AUTOMATIC GRADING PROGRAMS

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Abstract

The ALGOL grader programs are presented for the computer evaluation of student ALGOL programs. One is for a beginner's program; it furnishes random data and checks answers. The other provides a searching test of the reliability and efficiency of a rootfinding procedure. There is a statement of the essential properties of a computer system, in order that grader programs can be effectively used.

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Discussion

In connection with introductory programming and numerical analysis courses at Stanford University, grading programs have been used intermittently since 1961. Our programs furnish data, check student performance in various ways, sometimes keep track of running time, and keep a "grade book" for the problems.

The Stanford routines are written separately for each problem. The most flexible and useful system for elementary classes was used with the Burroughs 220 computer in the BALGOL language, a dialect of ALGOL 58, and will be described first. Each grader program was written as a BALGOL-language procedure. It was then compiled together with a procedure called BUTTERFLY, written by Roger Moore. The result was a relocatable machine-language procedure, with a mechanism for equating its variables to variables of any BALGOL program, in just the form of the BALGOL compiler's own machine-language library procedures (SIN, WRITE, READ, etc.). Finally, the grader program was added to the compiler library tape for the duration of its use.

The use of a powerful algebraic language and system made it easy for an instructor to write grader programs with sophistication appropriate to the problem. The student needed only furnish one or two procedure statements to call a grader; we often furnished him cards to decrease the chance of error. Since each grader was precompiled on the library tape, little time was lost in adding it to each student's program at compile time. A simple handcoded mechanism made it easy for the operator to rescue a program from a run-time loop and send it into the
next case without dismissing the program entirely,. It was possible to have several different graders concurrently on the library tape, to take care of different classes.

This powerful grading mechanism was possible only because of the BALGOL compiler with its own compiler-with-library generator, and because BUTTERFLY could generate relocatable machine-language programs. Neither our IBM 7090 BALGOL system nor our Burroughs B5000 ALGOL system has been so well adapted to the grading problem, to our regret, and we have had to make do with less desirable expedients. What these newer systems lack is an easy means of producing a machine-language library procedure which is fully equivalent to a source-language procedure with several parameters.

We recommend grading programs to all who teach programming and numerical analysis to masses of students, but the prospective user should first carefully investigate the systems available to him.

We give below a typical grading program,' GRADER2, which was used in connection with an early problem in a beginning programming course. GRADER2 is suitable for grading a student's program which is written as a block. It has been translated into ALGOL and is given as part of a block containing one or more student programs.

In ALGOL there is a practical difficulty in putting many beginner programs into the same block with GRADER2--a syntactical error in just one student program may upset the compiler and prevent the testing of any program. It would be better if we could have GRADER2 precompiled into a system library and called separately by each student.
The student's problem is this: Given the integer $N$ ($0 < N < 10$) and the real array elements $A[0], \ldots, A[N], B[0], \ldots, B[N]$, to write a program which makes $MAX$ the maximum of $A[0], \ldots, A[N]$ and which computes the numbers $C[0], \ldots, C[2N]$ defined by the polynomial multiplication
\[
\sum_{k=0}^{2N} C[k]t^k = \left( \sum_{k=0}^{N} A[k]t^k \right) \cdot \left( \sum_{k=0}^{N} B[k]t^k \right).
\]

The student is told that he must arrange his program in the form:

\[
\begin{align*}
\text{begin} \\
<\text{all declarations}> - \\
\text{GRADER2 (<student number>, 1, N, MAX, A, B, C, START, FIN)}; \\
\text{START: <all statements of his solution>} \\
\text{GRADER2 (<student number>, 2, N, MAX, A, B, C, START, FIN)}; \\
\text{FIN:} \\
\text{end};
\end{align*}
\]

Note that the subprocedure SET UP of GRADER2 goes to great trouble to be sure that no student will get the same data at different times, and that no two students will get the same data. This was intended to be sure that a student could not get correct answers from GRADER2 on one \textbf{run}, and use them for another run. We doubt the value of such precautions,

Observe that GRADER2 evaluates the correctness of the student answers, but in no way evaluates the running speed of the program nor the amount of storage used. This is appropriate for a beginning student of programming.
A more advanced student should have his performance examined more critically. As an example of this, we give a second grader program called Test, to be used in a numerical analysis class whose members can already program in ALGOL.

