

Algorithms in the Nashlib set in various programming languages – Part 3

John C Nash, retired professor, University of Ottawa Peter Olsen, retired ??

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Abstract

Algorithms 16-23 from the book Nash (1979) are implemented in a variety of programming languages including Fortran, BASIC, Pascal, Python and R. These concern rootfinding, function minimisation and nonlinear least squares.

Overview of this document

This section is repeated for each of the parts of Nashlib documentation.

A companion document **Overview of Nashlib and its Implementations** describes the process and computing environments for the implementation of Nashlib algorithms. This document gives comments and/or details relating to implementations of the algorithms themselves.

Note that some discussion of the reasoning behind certain choices in algorithms or implementations are given in the Overview document.

Algorithm 16 – Grid search

Grid search – establishing a regular pattern of parameter values for one or more arguments of a function and then evaluating that function on the “grid” – is a brute force approach to finding roots, minima, maxima and other features of a function surface. While it cannot be recommended as an efficient method for finding roots or minima, it offers a way to generate data for plotting the function surface and for localizing roots or minima when these are not unique. Furthermore, it is readily understood, and offers a useful starting point in presenting and understanding a problem.

Fortran

Listing

```
      SUBROUTINE A16GS(U,V,N,FNS,IFN,TOL,IPR,T,VAL)
C  ALGORITHM 16  GRID SEARCH
C  J.C. NASH    JULY 1978, FEBRUARY 1980, APRIL 1989
C  U,V DEFINE THE INTERVAL OF INTEREST
C  N  GIVES THE NUMBER OF DIVISIONS (N+1) POINTS
C  FNS IS THE NAME OF THE FUNCTION    VAL=FNS(B,NOCOM)
C  NOCOM SET .TRUE. IF NOT COMPUTABLE. PROGRAM HALTS IN THIS CASE
C  IFN  IS LIMIT ON FUNCTION EVALUATIONS ALLOWED. RETURNS ACTUAL USED
C  TOL =CONVERGENCE TOLERANCE ON ABS(V-U)*2/N
C  IPR = PRINT CHANNEL   IPR.GT.0 FOR PRINTING.
C  T   = LOWEST VALUE FOUND
C  VAL  =  WORKING VECTOR OF VALUES AT GRID POINTS
C  STEP 0
      LOGICAL NOCOM
      INTEGER N,K,J,LIM,N1
      REAL H,U,V,T,TOL,P,SV,X,VAL(N)
C  N.LE.2  CAN'T REDUCE INTERVAL
      IF(N.LT.3)STOP
      LIM=IFN
      IFN=0
      NOCOM = .FALSE.
      T=FNS(U,NOCOM)
      IF(NOCOM)STOP
      IFN=IFN+1
      IF(IPR.GT.0)WRITE(IPR,956)IFN,U,T
      VAL(1)=T
      SV=FNS(V,NOCOM)
      IF(NOCOM)STOP
      IFN=IFN+1
      IF(IPR.GT.0)WRITE(IPR,956)IFN,V,SV
C  STEP 1
10  K=0
      IF(SV.GE.T)GOTO 15
      K=N
      T=SV
15  H=(V-U)/N
C  STEP 2
C  S(U) ALREAD IN T
      N1=N-1
      DO 60 J=1,N1
C  STEP 3
```

```

        X=U+J*H
        P=FNS(X,NOCOM)
        IF(NOCOM)STOP
        IFN=IFN+1
        IF(IFN.GE.LIM)RETURN
        IF(IPR.GT.0)WRITE(IPR,956)IFN,X,P
956  FORMAT( 8H EVALN #,I4,4H F(,1PE16.8,2H)=,E16.8)
C  SAVE VALUE
        VAL(J+1)=P
C  STEP 4
        IF(P.GE.T)GOTO 60
C  STEP 5
        T=P
        K=J
C  STEP 6
60  CONTINUE
C  STEP 7
        IF(ABS(H).LT.0.5*TOL)RETURN
C  STEP 8
        V=U+(K+1)*H
        U=V-2*H
        IF(K.EQ.0)GOTO 82
C  S(U) IS IN VAL(K)
        T=VAL(K)
        GOTO 84
82  T=FNS(U,NOCOM)
        IF(NOCOM)STOP
        IFN=IFN+1
        IF(IPR.GT.0)WRITE(IPR,956)IFN,U,T
        IF(IFN.GE.LIM)RETURN
84  IF(K.GT.N-2)GOTO 86
        SV=VAL(K+2)
        GOTO 10
86  IF(K.EQ.N1)GOTO 10
C  SV ALREADY IN PLACE IF K=N-1
        SV=FNS(V,NOCOM)
        IF(NOCOM)STOP
        IFN=IFN+1
        IF(IPR.GT.0)WRITE(IPR,956)IFN,V,SV
        IF(IFN.GE.LIM)RETURN
        GOTO 10
END

