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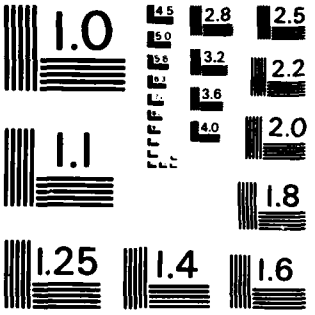

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W. Lewis Johnson, Stephen Draper
and Elliot Soloway

YaleU/CSD/RR #284

August 1983

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In order to build a computer-based programming tutor for novice programmers, ~~we needed~~ to first classify the bugs we found in their programs on the basis of type and frequency. However, the enterprise of classification turns out to be a complicated process. While one may want to be able to simply use features in the program itself as the basis for the classification, it turns out that such a scheme will result in classifications that seem to miss the mark, i.e., the classifications will not tell you what misconception the programmer was operating under which caused the bug. To remedy this situation ~~we~~ argue that the programming plans that the programmer intended to use should be the basis for a classification scheme. Thus, a bug classification must take the programmer directly into account. In this paper, ~~we~~ compare several different methods of bug classification currently being used in software engineering projects, and show their weaknesses; while ~~our~~ method of using intended programming plans is not without problems, ~~we argue~~ that it presents a better alternative than the other methods currently being employed.

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Classifying Bugs is a Tricky Business

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1. Context: Motivation and Goals

About 2 years ago we decided to build a computer-based programming tutor to help students learn to program in Pascal; we wanted the system to identify the *non-syntactic* bugs in a student's program and tutor the student with respect to the misconceptions that might have given rise to the bugs. The emphasis was on the system understanding what the student did and did not understand; we felt that simply telling the student that there was a bug in line 14 was not sufficient --- since oftentimes the bug in line 14 was really caused by a whole series of conceptual errors that could not be localized to a specific line in the program. However, in order to design the system we needed to know what bugs students did make in their programs and what misconceptions they typically labored under. On the basis of bug types found in a number of pencil-and-paper studies with student programmers (novices, intermediates, and advanced) [9, 10], we built and classroom tested a first version of such a programming tutor [11]. In the process of testing that system we instrumented the operating system on a CYBER 175 to automatically collect a copy of each syntactically correct program the student programmers attempted to execute while sitting at the terminal; we call this form of data "on-line protocols". We collected such protocols on 204 students for an entire semester (7 programming assignments). We have systematically analyzed only a small portion of these data: the basis for this paper is the hand analysis of the first syntactically correct program that students generated for their first looping assignment,[1] i.e., 204 programs.

The story we tell in this paper deals with our experiences in analyzing these 204 on-line protocols. In particular, we will describe the observations we made in trying to build a bug classification scheme; the actual details of what bugs we found, their frequency, etc. can be found in [5]. The key observation is the following: while one might think that building a classification scheme for the bugs would be straightforward, it turns out not to be so simple; in fact, we will argue that:

> *Bugs cannot be uniquely described on the basis of features of the buggy program alone; one must also take the programmer's intentions and knowledge state into account.*

2. A Simplified Example

Consider the problem statement in Figure 1, which is a simplified version of the first looping problem that the students in our study had to solve in Pascal. From a novice's perspective the difficult part of this problem is making sure that the negative inputs are filtered out before they are processed. There are two common approaches to solving this type of problem in an Algol-like language such as Pascal. In Figure 2 we depict a solution in which a negative input causes

---

[1] This problem is given in Figure 8, which will be discussed in section 4.

execution of one branch of a conditional, while a non-negative input causes execution of the major computation of the loop. We call this type of structure a ***Skip-guard Plan***:[2] a conditional statement is used to guard the main computation from illegal values. Notice that one pass through the loop will be made for each input value. The second approach is given in Figure 3; here an embedded loop filters out the illegal values. Notice that one pass through the outside loop will be made for each — and only each — legal value. We call the nested loop structure an ***Embedded Filter Loop Plan***.

Write a program that reads in integers, that represent the daily rainfall in the New Haven area, and computes the average daily rainfall for the input values. If the input is a negative number, do not count this value in the average, and prompt the user to input another, legal value. Stop reading when 99999 is input; this is a sentinel value and should not be used in the average calculation.