The procedure Test listed below is designed to examine rootfinding procedures. The students are asked to write an ALGOL procedure which finds an approximation to a 'root' x (i.e., point of sign-change) of a (not necessarily continuous) function f in the interval \([a, b]\). To be precise, x is any number such that

\[ f(x_0) \leq 0 \equiv f(x_1) \geq 0 \]  

(in the sense of ALGOL 60)

and

\[ a \leq x_0 \leq x \leq x_1 \leq b \]

and

\[ |x_0 - x_1| \leq \epsilon \]

where \(f, a, b, \) and \(\epsilon\) are given parameters. Such an \(x\) always exists, if \(f(a) \leq 0 \equiv f(b) > 0\). Each student is asked to submit an ALGOL program containing his procedure declaration and a single statement of the form

\[
\text{Test (rootfinder, 'student name')}\]

As with GRADER2, all submitted programs are then enclosed together in an outer block, whose head contains the declaration of the procedure Test. Thus no use of library tapes is required. The block structure of ALGOL plays the very important role that all identifiers used by the student, including the name of his rootfinder, are strictly local to his program. They can therefore be chosen freely and cannot interfere
with identifiers in any other program. Nor can an identifier of the procedure Test interfere with any student's program. Of course this technique requires that the contributions be syntactically correct, but this is considered to be the minimum requirement for acceptance of a program from students at this level.

In order to obtain an estimate of the quality of the programs, one would like to know the accuracy of the answers, the number of evaluations of the function \( f \) it took to find the root (with the possibility of terminating the test, if a limit is exceeded), and perhaps also the time it took to find the root. It is furthermore desirable to check that the limits \( a \) and \( b \) and the tolerance \( \varepsilon \) were not changed during a test (this might occur, for example, if these parameters were called by name instead of by value), and whether the argument of \( f \) always remained within the interval \([a, b]\).

The following description of the procedure Test explains the methods of achieving these goals within the framework of an ALGOL program. The declaration of Test contains the following variable-declarations:

- `grade` represents the student's grade; it is cumulated during execution of several partial tests of one student's program.
- `m` denotes his number of successful tests.
- `x` is a real variable used as abscissa for the evaluation of \( f \).
- `t` records the time spent by the rootfinder.

A procedure \( P \) declared inside Test is the heart of the entire grader. The body of Test contains a series of calls of \( P \); each call of \( P \) contains as actual parameters the data for one test example. E.g., the
call

\[ P(0,2,10^{-5},1,1-x, \text{true}, 20, 1) \]

would cause the testing of the student's program with the function \( f: f(x) = 1 - x \) in the interval \( a = 0, b = 2 \), with a desired accuracy of \( 10^{-5} \). The expected result (=1) is the fourth parameter to \( P \). The sixth parameter indicates that a solution exists, the seventh is a limit for the number of evaluations of \( f \), and the eighth indicates the number of the test case.

The procedure \( P \) subsequently calls the rootfinder (which is a formal parameter to Test) with the given parameters as data. However, \( P \) does not furnish the function \( f \) directly to the rootfinder, but rather substitutes a function procedure \( Q \), which is declared in the head of \( P \). Each call of \( Q \) then serves to increment the counter of calls of \( f \) and is also used to examine whether the argument of \( f \) lies within the prescribed interval.

The grader program has been used on the 7090 computer. In order to measure the time spent by the rootfinder and to recover from a possible error in the logic of the student's program, two code procedures have been introduced which cannot be described in ALGOL:

\[
\begin{align*}
\text{procedure Setime } (n, \text{L}) ; \ & \text{integer } n ; \ & \text{label } \text{L}; \\
\text{initializes the core-clock to trap after } n \text{ msec and to transfer control to } \text{L}. \ & \text{Also,} \\
\text{procedure Reset } (t) ; \ & \text{integer } t; \\
\text{disables the trap and assigns to } t \text{ the number of msec spent since initialization of the clock. These procedures protect the entire grading run from failure due to one particular examinee's inability to solve a certain test problem.}
\end{align*}
\]
The authors feel that particular emphasis should be put not only on the efficiency of the student's contribution, but also on its reliability. The choice of the test data reflects the possibilities of this grading method, since "wildly behaving" functions are used which are not likely to be foreseen by a careless programmer.

The program Test is believed to mark a further step in the automation of grading. Whereas GRADER2 bases its grade only on the binary answer "correct" or "wrong", Test also evaluates a program's quality i.e., reliability and effectiveness. It thus relieves the teacher from long and tedious grading work. Last, but not least, the machine may be more objective in grading than the human, because of its notable lack of prejudice and its inability to become bored.