```

Example output

```

gfortran ../fortran/dr16.f
mv ./a.out ../fortran/dr16f.run
../fortran/dr16f.run < ../fortran/dr16f.in

```

```

## OTEST- COUNT=    80 NBIS=     5 U=          0.00000 V=          3.00000 TOL=    0.0000100000
## EVALN #    1 F(  0.000000000E+00)= -5.000000000E+00
## EVALN #    2 F(  3.000000000E+00)=  1.600000000E+01
## EVALN #    3 F(  6.00000024E-01)= -5.98400021E+00
## EVALN #    4 F(  1.20000005E+00)= -5.67199993E+00

```

```

## EVALN # 5 F( 1.80000007E+00)= -2.76799941E+00
## EVALN # 6 F( 2.40000010E+00)= 4.02400112E+00
## EVALN # 7 F( 2.40000010E-01)= -5.46617603E+00
## EVALN # 8 F( 4.80000019E-01)= -5.84940815E+00
## EVALN # 9 F( 7.20000029E-01)= -6.06675196E+00
## EVALN # 10 F( 9.60000038E-01)= -6.03526402E+00
## EVALN # 11 F( 5.76000035E-01)= -5.96089697E+00
## EVALN # 12 F( 6.72000051E-01)= -6.04053545E+00
## EVALN # 13 F( 7.68000007E-01)= -6.08301544E+00
## EVALN # 14 F( 8.64000022E-01)= -6.08302736E+00
## EVALN # 15 F( 8.06400001E-01)= -6.08841324E+00
## EVALN # 16 F( 8.44799995E-01)= -6.08667755E+00
## EVALN # 17 F( 8.83200049E-01)= -6.07746649E+00
## EVALN # 18 F( 9.21600044E-01)= -6.06044197E+00
## EVALN # 19 F( 7.83360004E-01)= -6.08600903E+00
## EVALN # 20 F( 7.98720002E-01)= -6.08789349E+00
## EVALN # 21 F( 8.14080000E-01)= -6.08864784E+00
## EVALN # 22 F( 8.29439998E-01)= -6.08824968E+00
## EVALN # 23 F( 8.04863989E-01)= -6.08833218E+00
## EVALN # 24 F( 8.11007977E-01)= -6.08858871E+00
## EVALN # 25 F( 8.17152023E-01)= -6.08866119E+00
## EVALN # 26 F( 8.23296010E-01)= -6.08854866E+00
## EVALN # 27 F( 8.13465655E-01)= -6.08863974E+00
## EVALN # 28 F( 8.15923214E-01)= -6.08866119E+00
## EVALN # 29 F( 8.18380833E-01)= -6.08865356E+00
## EVALN # 30 F( 8.20838392E-01)= -6.08861589E+00
## EVALN # 31 F( 8.14448714E-01)= -6.08865166E+00
## EVALN # 32 F( 8.15431714E-01)= -6.08865929E+00
## EVALN # 33 F( 8.16414773E-01)= -6.08866215E+00
## EVALN # 34 F( 8.17397773E-01)= -6.08866024E+00
## EVALN # 35 F( 8.15824926E-01)= -6.08866119E+00
## EVALN # 36 F( 8.16218138E-01)= -6.08866215E+00
## EVALN # 37 F( 8.16611350E-01)= -6.08866215E+00
## EVALN # 38 F( 8.17004561E-01)= -6.08866119E+00
## EVALN # 39 F( 8.15982223E-01)= -6.08866119E+00
## EVALN # 40 F( 8.16139519E-01)= -6.08866167E+00
## EVALN # 41 F( 8.16296756E-01)= -6.08866215E+00
## EVALN # 42 F( 8.16454053E-01)= -6.08866215E+00
## EVALN # 43 F( 8.16768646E-01)= -6.08866215E+00
## EVALN # 44 F( 8.16516995E-01)= -6.08866215E+00
## EVALN # 45 F( 8.16579878E-01)= -6.08866215E+00
## EVALN # 46 F( 8.16642821E-01)= -6.08866215E+00
## EVALN # 47 F( 8.16705704E-01)= -6.08866215E+00
## EVALN # 48 F( 8.16391170E-01)= -6.08866215E+00
## EVALN # 49 F( 8.16416323E-01)= -6.08866215E+00
## EVALN # 50 F( 8.16441476E-01)= -6.08866215E+00
## EVALN # 51 F( 8.16466689E-01)= -6.08866215E+00
## EVALN # 52 F( 8.16491842E-01)= -6.08866215E+00
## EVALN # 53 F( 8.16366017E-01)= -6.08866215E+00
## EVALN # 54 F( 8.16376090E-01)= -6.08866215E+00
## EVALN # 55 F( 8.16386163E-01)= -6.08866215E+00
## EVALN # 56 F( 8.16396177E-01)= -6.08866215E+00
## EVALN # 57 F( 8.16406250E-01)= -6.08866215E+00
## EVALN # 58 F( 8.16355944E-01)= -6.08866215E+00