Figure 1: Simplified Looping Problem

```
....
....
READ(RAINFALL)
WHILE RAINFALL <> 99999 DO
    BEGIN
       IF RAINFALL < 0
          THEN
           WRITELN('BAD INPUT, TRY AGAIN')
          ELSE
           BEGIN
             TOTAL := TOTAL + RAINFALL;
             DAYS  := DAYS  + 1;
           END;
       READ(RAINFALL);

    END;
....
....
```

Figure 2: Using a ***Skip-Guard Plan***

Now consider the buggy program in Figure 4. The problem with this program is that if the user first types a negative input, and then types the sentinel value 99999, this value will — incorrectly — be processed as a legitimate value. A number of questions come to mind:

1. How should we classify this bug?
2. What piece of code is to blame?
3. What mental error on the student's part might have caused this bug?

---

[2]See [8, 3, 9]for a more complete discussion of programming plans.

```
....
....
READ(RAINFALL)
WHILE RAINFALL <> 99999 DO
    BEGIN
       WHILE RAINFALL < 0 DO
           BEGIN
              WRITELN('BAD INPUT, TRY AGAIN');
              READ(RAINFALL)
           END;
       IF RAINFALL <> 99999 THEN
           BEGIN
              TOTAL := TOTAL + RAINFALL;
              DAYS  := DAYS  + 1;
              READ(RAINFALL)
           END;
    END;
....
....
```

Figure 3: Using an *Embedded Filter Loop Plan*

4. What piece of code should we change to make the program correct?

In order to answer these questions, however, we need to answer another one first:

> What programming approach was the user trying to implement? That is, did the student intend to implement the ***skip-guard plan*** or did he try to implement the ***embedded filter loop plan***?

Answers to the first 4 questions will be different depending on how we answer this last question.

```
....
....
READ(RAINFALL)
WHILE RAINFALL <> 99999 DO
    BEGIN
       WHILE RAINFALL < 0 DO
           BEGIN
              WRITELN('BAD INPUT, TRY AGAIN');
              READ(RAINFALL)
           END;
       TOTAL := TOTAL + RAINFALL;
       DAYS  := DAYS  + 1;
       READ(RAINFALL)
    END;
....
....
```

Figure 4: Sample Buggy Program

We will continue this example by presenting first an argument that supports the choice of the ***skip-guard plan***, and then an argument that supports the choice of the ***embedded filter loop plan***; we will then describe a basis for making a choice between the two competing

positions. Consider, then, Figure 5 in which we depict the buggy program again, plus a generalized, template version of the ***skip-guard plan***. We can describe the buggy program in terms of a difference description between the it and the generalized plan. As shown in Figure 5, there are 3 differences:

1. need an IF instead of a WHILE inside the loop,
2. have an extra read inside the loop,
3. will always execute the processing steps since there is no way to skip around the processing.

The first difference is a plausible bug for a novice to make; in our examination of novice programs we have seen novices confuse IF and WHILE: students sometimes construct a loop with simply an IF, and sometimes they use just the test part of the WHILE statement[3] [2, 6]. Similarly, the second difference is also plausible for novices; again, we have found that novices often add bits of spurious code, oftentimes attempting to mimic the redundancy they often use in formulating plans and actions in the real world. Finally, if we assume that the programmer really meant to simply test RAINFALL, then all that is missing is an ELSE to cause the skip around the computation; novices notoriously have trouble with the ELSE parts of conditionals. Thus, the buggy code in Figure 5 is not that different from the ***skip-guard plan***; ***when considering differences from only this plan*** it is entirely conceivable that the novice programmer was trying to implement this plan in his code.

Now consider Figure 6 in which we again depict the buggy program. This time, however, we show differences between it and a generalized, template version of an ***embedded filter loop plan***. Notice that the code matches the plan well; the only bug is a missing guard before the code that processes the input: the running total update and the counter update must be protected from including a sentinel value in the computation.