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An elementary grader program

begin

procedure GRADER2 (STUDENT, ENTRY, N, MAX, A, B, C, START, FIN);
  value STUDENT, ENTRY; integer STUDENT, ENTRY, N; real MAX;
  real array A, B, C; label START, FIN;
  comment We assume the existence of a library real procedure
  TIME which produces the time of day as an integer in the
  interval [0, 2359];
begin
real procedure RANDOM;
begin
  comment The value of RANDOM at each call is a different
  pseudo-random number from a flat distribution in the
  interval [0, 1]. The body is not written here ...;
end RANDOM;

own real array CC[0:10];
real S; own real MAX;
integer B3, B4, J, K;

own integer TALLY, B1, B2;

switch JUMP := L1, L2;

procedure SET UP (CASE, N);
  value CASE; integer CASE, N;
  comment SET UP furnishes the student's data, which depend on
  the student's number, the time of day, and a pseudo-random
  number  SET UP also solves the case for the use of EVALUATE;
begin

for K := 0 step 1 until N do
begin

B[K] := RANDOM × sign(RANDOM - 0.5)
end;

comment Now the student is messaged on the line-printer what data have been generated for him;
outstring (1, 'FOR uCASE'); outinteger (1, CASE);
outstring (1, 'GRADER2 uFURNISHES uSTUDENT'); outinteger(1, STUDENT);
outstring (1, 'THE uFOLLOWING uDATA: A uIS');
for K := 0 step 1 until N do outreal (1, A[K]);
outstring (1, 'B uIS');
for K := 0 step 1 until N do outreal (1, B[K]);
comment Now GRADER2 solves the student's case for itself.

GRADER2 does not use A[K] or B[K] for any values of K outside 0 < K < N;

MMAX := A[0];
for K := 1 step 1 until N do
if A[K] > MMAX then MMAX := A[K];
for K := 0 step 1 until N do
begin

s := 0;
CC[K] := S
end;
for K := N+1 step 1 until 2×N do
begin
s := 0;
CC[K] := S
end;
comment Now SET UP has solved the problem, and we exit
to START, the entry to the student's solution. The
next call of GRADER2 will bring us back to EVALUATE;
TALLY := TALLY + 1;
go to START;
end SET UP;

procedure EVALUATE (CASE, N);
value CASE; integer CASE, N;
begin
B3 := 1;
comment EVALUATE examines the student's answers, writing
them and its own answers, with comments on the student's
performance, all on the line-printer;
outstring (1, 'FOR _CASE'); outinteger (1, CASE);
outstring (1, (STUDENT'); outinteger (1, STUDENT);
outstring (1, 'COMPUTES-C _TO _BE');
for J := 0 step 1 until 2 × N do outreal (1, C[J]);
outstring (1, 'GRADER2 COMPUTES _C _TO _BE');
for j := 0 step 1 until 2 × N do outreal (1, CC[J]);
for K := 0 step 1 until 2 × N do
  if abs(C[K] - CC[K]) > 10^-4 then B3 := 0;
end EVALUATE;
If $B_3 = 1$ then outstring (1, 'C IS ACCEPTABLE');
else outstring (1, 'C IS NOT ACCEPTABLE');
comment A large tolerance was allowed for possible differences in the solutions because of different rounding off;

$B_4 := 0$;

if $MAX = MMAX$ then
begin
  $B_4 := 1$;
  outstring (1, 'MAX IS CORRECT')
end
else outstring (1, 'MAX IS INCORRECT');
end EVALUATE;

comment Now come the statements of GRADER2 itself;

if $ENTRY = 1$ then $TALLY := 0$ else go to JUMP[TALLY];
comment On the first call of GRADER2 by each student, $ENTRY$ is 1. On the later calls it is 2. This and $TALLY$ provide the mechanism for permitting different entries to GRADER2 on different calls;

$N := 5$;
SET UP (1, 5);

L1: EVALUATE (1, 5);

$B_1 := B_3$; $B_2 := B_4$;

$N := 4$;
SET UP (2, 4);
L2: EVALUATE (2,4);

    comment Case 2 is now complete, and GRADER2 punches a card for the "grade book!";
    for K := STUDENT, 2, B1, B2, B3, B4 do outinteger (2, K);
    comment GRADER2 now summarizes the situation for the student's line-printer listing;
    outstring (1, 'STUDENT'); outinteger (1, STUDENT);
    outstring (1, 'SCORES'); outinteger (1, B1+B2+B3+B4);
    outstring (1, 'OUT OF 4 ON PROBLEM 2. IF SCORE IS LESS THAN 4, PLEASE SUBMIT REVISED PROGRAM LATER. ');
    comment Now the program exits to the conclusion of the student's solution;
    go to FIN
end GRADER2;

