8%	22%	0.17	6%	44%	0.26	3%	38%	0.13
syntax cond	14%	51%	0.59	4%	50%	0.31	6%	26%	0.24	10%	28%	0.25	9%	20%	0.17	11%	11%	0.12
syntax define	16%	50%	0.68	14%	50%	1.14	6%	15%	0.14	7%	24%	0.14	2%	17%	0.03	3%	38%	0.10
syntax func call	14%	64%	0.74	14%	17%	0.37	12%	14%	0.26	23%	27%	0.55	4%	29%	0.12	13%	38%	0.48
syntax struct	0%	0%	0.00	8%	32%	0.43	5%	92%	0.73	0%	0%	0.00	1%	0%	0.00	0%	0%	0.00
unbound id.	16%	16%	0.21	13%	40%	0.85	16%	14%	0.32	16%	0%	0.00	20%	7%	0.14	34%	13%	0.44

%error: Percentage of error messages during lab of the given category of errors
KEY: %bad: Percentage of error messages that were poorly responded to
#bad: Estimate of the number of errors in the category that each student responded poorly to

Figure 1: Results from DrRacket study

We use C++ and Java in several examples throughout this paper. C++ and Java are widely used programming languages not designed for introductory programming. However, C++ and Java are often taught in a first computer science course. C++ and Java are both imperative languages. Imperative programming is a programming style that, as opposed to functional programming, uses a sequence of statements to build a computation using memory manipulation and changing the state of objects. These languages fall in the category of object-oriented programming, or OOP, which is a method of programming based on class hierarchy and is based around creating objects, which are data structures that contain a set of routines called methods. Java and C++ are statically typed languages, so a programmer will receive type errors during compile time.

3. ANALYSES

In this section, we discuss two different studies performed on the usability of error messages. The first analysis will discuss how well the error messages in Racket and DrRacket help introductory students debug their programs. The second analysis will discuss the effectiveness of compiler error messages in the C++ programming language.

3.1 Analysis of error messages in Racket and DrRacket

Marceau, Fisler, and Krishnamurthi helped design DrRacket's error messages so that they can be more helpful to beginner programmers. However, Marceau et al. still noticed students struggling with debugging and understanding the error messages, so the authors were interested in seeing how their students responded to these error messages and identifying specific error messages that performed poorly [5]. In the spring of 2010, Marceau, Fisler, and Krishnamurthi ran a case study on error messages in DrRacket. The study involved configuring DrRacket to save a copy of each program a student tried to run and the error message the student received through six 50 minute once-per-week lab ses-

sions [4]. The authors were interested in which error messages are effective and how well DrRacket's text highlighting can help a student find the error in their program.

In order to measure effectiveness, the authors developed a rubric to determine whether the student made a reasonable edit in response to the error message [4]. The rubric was meant to distinguish whether an error message would fail or succeed. They determined that an error message is effective if a student can read it, understand it, and use that information to figure out how to resolve the issue.

The following Racket code (modified from [4]) shows an example of an error message in DrRacket that Marceau et al. found as not effective for helping a student debug their program.

```
1 (define (label-near? name bias word1 word2)
2   (cond
3     (and (cond [(string=? name word1) "Name Located"]
4               [(string=? bias word2) "Bias Located"])
5         (cond [(string=? name word2) "Name Located"]
6               [(string=? bias word2) "Bias Located"])
7     "Mark")
8 ))
```

-> and: found a use of 'and' that does not follow an open parenthesis

The message is contradicting the code as `and` does follow an open parenthesis, but the parser thinks `and` does not have an open parenthesis before it and claims that there needs to be an open parenthesis. Unfortunately, to understand it, the programmer must realize that parser attributed the open parenthesis before the `and` to the `cond`. The actual underlying issue is a misuse of `and` on line 3 with the `cond` on line 2, but trying to decipher that issue from the provided error message may be confusing to an introductory programmer.