```

```

## EVALN # 59 F( 8.16359997E-01)= -6.08866215E+00
## EVALN # 60 F( 8.16363990E-01)= -6.08866215E+00
## EVALN # 61 F( 8.16368043E-01)= -6.08866215E+00
## EVALN # 62 F( 8.16372037E-01)= -6.08866215E+00
## OFINAL INTERVAL=( 8.16355944E-01, 8.16376090E-01)  LOWEST VALUE= -6.08866215E+00 COUNT= 62
## OTEST- COUNT= 5 NBIS= 10 U= 0.00000 V= 3.00000 TOL= 0.0000000000
## EVALN # 1 F( 0.00000000E+00)= -5.00000000E+00
## EVALN # 2 F( 3.00000000E+00)= 1.60000000E+01
## EVALN # 3 F( 3.00000012E-01)= -5.57299995E+00
## EVALN # 4 F( 6.00000024E-01)= -5.98400021E+00
## OFINAL INTERVAL=( 0.00000000E+00, 3.00000000E+00)  LOWEST VALUE= -5.98400021E+00 COUNT= 5
## OTEST- COUNT= 0 NBIS= 0 U= 0.00000 V= 0.00000 TOL= 0.0000000000

```

Pascal

Listing

```

procedure gridsrch( var lbound, ubound : real;
                    nint : integer;
                    var fmin: real;
                    var minarg: integer;
                    var changarg: integer );

var
  j : integer;
  h, p, t : real;
  notcomp : boolean;

begin
  writeln('alg16.pas -- one-dimensional grid search');
  writeln('In gridsrch lbound=',lbound,' ubound=',ubound);
  notcomp:=false;
  t:=fn1d(lbound, notcomp);
  writeln(' lb f(',lbound,')=',t);
  if notcomp then halt;
  fmin:=t;
  minarg:=0;
  changarg:=0;
  h:=(ubound-lbound)/nint;
  for j:=1 to nint do

    begin
      p:=fn1d(lbound+j*h, notcomp);
      write('      f(',lbound+j*h,')=',p);
      if notcomp then halt;
      if p<fmin then
        begin
          fmin:=p; minarg:=j;
        end;
      if p*t<=0 then
        begin
          writeln(' *** sign change ***');
          changarg:=j;
        end
    end
  end

```

```

else
begin
    writeln;
end;
t:=p;
end;
writeln('Minimum so far is f(',lbound+minarg*h,')=',fmin);
if changarg>0 then
begin
    writeln('Sign change observed last in interval ');
    writeln(' [',lbound+(chchangarg-1)*h,',',lbound+chchangarg*h,']');
end
else
begin
    writeln('Apparently no sign change in [',lbound,',',ubound,']');
end;
end;
end;

```

Example output

The driver for presenting the example of the Pascal version of Algorithm 16 is combined with that of Algorithm 17 below.