The analysis in Figures 5 and 6 would lead to different answers to the first 4 questions above. For example, if we believe that the analysis in Figure 5 is correct, we might say the following to the student:[4]

> It seems that you are having some trouble with conditional statements. For example, did you realize that there exists a statement called IF that allows you to test ....
>
> To correct your program, you might want to add an ELSE clause...

---

[3]While this may seem strange to us as expert programmers, if we take a moment to reflect, we can see that using WHILE for a conditional and a loop, and IF for only the conditional part is somewhat arbitrary, given their meanings in English.

[4]We do not want to argue about the best pedagogical strategy for interacting with the student; that in itself is a very difficult question. The particular response shown is simply meant to illustrate one type of response to this situation.

```
....
....
READ(RAINFALL)
WHILE RAINFALL <> 99999 DO
    BEGIN
      WHILE RAINFALL < 0 DO
          BEGIN
             WRITELN('BAD INPUT, TRY AGAIN');
             READ(RAINFALL)
          END;
      TOTAL := TOTAL + RAINFALL;
      DAYS  := DAYS  + 1;
      READ(RAINFALL)
    END;
....
....
```

Skip-Guard Plan

```
IF x < min
   THEN
      BEGIN
         print error message
      END
   ELSE
      BEGIN
         process input
      END
```

BUG DESCRIPTION:

1. need an IF instead of a WHILE
2. have an extra READ in inner loop
3. missing ELSE; processing of input will never be skipped

Figure 5: Bug Description Assuming ***Skip-Guard Plan***

Moreover, we would classify the bugs as an (1) incorrect statement type, (2) spurious read, (3) missing ELSE. On the other hand, if we believe that the analysis in Figure 6 is correct, then we might say something like the following to the student:

> You should notice if the sentinel value follows the input of a negative value that your program will compute an incorrect average. ....

The bug type then might be a missing guard (conditional) plan.

By this time the reader's intuition is surely saying that the correct analysis of the buggy program in Figure 4 is that the programmer intended to implement an ***embedded filter loop plan***. The bug counts (3 for the ***skip-guard plan*** and 1 for the ***embedded filter loop plan***) provide quantitative *support* for this decision. However, we feel that the key in the decision process --- and the basis for our intuition --- is our *understanding* of the student's program provided by the plan analysis in Figure 5: thus, the bug categorization and bug count *follow* from our understanding of the program --- and not the other way around. We purposely choose an example over which there would be little controversy. However, the point was (1) to show how much reasoning we often do about programs implicitly, and (2) to show how different bug categorization and bug counts could be as a function of choice of intended underlying plan.

While the above decision was relatively clear, let us perturb the buggy code a bit further and

```
....
....
READ(RAINFALL)
WHILE RAINFALL <> 99999 DO
    BEGIN
       WHILE RAINFALL < 0 DO
           BEGIN
              WRITELN('BAD INPUT, TRY AGAIN');
              READ(RAINFALL)
           END;
       TOTAL := TOTAL + RAINFALL;
       DAYS  := DAYS  + 1;
       READ(RAINFALL)
    END;
....
....
```

Embedded Filter Loop Plan

```
WHILE x < min DO
   BEGIN
      print error message
      READ x
   END
sentinel guard plan
   process input
```

BUG DESCRIPTION:

1. missing conditional (guard) on processing the input

Figure 6: Bug Description Assuming *Embedded Filter Loop Plan*

see how murky these type of decisions can — and do — become. In Figure 7 we show three buggy program fragments; let us compare the bug categorization and bug counts using the two alternative plans for each of the programs.

- Figure 7a
  - Using the ***embedded filter loop plan*** we get the following bug differences:
    1. the WHILE and IF keywords have been interchanged
    2. there is a missing read for a new value
    3. there is a missing guard on the subsequent input processing
  - Using the ***skip-guard plan*** we get the following bug differences:
    1. missing ELSE on the internal IF
- Figure 7b
  - Using the ***embedded filter loop plan*** we get the following bug differences:
    1. the WHILE and IF keywords have been interchanged
    2. there is a missing guard on the subsequent input processing
  - Using the ***skip-guard plan*** we get the following bug differences:
    1. spurious READ
    2. missing ELSE on the internal IF