Figure 1 shows the results (modified from [4]) of the study by Marceau et al. They grouped messages into the nine

most common error categories in the results gathered from the study, as seen on the left side of the table. The results of their data analysis are seen in figure 1. The values of interest are the *#bad* values enclosed in a box and the highest *%bad* values.

The data the authors gathered helped identify errors students found challenging. The authors found that students have difficulties with certain errors at different points in the course, as expected since curricular aspects of the labs affect error patterns. Many of the errors students struggled with were consistent with the progression of the course material, such as difficulties with syntax errors in the first lab since students are still beginning to learn the language syntax.

However, the data is not entirely a representation of students' conceptual difficulties with the course, as Marceau et al. found. The error message a student receives, according to Marceau et al., "is often not a direct indicator of the underlying error" [4]. For example, in lab number six, numerous `unbound-id` errors or unbound identifiers occurred. An `unbound-id` is when the compiler finds a variable that was not defined. However, the authors found that the actual problem students had was with improperly using field reference operators. The actual errors the students should have received was not given. This suggests that there are some issues in the effectiveness of the error messages.

3.2 Analysis of compiler messages in C++

Compiler error messages are often cryptic and difficult to understand for many programmers, especially for students who are new to programming. Unfortunately, as Traver notes, "most related disciplines, including compiler technology, have not paid much attention to this important aspect that affects programmers significantly, apparently because it is felt that programmers should adapt to compilers" [7]. Traver proposed to research compiler error message usability from a strictly HCI viewpoint. Thus, the discussion below does not consider technical restraints, but rather how usable compiler error messages are for helping introductory programmers resolve issues with their program.

In the Fall semester of 2002 at Jaume I University, Traver conducted a case study on students' work with compiler error messages in C++ in an introductory computer science course. The motivation of this study is to gain insight on which errors students are struggling with in the course. Traver gathered data from the students' interactions with C++ throughout the semester and wrote up analyses of the error messages received in 5 separate parts.

- *The error message* received from the compiler
- *The source code* that caused the original error
- *The diagnostic* of why the error occurred
- *An alternative error message* that may help lead more directly to the true diagnosis of the issue.
- *A comment* about why the error message is not helpful

Below is an example of an error message in C++ analyzed in the study along with the source code that caused the error [7] (in the interest of space, we have not included the other parts of the analysis):

Offending Code:

```
SavingAccount::SavingAccount(){
    float SavingAccount::getInterestRate() {
        return rate;
    }
}
```

Error Message:

```
In method 'SavingAccount::SavingAccount()':
declaration of
'float SavingAccount::getInterestRate()'
outside of class is not definition
```

Alternative error message:

```
A function declaration inside a function body is
not possible. Did you forget '}' to close the
body of the previous function definition?
```

In this case, the programmer forgot to close the curly bracket for the body of the method, so a syntax error would be thrown. Although this is a relatively easy error to identify, when a program has multiple sets of braces, it can be easy to miss some braces along the way. Traver found that this error message might not be suitable for every programmer because it does not provide any noticeable clues that the error is a missing bracket. The author of the study noted that this type of error message should "convey a clear message that the programmer can quickly understand and that is useful for fixing the error", but the error message given to the user would not accomplish this for students who are still new to programming [7].

No quantitative data was gathered in this case study. However, Traver found from this research (and previous research) that the usability of compiler errors is a well-known issue and they do not always properly indicate the cause of an error to the programmer. However, the author hopes that approaches will be considered to address the issues in compiler error message design.

4. METHODOLOGIES

In this section, we discuss three methodologies and tools proposed to improve the usability of error messages. The first methodology we discuss is a set of recommendations for improving the usability of error messages in IDEs, specifically in DrRacket. For the second approach, we discuss an attempt to enhance syntax error messages in Java and how well these modified error messages improve over the original.