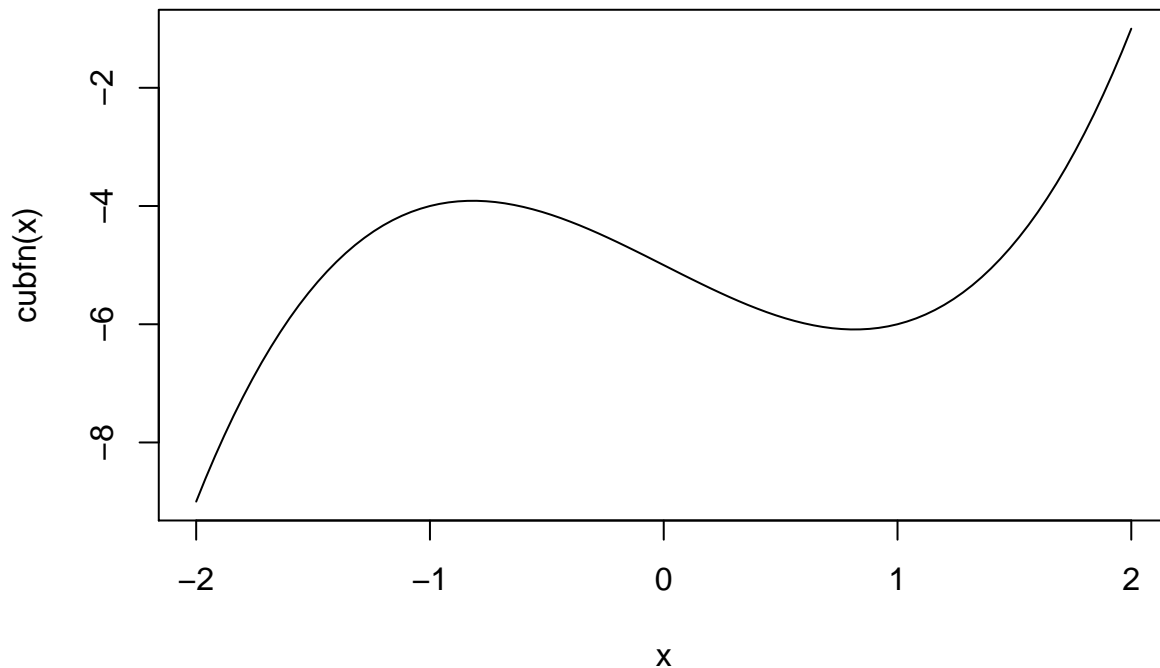
Algorithm 17 – Minimize a function of one parameter

It is helpful to be able to visualize a one-parameter function before trying to find a minimum. R provides a nice way to do this, and also provides (via the **Brent** method of `optim()`) a way to seek a local minimum, though we need to provide lower and upper bounds. The original Algorithm 17 from Nashlib uses a starting guess and a starting stepsize, which leads to a different approach to finding a minimum. However, the upper and lower bound approach was used in the 1990 Second Edition and its Turbo Pascal variant of the code.

```

cubfn <- function(x) { x*(x*x-2)-5}
curve(cubfn, from=-2, to=2)

```



```
res <- optim(par=0.0, fn=cubfn, method="Brent", lower=c(0), upper=c(1))
cat("Minimum proposed is f(",res$par,")=",res$value,"\n")
```

```
## Minimum proposed is f( 0.8164966 )= -6.088662
```

Fortran

Listing

```

      SUBROUTINE A17LS(B,ST,FUNS,IFN,NOCOM,IPR)
C  ALGORITHM 17 SUCCESS-FAILURE LINEAR SEARCH WITH PARABOLIC
C  INVERSE INTERPOLATION
C  J.C. NASH    JULY 1978, FEBRUARY 1980, APRIL 1989
C  B=INITIAL GUESS TO MINIMUM OF FUNCTION FUNS ALONG THE REAL LINE
C  ON OUTPUT B IS COMPUTED MINIMUM
C  ST=INITIAL STEP SIZE
C  ON OUTPUT ST CONTAINS COMPUTED MINIMUM FUNCTION VALUE
C  FUNS=NAME OF FUNCTION SUBPROGRAM
C  CALLING SEQUENCE IS      FVAL=FUNS(B,NOCOM)
C  NOCOM SET .TRUE. IF B NOT A VALID (OR DESIRABLE) ARGUMENT
C  NOCOM=LOGICAL FLAG SET .TRUE. IF INITIAL ARGUMENT INVALID
C  NORMAL RETURN FROM A17LS LEAVES NOCOM .FALSE.
C  IFN=LIMIT ON NO. OF FUNCTION EVALUATIONS (ON INPUT)
C  =NO. OF FUNCTION EVALUATIONS ACTUALLY USED (ON OUTPUT)
C  IPR=PRINTER CHANNEL IPR.GT.0 CAUSES INTERMEDIATE OUTPUT
C  STEP 0
      LOGICAL NOCOM
      INTEGER IFN,LIFN,IPR
      REAL FUNS,B,ST,A1,A2,P,S1,S0,X0,X2,BMIN,BIG,X1
C  FOR ALTERNATE TEST AT STEP 4
C  REAL EPS
C  EPS=16.0**(-5)
C  IBM VALUES