- Figure 7c
  - ▸ Using the ***embedded filter loop plan*** we get the following bug differences:
    1. missing read for a new value
    2. there is a missing guard on the subsequent input processing
  - ▸ Using the ***skip-guard plan*** we get the following bug differences:
    1. the WHILE and IF keywords have been interchanged
    2. missing ELSE on the internal IF

We would argue that the programmer of the code in Figure 7a intended to encode a ***skip-guard plan***: again, the bug counts (3 for the ***embedded filter loop plan*** and 1 for the ***skip-guard plan***) support the intuition that it is more plausible that the programmer simply left out an ELSE, as opposed to swapping keywords, etc. However, the code in Figures 7b and c are not so easily analyzed: the bug counts are the same and the plausibility of the bug types are reasonably similar. In order to make a reasoned decision we need to bring *other* evidence from the program to bear. For example, in Figure 7b the programmer used a WHILE loop to correctly implement the outer loop; this is some evidence that he understands how and when to use this construct. Thus, we might be confident that the programmer really meant IF in the program in Figure 7b. On the other hand, the inclusion of the spurious READ is unsettling. However, the program in Figure 7c is certainly the most problematic: the bug counts are the same, the plausibility of the bugs are similar, and the additional outside information is equivocal. The moral of this program is that it can be exceedingly difficult to make decisions about plans --- and bugs --- by *simply looking at the code.*

The point of these latter examples is to illustrate how quickly the decision about what the programmer intended gets murky, and how additional information outside the buggy area needs to be brought to bear. We see again that for the programs in Figure 7 the bug categorization and bug frequencies change depending on what decision is made about the programmer's intention.

Finally, the fact that the programs we have shown are *novices'* programs is really irrelevant to the point in question: the problem is that the intention of the programmer effects the bug categorization and the bug count. Quite reasonably, we would not expect a professional programmer to mistake an IF for a WHILE. The observation that we would not expect this particular confusion would in fact aid us in inferring the intention --- it would not, we believe, simply make the problem go away. In fact, we might well see buggy code such as Figure 4, Figure 7 from a professional programmer.

a

```
READ(RAINFALL)
WHILE RAINFALL <> 99999 DO
    BEGIN
       IF RAINFALL < 0 THEN
             WRITELN('BAD INPUT  TRY AGAIN').
       TOTAL  = TOTAL + RAINFALL
       DAYS   = DAYS  + 1
       READ(RAINFALL)
    END
```

b

```
READ(RAINFALL)
WHILE RAINFALL <> 99999 DO
    BEGIN
       IF RAINFALL < 0 THEN
          BEGIN
             WRITELN('BAD INPUT  TRY AGAIN')
             READ(RAINFALL).
          END.
       TOTAL  = TOTAL + RAINFALL.
       DAYS   = DAYS  + 1
       READ(RAINFALL)
    END
```

c

```
READ(RAINFALL)
WHILE RAINFALL <> 99999 DO
    BEGIN
       WHILE RAINFALL < 0 DO
             WRITELN('BAD INPUT  TRY AGAIN').
       TOTAL  = TOTAL + RAINFALL.
       DAYS   = DAYS  + 1.
       READ(RAINFALL)
    END
```

Figure 7: Clouding the Waters: Additional Buggy Programs

3. Methods for Specifying the Intention of a Program

In the above section, the basis for describing bugs was the difference between a program and the programming plans that specified a correct program. There are other methods of specifying the intention of a program:

- I/O Behavior
- Programming Plans
- Corrected Version of the Buggy Program
- Program Description Language (PDL)

In what follows we will examine each of these in turn, and explore their good points and the bad points with respect to using a method as a basis for developing bug difference descriptions.

I/O BEHAVIOR

An I/O specification for the problem in Figure 1 would be quite close to the problem statement itself. The obvious problem with this method is its vagueness with respect to the code: many different code fragments can misbehave in the same manner (e.g., there are many, many ways to generating an infinite loop --- but the I/O result is the same in all cases). One needs to be able to make finer-grain distinctions than are facilitated by a comparison of the code to simply I/O

specifications.