4.1 Recommendations for error messages in IDEs

After Marceau et al. analyzed their data from the case study (as detailed in section 3.1), they found that students struggled to respond to error messages. Through their research, they were able to develop a list of proposed methods of improving error messages, specifically for DrRacket, "but they should apply just as well in any other programming language used for teaching, including those with graphical syntaxes" [5]. They wanted to maintain two integral principles in error message design for their proposals:

- Error messages should not propose solutions as these solutions can lead students down the wrong path and can not cover every scenario a student may encounter.
- Error messages should not prompt students toward incorrect edits. Source highlighting can cause issues and when not correctly implemented can cause more errors.

```

;; Produces a true or false answer depending on if the label
appears within three words of the name
(define (label-near? label name word-one word-two word-three)
  (cond [(and (string=? "name" "word-one")
              (string=? "label" "word-two") "true")
         (and (string=? "name" "word-one")
              (string=? "label" "word-three") "true")]
        [(and (string=? "name" "word-two")
              (string=? "label" "word-one") "true")
         (and (string=? "name" "word-two")
              (string=? "label" "word-three") "true")]
        [else "false"]])
Welcome to DrScheme, version 4.2.2 [3m].
Language: Beginning Student, memory limit 128 megabytes.
cond expected a clause with a question and answer, but found a
with only one part
>

```

Figure 2: Example of color coded message

The first recommendation is simplifying vocabulary used in error messages. The authors found that while DrRacket is “accurate and consistent in its use of technical vocabulary”, “some of its terms are overly precise relative to terms that students already know” [5]. For example, the term *identifier* is used in DrRacket error messages. However, the term *variable* is a term students are more likely to be familiar with [5]. Marceau et al. also argue that non-simplified vocabulary is appropriate for an introductory computer science course, and thus decided simpler vocabulary may be better suited in beginner levels of DrRacket.

Marceau et al. also wanted error messages to be explicit about inconsistencies, specifically with function or constructor usage. They found that DrRacket highlights the source expression where the variable or constructor is called, but not the definition. The highlighting suggests edits should be made in the expression, but the error can also occur within the definition of the variable or constructor, which does not get highlighted when an error like this occurs. While an IDE may not be able to identify whether a definition or its usage is the issue, it should not steer students in the wrong direction [5].

The authors then propose that error messages should highlight every reference and its corresponding code with a distinct color in order to help students match message terms to code fragments. They believe this should help resolve ambiguity about highlighting and ambiguous references (an example of an ambiguous reference is highlighted in blue in figure 2). Figure 2 shows an example of a color coded error message, modified from [5]. The red highlights the definition, the green highlights the clause, and the blue highlights the reference.

The last three recommendations are design suggestions for introductory courses that use DrRacket to help students with error messages, so in the interest of space, we will not be covering them. As of the writing of the recommendations, the authors had not implemented these suggestions.

4.2 Syntax error message enhancement and results

Language syntax is often one of the first difficulties a student experiences when learning programming [1]. Because of this, introductory students may see many syntax errors while learning the syntax of a language. Denny et al. found that “syntax errors can be a significant barrier to student success” and thus propose to improve the existing error mes-

sages that deal with syntactical issues in a Java-based development environment for introductory programmers [1].

Denny et al. decided to implement the enhanced error message system through CodeWrite, a web-based tool for students to complete various Java exercises. Code is written directly in the browser and the students need to write only the body of a method, as the header of the method is always provided. In order to create the enhanced feedback, the authors began by examining student submissions in CodeWrite and found the errors that had ambiguous compiler error messages. They achieved this by performing an analysis of the code and used regular expressions to match commonly occurring patterns of code that caused errors and extracting the line containing the error. Denny et al. then categorized the error messages according to error type by building a program called a recognizer that would parse source code and raw compiler error messages. Once the original error is extracted, the authors highlight the line and insert their enhanced error message. The enhanced error messages contain the line number of the offending line of code and a detailed explanation of the error. They also show an example of incorrect code and correct code of the corresponding syntax error with an explanation. Figure 3 shows an example of an enhanced error message, modified from [1] for readability. This message was produced from the following erroneous code fragment:

```

if (score < 0) || (score > 100)
Syntax error on token "||", if expected

```

This statement is syntactically incorrect because the `if` statement is missing surrounding parenthesis. The corrected statement is in the “Correct Code” block in figure 3.