```



```

C&&&      BIG=R1MACH(2)
          BIG = 1.0E+35
          NOCOM=.FALSE.
          LIFN=IFN
          IFN=0
C  STEP CHANGE FACTORS
          A1=1.5
          A2=-0.25
C  CHECK STEPSIZE
          IF(ST.EQ.0.0) NOCOM=.TRUE.
          IF(NOCOM) RETURN
C  STEP 1
          IFN=IFN+1
          IF(IFN.GT.LIFN) GOTO 210
          P=-BIG
          P=FUNS(B,NOCOM)
          IF(IPR.GT.0) WRITE(IPR,965) IFN,B,P
965  FORMAT(13H EVALUATION #,I4, 5H  F(,1PE16.8,2H)=,E16.8)
          IF(NOCOM) RETURN
C  STEP 2
20  S1=P
          S0=-BIG
          X1=0.0
          BMIN=B
C  STEP 3
30  X2=X1+ST
          B=BMIN+X2
C  STEP 4
          IF(B.EQ.BMIN+X1) GOTO 220
C  ALTERNATIVE STEP 4
C  IF(ABS(B)+EPS.EQ.ABS(BMIN)+ABS(X1)+EPS) GOTO 210
C  STEP 5
          IFN=IFN+1
          IF(IFN.GT.LIFN) GOTO 210
          NOCOM=.FALSE.
          P=FUNS(B,NOCOM)
          IF(NOCOM) GOTO 90
          IF(IPR.GT.0) WRITE(IPR,965) IFN,B,P
C  STEP 6
          IF(P.LT.S1) GOTO 100
C  STEP 7
          IF(S0.GE.S1) GOTO 110
C  STEP 8
          S0=P
          X0=X2
C  STEP 9
90  ST=A2*ST
          GOTO 30
C  STEP 10
100 X0=X1
          S0=S1
          X1=X2
          S1=P

```

```

        ST=A1*ST
        GOTO 30
C  STEP 11
110  X0=X0-X1
        S0=(S0-S1)*ST
        P=(P-S1)*X0
C  STEP 12
        IF(P.EQ.S0)GOTO 180
C  STEP 13
        ST=0.5*(P*X0-S0*ST)/(P-S0)
C  STEP 14
        X2=X1+ST
        B=BMIN+X2
C  STEP 15
        IF(B.EQ.BMIN+X1)GOTO 180
C  FIXED TO JUMP TO STEP 18, NOT STEP 20 (APRIL 1989)
C  STEP 16
        IFN=IFN+1
        IF(IFN.GT.LIFN)GOTO 210
        NOCOM=.FALSE.
        P=FUNS(B,NOCOM)
        IF(NOCOM)GOTO 180
        IF(IPR.GT.0)WRITE(IPR,965)IFN,B,P
C  STEP 17
        IF(P.LT.S1)GOTO 190
C  STEP 18
180  B=BMIN+X1
        P=S1
        GOTO 200
C  STEP 19
190  X1=X2
C  STEP 20
200  ST=A2*ST
        GOTO 20
210  IFN=LIFN
220  B=BMIN
        ST=S1
        RETURN
        END

```

Example output

```

gfortran ../fortran/dr17.f
mv ./a.out ../fortran/dr17f.run
../fortran/dr17f.run < ../fortran/dr17f.in

```

```

## TEST A17LS STARTING POSN=          0.00000  INITIAL STEP=          1.00000
## CONVERGED IN  19 EVALS TO F( 8.16470623E-01)= -6.08866215E+00
##
## TEST A17LS STARTING POSN=          0.00000  INITIAL STEP=          0.10000
## CONVERGED IN  18 EVALS TO F( 8.16489398E-01)= -6.08866215E+00
##
## TEST A17LS STARTING POSN=          0.00000  INITIAL STEP=          0.01000
## CONVERGED IN  27 EVALS TO F( 8.16469610E-01)= -6.08866215E+00

```

```
##
## TEST A17LS STARTING POSN=          1.00000  INITIAL STEP=          1.00000
## CONVERGED IN 18 EVALS TO F( 8.16750884E-01)= -6.08866215E+00
##
## TEST A17LS STARTING POSN=          1.00000  INITIAL STEP=         -0.10000
## CONVERGED IN 17 EVALS TO F( 8.16494286E-01)= -6.08866215E+00
##
## TEST A17LS STARTING POSN=          1.00000  INITIAL STEP=          20.00000
## FAILURE??
## CONVERGED IN 100 EVALS TO F( -4.99425268E+00)= -1.19580940E+02
##
## TEST A17LS STARTING POSN=          0.00000  INITIAL STEP=          0.00000
```