PROGRAMMING PLANS

The major problem with this method is the need to guess what plan the programmer intended to implement. However, once the decision is made, then describing the bug as a difference between the plan and the code is relatively easy. One method of coping with the plan decision problem is interviews with the original programmers; this technique has been used to "validate" change report data in several software monitoring projects (e.g., [12]). Unfortunately, in a class of 200 students writing code at different terminals, interviews with subjects is a bit more difficult.

The major benefit derived from building a bug description using this method is an accurate reporting of the *cause* of the bug. That is, clearly the goal of a bug taxonomy in which one captures bug type and bug frequency is the ability to pinpoint the sources of the bugs: one would like to know which bugs came from misunderstandings of the specifications document and which bugs arose from coding errors, etc. For example, in the previous section if we assumed that the programmer intended to implement a ***skip-guard plan*** then we would say that there were a number of coding level bugs (e.g., WHILE instead of IF, missing ELSE, spurious READ). However, if we assume that the programmer intended to implement an ***embedded filter loop plan***, then the source of the bug may be a problem of specification interpretation: the programmer may not have thought that someone would ever input the sentinel value after inputing an illegal (negative) value. Thus he felt no need to guard subsequent computation. (An interview with the programmer would be particularly useful in this specific case.) Thus, bug categorization *and bug origin* is directly influenced by the choice of underlying plan structure in the buggy program.

CORRECTED VERSION OF THE BUGGY PROGRAM

The typical method of describing a bug is to compare the original buggy program with the corrected version of that program (e.g., [12, 7, 1]). While there is no guessing as to the intention of the original programmer, we see 2 basic problems with this approach:

- *The choice of the particular corrected program used as the measure is relatively arbitrary*. That is, there are few hard guidelines for making changes to code. Thus, different programmerss could well take the same buggy program and correct it in different ways. This would result in two different bug descriptions — an intuitively unsatisfactory situation. Moreover, different bug descriptions could lead to different conclusions as to the origins of the bugs, which, afterall, is the the point of doing the bug categorization in the first place. For example, if the buggy program in Figure 4 were corrected by implementing a ***skip-guard plan***, then the difference between the buggy program and the corrected program would result in a bug description containing 3 coding level bugs. On the other hand, if the program is corrected by putting in aguard around the subsequent computation to protect against a sentinel value, then the bug description would only contain 1 bug, a missing conditional

(guard plan) — which may or may not be a coding level bug (as discussed above). While we might prefer the programmer to make the latter change, there is no way to guarentee this situation.

Interviewing the *original programmer* might shed some light on his intentions — and guide the subsequent bug analysis or even bug correction. However, this additional, programmer-supplied, information goes beyond the corrected program — and approaches a bug description based on *the programmers original plan* While we have some methodological reservations about using interviews collected after the fact,[5] the main issue is that information gotten from the interview is of a different sort than the information gotten from the corrected program — where the former information is much more akin to the programming plans described above.

- *What is actually counted can be quite problematic.* For example, if we correct the buggy program in Figure 7c by adding the missing ELSE, we also need to add a BEGIN-END block around the running total update and the counter update. Should we count this as 1 bug or 2 bugs? It seems unfair to count the BEGIN-END block against the programmer, since this change is required by the "real" change. On the other hand, however, in the next section we will show programs in which the "real" bug *is* a missing BEGIN-END block. Thus, it is not inconceivable that a programmer could add the ELSE in Figure 7c, but forget to put in the now necessary BEGIN-END block. What one counts is a tricky issue.

The upshot of these two problems with categorising and counting bugs based on a corrected version of the program was suggested above: one is less confident of the origins of the bugs, and thus is less confident about percentages of bugs with those origins. Depending on the particular corrected solution and the particular choice of counting scheme, one could paint a picture of a program that contained many more coding level errors, say, than specification-based errors. The worst part of this situation is that we would not have a good way of knowing how right or wrong this analysis was — since we don't know how the bug categories and counts would have turned out if a different corrected version were used as the basis for difference descriptions.

PROGRAM DESCRIPTION LANGUAGE (PDL)

PDL's come in all flavors; some are very close to the code, while others are more high level, and closer to the plan level description. The former PDL would suffer from the same problems as using a corrected version as the standard. The latter type of PDL would suffer from the problems associated with using the programming plans as the standard.