The authors were interested in helping students improve their debugging skills [1]. After creating these enhanced error messages, the authors wanted to examine whether they had an impact on:

- The number of non-compiling submissions made while attempting an exercise.
- The total number of non-compiling submissions out of the total number of submissions.
- The number of attempts needed to resolve the most common syntax errors students typically encounter.

Denny et al. had students in a summer course randomly put in a control group that received the original error message or the intervention that received their new error messages and submit their code in CodeWrite, where the authors could compare the submissions of the same exercise of each group. Unfortunately, after testing whether their enhanced error messages had an impact on the above items, they found that their new feedback had no significant differences between the groups.

Denny et al. measured the effectiveness by comparing the attempts of students submissions, specifically looking for syntax errors. Denny et al. ran a t-test to see if their program would reduce the number of non-compiling submissions while attempting an exercise. They found for each problem a p-value > 0.05 , which means there were no significant differences between the groups. Denny et al. found similar results for whether their program would reduce the total number of non-compiling submissions. The t-test gave

It appears that there is an error in the condition below:

```
if (score < 0) || (score > 100)
```

Remember that the condition for an `if` statement must be surrounded by opening and closing parentheses:

```
if (condition)
```

This is true even if the condition consists of more than one boolean expression combined with logical operators like `&&` or `||`.

	Incorrect Code	Correct Code	Explanation
Example	<pre>int a = 6; double x = 9.4; if (x > 10) && (a == 0) { return true; }</pre>	<pre>int a = 6; double x = 9.4; if ((x > 10) && (a == 0)) { return true; }</pre>	<p>The condition of an <code>if</code> statement needs to be enclosed in parentheses. Even if the condition is made up of the combination of other conditions, the entire thing still needs to be wrapped in parentheses</p>

Figure 3: Example of an enhanced syntax error message

a p-value = 0.9471, showing non-significance. Finally, they tested whether their program reduced the number of attempts needed to resolve the most common types of errors (variable undefined, type error, missing semicolon). Again, they found for each case, the p-value was large and thus their program had no significant effect.

Denny et al. suggested numerous possibilities for why their enhanced feedback system was not effective on helping introductory students improve their debugging skills. For example, they thought that students did not put more attention into the additional information the authors placed in the error messages. The authors hope to apply additional research regarding their enhanced errors to further examine why they were not any more helpful than the original messages [1].

5. CONCLUSIONS AND FUTURE WORK

In this paper, we discussed studies conducted on error messages in DrRacket and compiler error messages and how well introductory students can use them for debugging. The research on DrRacket error messages found that students have difficulties with understanding error messages on unfamiliar concepts. However, some errors in DrRacket incorrectly report the problem to the students and thus there is room for improvement. The analysis on compiler error messages deduced that compiler messages are generally unusable for introductory programmers. However, there is research being done on error message usability and methods attempting to improve them are being developed.

We discussed a set of recommendations on designing error messages toward introductory students. We also discussed a system of enhanced error messages for syntactical issues, but was ineffective at being more helpful than the original messages. Marceau et al. created a series of recommendations that have been implemented in How to Design Programs libraries for DrRacket. How to Design Programs, or HtDP, is a library that offers the recommendations for error messages from Marceau et al.'s research [6].

Traver noted in his research on compiler errors that some approaches have been made in an attempt to enable these messages to better communicate the problem to the programmer, such as Denny et al.'s syntax error enhancement, but "the problem is far from being properly solved" [7]. User-friendly error messages are important to ease new students into learning a programming language. Thus, making sure the messages offer beginner-friendly features, such as famil-

iar vocabulary or showing hints, is imperative in error message design.

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