Pascal

Example output

First we compile the codes.

```
fpc ../Pascal2021/dr1617.pas
# copy to run file
mv ../Pascal2021/dr1617 ../Pascal2021/dr1617p.run
```

```
## Free Pascal Compiler version 3.0.4+dfsg-23 [2019/11/25] for x86_64
## Copyright (c) 1993-2017 by Florian Klaempfl and others
## Target OS: Linux for x86-64
## Compiling ../Pascal2021/dr1617.pas
## Linking ../Pascal2021/dr1617
## /usr/bin/ld.bfd: warning: link.res contains output sections; did you forget -T?
## 282 lines compiled, 0.1 sec
```

Then we run the grid search (Algorithm 16) followed by the line search routine (Algorithm 18).

```
../Pascal2021/dr1617p.run <../Pascal2021/dr1617p.in >../Pascal2021/dr1617p.out
```

```
Enter lower bound for search 0.000000000000000E+000
Enter upper bound for search 1.000000000000000E+000
Enter a tolerance for search interval width 1.000000000000000E-010
Enter the number of intervals per search (0 for no grid search) 10
alg16.pas -- one-dimensional grid search
In gridsrch lbound= 0.000000000000000E+000 ubound= 1.000000000000000E+000
  lb f( 0.000000000000000E+000)=-5.000000000000000E+000
    f( 1.000000000000000E-001)=-5.198999999999998E+000
    f( 2.000000000000000E-001)=-5.392000000000000E+000
    f( 3.000000000000000E-001)=-5.573000000000000E+000
    f( 4.000000000000000E-001)=-5.735999999999998E+000
    f( 5.000000000000000E-001)=-5.875000000000000E+000
    f( 6.000000000000000E-001)=-5.984000000000000E+000
    f( 7.000000000000000E-001)=-6.057000000000000E+000
    f( 8.000000000000000E-001)=-6.088000000000000E+000
    f( 9.000000000000000E-001)=-6.070999999999997E+000
    f( 1.000000000000000E+000)=-6.000000000000000E+000
Minimum so far is f( 8.000000000000000E-001)=-6.088000000000000E+000
Apparently no sign change in [ 0.000000000000000E+000, 1.000000000000000E+000]
New lowest function value =-6.088000000000000E+000 in [ 6.999999999999996E-001, 9.000000000000000E-001]
Now call the minimiser
```

```

alg17.pas -- One dimensional function minimisation
Failure1
Triple ( 8.0000000000000004E-001,-6.0880000000000001E+000)
      ( 8.2000000000000006E-001,-6.0886320000000005E+000)
      ( 8.5000000000000009E-001,-6.0858749999999997E+000)
Paramin step and argument :-3.6032388663950385E-003  8.1639676113360504E-001
New min f( 8.1639676113360504E-001)=-6.0886620834979350E+000
4 evalns    f( 8.1639676113360504E-001)=-6.0886620834979350E+000
Failure2
Triple ( 8.1279352226721002E-001,-6.0886285697028972E+000)
      ( 8.1639676113360504E-001,-6.0886620834979350E+000)
      ( 8.1729757085020383E-001,-6.0886605358342081E+000)
Paramin step and argument : 9.9272800009582988E-005  8.1649603393361458E-001
New min f( 8.1649603393361458E-001)=-6.0886621079029020E+000
7 evalns    f( 8.1649603393361458E-001)=-6.0886621079029020E+000
Failure2
Triple ( 8.1659530673362413E-001,-6.0886620840280230E+000)
      ( 8.1649603393361458E-001,-6.0886621079029020E+000)
      ( 8.1647121573361214E-001,-6.0886621063276660E+000)
Paramin step and argument : 5.4647738345575687E-007  8.1649658041099804E-001
New min f( 8.1649658041099804E-001)=-6.0886621079036347E+000
10 evalns    f( 8.1649658041099804E-001)=-6.0886621079036347E+000
Failure2
Triple ( 8.1649712688838150E-001,-6.0886621079029046E+000)
      ( 8.1649658041099804E-001,-6.0886621079036347E+000)
      ( 8.1649644379165220E-001,-6.0886621079035885E+000)
Paramin step and argument : 6.6320070817813863E-010  8.1649658107419876E-001
13 evalns    f( 8.1649658041099804E-001)=-6.0886621079036347E+000
Apparent minimum is f( 8.1649658041099804E-001)=-6.0886621079036347E+000
      after 13 function evaluations

```

But we can run just the minimizer. Note that above we use only 13 function evaluations in the minimizer, but now use 17 (for the input used in this example). However, the grid search used 11 function evaluations prior to the call to the minimizer for a total of 24.

```

../Pascal2021/dr1617p.run <../Pascal2021/dr17p.in >../Pascal2021/dr17p.out