comment Now follow the students' programs;
begin
    comment Here, for example, is the program for student number 515, with its calls on GRADER2;
    real array A, B, C [0:25];
    real S, MAX;
    integer J, K, N;
    GRADER2 (515, 1, N, MAX, A, B, C, START, FINISH);
    MAX := A[N];
    for K := N-1 step -1 until 0 do
        if MAX < A[K] then MAX := A[K];
\begin{verbatim}
for K := 0 step 1 until 2xN do
begin
    s := 0;
    for J := 0 step 1 until K do S := S + A[J]xB[K-J];
    C[K] := S
end;
GRADER2(515, 2, N, MAX, A, B, C, START, FINISH);
FINISH:
end program of student 515;
begin
    comment Program of another student . . . ;
end
.....
end tests of all student programs
\end{verbatim}
An advanced grader program

begin comment grader program for root-finding procedures;

procedure Test (Rootfinder, Name); procedure Rootfinder; string Name;
begin real x; integer m, grade, time;
    procedure P (low, up, eps, root, f, is root, iteration limit, problem no);

    value low, up, eps, root, is root, iteration limit, problem no;
    real low, up, eps, root, f;
    integer iteration limit, problem no;

    Boolean is root;

    begin real low 1, up 1, eps 1, root 1;
        integer n, t; Boolean is root 1;

    procedure Setime (n, L); integer n; label L; code;
    procedure Reset (t); integer t; code;
    procedure error (text, charge);

        value charge; integer charge; string text;

        begin outstring (text); grade := grade - charge;

        if grade < 0 then 
            begin outstring ('grade = 0');
            go to T exit

        end

        end error;

    real procedure Q(y); value y; real y;

    begin if y < low 1 \ y \ > up 1 then

        begin error ('Argument outside interval', 10);
            Reset(t); go to P exit

#14#
end;

n := n + 1; if n > iteration limit then
begin error ('Convergence is too slow', 5);
    Reset(t); go to P exit
end;

x := y; Q := f

end

low1 := low; up 1 := up; eps 1 := eps; n := 0;
outstring ('problem no. ='); outreal (problem no);
Setime(100, fail);
Rootfinder (low 1, up 1, eps 1, Q, root 1, is root 1);
Reset(t); time := time + t;
if low 1 # low V up 1 # up then
    error ('boundary was altered?', 3);
if eps 1 # eps then error ('tolerance was altered', 5);
if 1 is root then
    begin if is root 1 then
        error ('solution found where none exists', 5)
    else begin outstring ('correct reaction for root');
        m := m + 1
    end.
end
else
begin real tol; tol := abs (root - root 1);
    if tol > eps then error ('incorrect root', 5)
else begin outstring ('correct root found'); m := mt1
end.

outstring ('no. of iterations ='); outreal (n);
end;

go to P exit;

fail: error ('failure', 10);
P exit:
end P;

m := 0; grade := 100; time := 0; outstring (Name);
P(-2, 2, 10, -1, x+1, true, 10, 1);
P(-1, 1, 10^-1, x+1, true, 10, 2);
P(-1, 1, 10, 1, x-1, true, 10, 3);
P(2, 5, 10^-6, 0, x-1, false, 10, 4);
P(-2, 3.5, 10^-5, 2, x+3 = x * 3 - 2 * 10^-20, true, 30, 5);
P(10^-3, 99.9, 10^-5, 0.01, x + 1/x - 100.01, true, 50, 6);
P(-1, 2, 10^-5, 0, sign(x), true, 30, 7);
P(-3, 100, 10^-4, 0, exp(-x) - 1, true, 50, 8);
P(0, 20, 10^-4, 0.95, (x + 0.05) + 0.1 = 1, true, 30, 9);
P(0, 100, 10^-5, 1, if x < 1 then x - 1 else 10^-10, true, 30, 10);
~(-2.4, 4.2, 10^-4, 3, (((x-3)x x+5) x x-15) x x+4) x x-12,
true, 50, 11);
P(10^-3, 1, 510^-3, 0.0265, if x < 0.02122 then -1 else
if x > 0.03183 then 1 else cos(1/x), true, 30, 12);
outstring ('end of test. No. of correct- problems =');
outreal (m); outstring ('time ='); outreal (time);
outstring ('grade ='); outreal (grade);

T exit:
end T;
comment Subsequently follow the students' programs, each containing a procedure declaration and a call of Test enclosed in a block;

begin

procedure Bisect (x0, x1, tol, func, result, is result);
real x0, x1, tol, result;
real procedure func;
Boolean is result;

begin ................

.............

end Bisect;

Test (Bisect, 'Tom Jones')

end;

.............

comment further students' programs follow here;

.............

end Grader program