---

[5]The problems with using interview data has received significant attention in psychology. For example, Ericsson and Simon [4] have argued that one can reliably only use verbal information given by the subject *as the subject is doing the task*. They argue that such a concurrent verbal report is effectively an on-line dump from short-term memory. In contrast, a report after the fact could be a story about what the subject thought he was thinking, and that significant distortions can occur in this type of situation. While one might arguably feel that the Ericsson and Simon position is a bit extreme, nonetheless, it seems only prudent to exercise care in interpreting interview data.

4. An Extended Example

Let us now consider an actual example from the on-line protocol data. In Figure 8 we depict the problem the students were trying to solve; in Figure 9 the program on the left is a buggy program generated by a student in our study. If we take a "local view" of the bugs in this program, we can generate a corrected version as shown in Figure 9 (right hand side). Notice that if we do a difference description between the corrected and the buggy versions we can come up with 8 changes:

- The rainyday counter, COUNT1, will be always be updated; in order to correct for the times when a negative rainfall is input, we need to decrement COUNT1. Thus, [1] *added a begin-end block after (NUM < 0) test, and* [2] *added a decrement of the rainyday counter.*
- COUNT2 must be made to contain the number of rainy (not just valid) days. COUNT2 keeps track of the non-rainy valid days in the loop. Thus, we need to subtract the non-rainy days (COUNT2) from the total valid days (COUNT1) in order to get the number of rainy days: [3] *changed addition of COUNT1 and COUNT2 to subtraction of COUNT2 from COUNT1.*
- The guard on the average calculation is incorrect. Thus, [4] *changed guard on average calculation to COUNT1.*
- The divisor in the average calculation should be the valid day counter, COUNT1, not the valid, but non-rainy day counter, COUNT2. Thus, [5] *changed COUNT2 to COUNT1 in the divisor of the average calculation.*
- If there is no valid input the program should neither calculate the average, nor should the program print it out --- as well as not printing out the maximum. Thus, [6] *added a begin-end block after division guard around average calculation and output statements.*
- The WRITELNs give a message about what should be output; in order to make the message agree with the actual output, the variables need to be changed: [7] *the valid day counter needs to be COUNT1, while the* [8] *rainy day counter needs to COUNT2.*

Given the number of changes that need to be made to the counters (COUNT1 and COUNT2), it would appear that the student has some confusion over the roles of the two counters.

> *The Noah Problem:* Noah needs to keep track of the rainfall in the New Haven area to determine when to launch his ark. Write a program which he can use to do this. Your program should read the rainfall for each day, stopping when Noah types "99999", which is not a data value, but a sentinel indicating the end of input. If the user types in a negative value the program should reject it, since negative rainfall is not possible. Your program should print out the number of valid days typed in, the number of rainy days, the average rainfall per day over the period, and the maximum amount of rainfall that fell on any one day.

Figure 8: The Noah Problem: A First Looping Problem

However, consider now a different corrected version of this buggy program as depicted in Figure 10. A difference description between the buggy version and the corrected version yields the following set of bugs:

- We can make COUNT1 only keep track of the rainy days; this is consistent with code

BUGGY EXAMPLE

```
BEGIN
WRITELN ('PLEASE' INPUT AMOUNT OF RAINFALL')
READLN
READ(NUM)
COUNT1  = 0
COUNT2  = 0
SUM  = 0
HIGHNUM  = 0
WHILE (NUM <> SENTINAL) DO
  BEGIN
  IF (NUM > 0)
    THEN
    SUM  = SUM + NUM
    COUNT1  = COUNT1 + 1
    IF (NUM > HIGHNUM)
      THEN
      HIGHNUM  = NUM
  IF (NUM = 0)
    THEN
    COUNT2  = COUNT2 + 1
  IF (NUM < 0)
    THEN
    WRITELN ('ILLEGAL INPUT  INPUT NEW VALUE')
  READLN
  READ(NUM)
  END
COUNT2  = COUNT2 + COUNT1
IF (NUM > 0)
  THEN
  TOTAL  = SUM/COUNT2
  WRITELN ('AVERAGE RAINFALL WAS ' TOTAL ' INCHES PER DAY')
  WRITELN ('HIGHEST RAINFALL WAS ' HIGHNUM ' INCHES')
WRITELN (COUNT2 ' VALID DAYS WERE ENTERED')
WRITELN ( COUNT1 ' RAINY DAYS IN THIS PERIOD ')
END
```