```

```

Enter lower bound for search 0.0000000000000000E+000
Enter upper bound for search 1.0000000000000000E+000
Enter a tolerance for search interval width 1.0000000000000000E-010
Enter the number of intervals per search (0 for no grid search) 0
Now call the minimiser
alg17.pas -- One dimensional function minimisation
Success1 Failure1
Triple ( 5.9999999999999998E-001,-5.9840000000000000E+000)
      ( 7.5000000000000000E-001,-6.0781250000000000E+000)
      ( 9.7500000000000009E-001,-6.0231406249999999E+000)
Paramin step and argument : 5.9946236559139748E-002  8.0994623655913978E-001
New min f( 8.0994623655913978E-001)=-6.0885572886751467E+000
5 evalns    f( 8.0994623655913978E-001)=-6.0885572886751467E+000
Failure2
Triple ( 8.6989247311827955E-001,-6.0815260773512261E+000)
      ( 8.0994623655913978E-001,-6.0885572886751467E+000)
      ( 7.9495967741935480E-001,-6.0875359305980759E+000)
Paramin step and argument : 6.2758433158830399E-003  8.1622207987502282E-001

```

```

New min f( 8.1622207987502282E-001)=-6.0886619233532384E+000
8 evalns    f( 8.1622207987502282E-001)=-6.0886619233532384E+000
Failure2
Triple ( 8.2249792319090587E-001,-6.0885736706691658E+000)
      ( 8.1622207987502282E-001,-6.0886619233532384E+000)
      ( 8.1465311904605209E-001,-6.0886537899407127E+000)
Paramin step and argument : 2.7201374487455200E-004 8.1649409361989733E-001
New min f( 8.1649409361989733E-001)=-6.0886621078884806E+000
11 evalns    f( 8.1649409361989733E-001)=-6.0886621078884806E+000
Failure2
Triple ( 8.1676610736477184E-001,-6.0886619299420968E+000)
      ( 8.1649409361989733E-001,-6.0886621078884806E+000)
      ( 8.1642609018367873E-001,-6.0886620957326052E+000)
Paramin step and argument : 2.4833291744350515E-006 8.1649657694907174E-001
New min f( 8.1649657694907174E-001)=-6.0886621079036347E+000
14 evalns    f( 8.1649657694907174E-001)=-6.0886621079036347E+000
Failure2
Triple ( 8.1649906027824615E-001,-6.0886621078885774E+000)
      ( 8.1649657694907174E-001,-6.0886621079036347E+000)
      ( 8.1649595611677817E-001,-6.0886621079026781E+000)
Paramin step and argument : 4.0734727830310040E-009 8.1649658102254452E-001
17 evalns    f( 8.1649657694907174E-001)=-6.0886621079036347E+000
Apparent minimum is f( 8.1649657694907174E-001)=-6.0886621079036347E+000
after 17 function evaluations

```

Algorithm 18 – Roots of a function of one parameter

We use the same cubic polynomial for our rootfinding test as for the 1D minimizer (Algorithm 17). R has a built-in 1D rootfinder, `uniroot`. This uses ideas in Brent (1973). As of UseR!2011 in Warwick, the R multiple-precision package `Rmpfr` (Maechler (2020)) did not have a rootfinder because it needed to have a pure-R code to extend the precision. During a quite period of the conference, the author (JN) translated the C code of `uniroot` to plain R, and it is now the `unirootR` function of `Rmpfr`. The code is in the `rootoned` package at http://download.r-forge.r-project.org/src/contrib/rootoned_2018-8.28.tar.gz.

Note that this is a different algorithm to that in Nashlib. Moreover, even the Nashlib codes are not necessarily fully equivalent, as over time minor variations have crept in. We are also fairly certain that the ideas of Algorithm 18 are NOT the best for performance. They were written initially for the Data General NOVA which had very poor quality floating point (24 bit mantissa, likely no guard digit, no double precision), and with very limited storage. Thus the programming goal was reliability rather than efficiency.

```

cubfn <- function(x) { x*(x*x-2)-5}
## curve(cubfn, from=-2, to=2)
cat("The first attempt fails -- see the plot of the function above.\n")

## The first attempt fails -- see the plot of the function above.

res <- try(uniroot(f=cubfn, lower=0, upper=1))

## Error in uniroot(f = cubfn, lower = 0, upper = 1) :
##   f() values at end points not of opposite sign

res <- try(uniroot(f=cubfn, lower=-3, upper=3))
cat("Root proposed is f(",res$root,")=",res$f.root,"\n")

## Root proposed is f( 2.094555 )= 3.690185e-05