CORRECTED VERSION

```
BEGIN
WRITELN ('PLEASE' INPUT AMOUNT OF RAINFALL').
READLN
READ(NUM).
COUNT1  = 0
COUNT2  = 0
SUM  = 0
HIGHNUM  = 0.
WHILE (NUM <> SENTINAL) DO
  BEGIN
  IF (NUM > 0)
    THEN
    SUM  = SUM + NUM.
    COUNT1  = COUNT1 + 1.
    IF (NUM > HIGHNUM)
      THEN
      HIGHNUM  = NUM
  IF (NUM = 0)
    THEN
    COUNT2  = COUNT2 + 1
  IF (NUM < 0)
    THEN
      begin                          (* add this line *)
        count1 := count1 - 1;        (* add this line *)
        WRITELN ('ILLEGAL INPUT  INPUT NEW VALUE')
      end;                           (* add this line *)
  READLN
  READ(NUM)
  END
count2  = count1 - count2;           (* changed this line *)
IF (count1 > 0 )                     (* changed this line *)
  THEN
    begin                            (* add this line *)
        TOTAL  = SUM/count1,         (* changed this line *)
        WRITELN ('AVERAGE RAINFALL WAS ' TOTAL ' INCHES PER DAY')
        WRITELN ('HIGHEST RAINFALL WAS ' HIGHNUM ' INCHES')
    end;                             (* add this line *)
WRITELN(count1,' VALID DAYS WERE ENTERED')     (* changed this line *)
WRITELN(count2,' RAINY DAYS IN THIS PERIOD ')  (* changed this line *)
END
```

- [1] added a begin-end block after (NUM < 0) test, and [2] added a decrement of the rainyday counter
- [3] changed addition of COUNT1 and COUNT2 to subtraction of COUNT2 from COUNT1
- [4] changed guard on average calculation to COUNT1
- [5] changed COUNT2 to COUNT1 in the divisor of the average calculation
- [6] added a begin-end block after division guard around average calculation and output statements
- [7] the valid day counter needs to be COUNT1 while the [8] rainy day counter needs to COUNT2

Figure 9: A Buggy Program and a Corrected Version

already in the program: the line that adds COUNT2 and COUNT1 now makes sense --- COUNT2 now keeps track of the valid days, and the divisor in the average calculation suggests that COUNT2 should be the valid day counter. In order to make COUNT1 perform in this manner, we need to [1] *add a begin-end pair around all computation after NUM > 0 test, up to the NUM = 0 test.*

- If there is no valid input the program should neither calculate the average, nor should the program print it out --- as well as not printing out the maximum. Thus, we need to [2] *add a begin-end block after division guard around average calculation and output statements.*
- The guard on the average calculation is incorrect. Thus, [3] *changed guard on average calculation to COUNT1.*

Which description should we choose? And why? Notice that neither of the corrected versions were that unreasonable. However, it would seem to us that one should choose the second bug description over the first. The basis for that decision is the hypothesized plan structure underlying the buggy version: it appears to us that the student was trying to structure the actions in the main loop in terms of cases. For example, the program explicitly tested for NUM > 0, NUM = 0, and NUM < 0 and took the appropriate actions --- almost. In order to make the case structure work, the code following the NUM > 0 up to the NUM = 0 test should be grouped together. While one cannot put too much faith in the indentation of a novice's program,[6] it appears that the indentation supports this analysis. Thus, what is missing from the main loop is a *begin-end* pair surrounding the code between the NUM > 0 test and the NUM = 0 test. On this analysis, the student does not have a misunderstanding surrounding the two counters, but rather has a coding level misunderstanding about how to block code together. Moreover, this same misunderstanding can explain the lack of a *begin-end* pair surrounding the average calculation in the next two write statements. The reduced bug count in the second description follows directly from this analysis: in effect there are only 3 bugs in this program, 2 of which have the same underlying origin.

This example illustrates a point made earlier: *the bug categorization and bug count follow from an understanding of the program that is provided by the hypothesized plan structure of the program.* That is, to understand a buggy program, one must make inferences about what plan structure the programmer intended to implement; the program only "makes sense" in terms of these plan descriptions.

---

[6] We have observed in the on-line protocols that the physical layout of a student's program suffers as the student makes changes to his program in the process of debugging it.

BUGGY EXAMPLE

```
BEGIN
WRITELN ('PLEASE' INPUT AMOUNT OF RAINFALL').
READLN
READ(NUM)
COUNT1  = 0
COUNT2  = 0
SUM  = 0
HIGHNUM  = 0
WHILE (NUM <> SENTINAL) DO
  BEGIN
  IF (NUM > 0)
    THEN
    SUM  = SUM + NUM
    COUNT1  = COUNT1 + 1
    IF (NUM > HIGHNUM)
      THEN
      HIGHNUM  = NUM
  IF (NUM = 0)
    THEN
    COUNT2  = COUNT2 + 1
  IF (NUM < 0)
    THEN
      WRITELN ('ILLEGAL INPUT  INPUT NEW VALUE')
  READLN
  READ(NUM)
  END
COUNT2  = COUNT2 + COUNT1
IF (NUM > 0)
  THEN
  TOTAL  = SUM/COUNT2
  WRITELN ('AVERAGE RAINFALL WAS ' TOTAL ' INCHES PER DAY')
  WRITELN ('HIGHEST RAINFALL WAS ' HIGHNUM ' INCHES')
WRITELN (COUNT2 ' VALID DAYS WERE ENTERED')
WRITELN (COUNT1 ' RAINY DAYS IN THIS PERIOD ')
END
```

ANOTHER CORRECTED VERSION

```
BEGIN
WRITELN ('PLEASE' INPUT AMOUNT OF RAINFALL').
READLN.
READ(NUM)
COUNT1  = 0
COUNT2  = 0
SUM  = 0
HIGHNUM  = 0
WHILE (NUM <> SENTINAL) DO
  BEGIN
    IF (NUM > 0)
      THEN
        begin                          (* add this line *)
          SUM  = SUM + NUM
          COUNT1  = COUNT1 + 1
          IF (NUM > HIGHNUM)
            THEN
            HIGHNUM  = NUM
        end;                           (* add this line *)
  IF (NUM = 0)
    THEN
    COUNT2  = COUNT2 + 1
  IF (NUM < 0)
    THEN
    WRITELN ('ILLEGAL INPUT  INPUT NEW VALUE')
  READLN
  READ(NUM)
  END
COUNT2  = COUNT2 + COUNT1
IF (count2 > 0)                    (* changed this line *)
THEN
 begin                             (* add this line *)
      TOTAL  = SUM/COUNT2
     WRITELN ('AVERAGE RAINFALL WAS ' TOTAL ' INCHES PER DAY')
      WRITELN ('HIGHEST RAINFALL WAS ' HIGHNUM ' INCHES')
 end;                              (* add this line *)
WRITELN (COUNT2 ' VALID DAYS WERE ENTERED')
WRITELN (COUNT1 ' RAINY DAYS IN THIS PERIOD ')
END
```

- [1] add a begin-end pair arround all computation after NUM > 0 test up to the NUM = 0 test
- [2] add a begin-end block after division guard around average calculation and output statements
- [3] changed guard on average calculation to COUNT1

Figure 10: A Buggy Program an an Alternative Corrected Version

5. Concluding Remarks

We have argued that a bug description is a difference description between the realization and the intention specification. We have presented a number of techniques for specifying the intention and have pointed out the problems associated with each type of specification in developing an accurate picture of bug types and bug frequency. While no technique is without its problems, we have argued that the understanding provided by a plan analysis of the buggy program stands a better chance, as compared to the other techniques, of providing a more accurate categorization and count of the bugs --- and thus a more accurate reflection of the origins of the bugs.

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