```

```
cat("Tighter tolerance?\n")
```

```
## Tighter tolerance?
```

```
res <- try(uniroot(f=cubfn, lower=-3, upper=3, tol=1e-10))  
cat("Root proposed is f(",res$root,")=",res$f.root,"\n")
```

```
## Root proposed is f( 2.094551 )= -7.01661e-14
```

Fortran

Listing

```
      SUBROUTINE A17LS(B,ST,FUNS,IFN,NOCOM,IPR)  
C  ALGORITHM 17 SUCCESS-FAILURE LINEAR SEARCH WITH PARABOLIC  
C  INVERSE INTERPOLATION  
C  J.C. NASH    JULY 1978, FEBRUARY 1980, APRIL 1989  
C  B=INITIAL GUESS TO MINIMUM OF FUNCTION FUNS ALONG THE REAL LINE  
C  ON OUTPUT B IS COMPUTED MINIMUM  
C  ST=INITIAL STEP SIZE  
C  ON OUTPUT ST CONTAINS COMPUTED MINIMUM FUNCTION VALUE  
C  FUNS=NAME OF FUNCTION SUBPROGRAM  
C  CALLING SEQUENCE IS      FVAL=FUNS(B,NOCOM)  
C  NOCOM SET .TRUE. IF B NOT A VALID (OR DESIRABLE) ARGUMENT  
C  NOCOM=LOGICAL FLAG SET .TRUE. IF INITIAL ARGUMENT INVALID  
C  NORMAL RETURN FROM A17LS LEAVES NOCOM .FALSE.  
C  IFN=LIMIT ON NO. OF FUNCTION EVALUATIONS (ON INPUT)  
C  =NO. OF FUNCTION EVALUATIONS ACTUALLY USED (ON OUTPUT)  
C  IPR=PRINTER CHANNEL IPR.GT.0 CAUSES INTERMEDIATE OUTPUT  
C  STEP 0  
      LOGICAL NOCOM  
      INTEGER IFN,LIFN,IPR  
      REAL FUNS,B,ST,A1,A2,P,S1,S0,X0,X2,BMIN,BIG,X1  
C  FOR ALTERNATE TEST AT STEP 4  
C  REAL EPS  
C  EPS=16.0**(-5)  
C  IBM VALUES  
C&&&      BIG=R1MACH(2)  
      BIG = 1.0E+35  
      NOCOM=.FALSE.  
      LIFN=IFN  
      IFN=0  
C  STEP CHANGE FACTORS  
      A1=1.5  
      A2=-0.25  
C  CHECK STEPSIZE  
      IF(ST.EQ.0.0) NOCOM=.TRUE.  
      IF(NOCOM) RETURN  
C  STEP 1  
      IFN=IFN+1  
      IF(IFN.GT.LIFN) GOTO 210  
      P=-BIG  
      P=FUNS(B,NOCOM)  
      IF(IPR.GT.0) WRITE(IPR,965) IFN,B,P
```

```

965  FORMAT(13H EVALUATION #,I4, 5H  F(,1PE16.8,2H)=,E16.8)
      IF(NOCOM)RETURN
C  STEP 2
20   S1=P
      S0=-BIG
      X1=0.0
      BMIN=B
C  STEP 3
30   X2=X1+ST
      B=BMIN+X2
C  STEP 4
      IF(B.EQ.BMIN+X1)GOTO 220
C  ALTERNATIVE STEP 4
C      IF(ABS(B)+EPS.EQ.ABS(BMIN)+ABS(X1)+EPS)GOTO 210
C  STEP 5
      IFN=IFN+1
      IF(IFN.GT.LIFN)GOTO 210
      NOCOM=.FALSE.
      P=FUNS(B,NOCOM)
      IF(NOCOM)GOTO 90
      IF(IPR.GT.0)WRITE(IPR,965)IFN,B,P
C  STEP 6
      IF(P.LT.S1)GOTO 100
C  STEP 7
      IF(S0.GE.S1)GOTO 110
C  STEP 8
      S0=P
      X0=X2
C  STEP 9
90   ST=A2*ST
      GOTO 30
C  STEP 10
100  X0=X1
      S0=S1
      X1=X2
      S1=P
      ST=A1*ST
      GOTO 30
C  STEP 11
110  X0=X0-X1
      S0=(S0-S1)*ST
      P=(P-S1)*X0
C  STEP 12
      IF(P.EQ.S0)GOTO 180
C  STEP 13
      ST=0.5*(P*X0-S0*ST)/(P-S0)
C  STEP 14
      X2=X1+ST
      B=BMIN+X2
C  STEP 15
      IF(B.EQ.BMIN+X1)GOTO 180
C  FIXED TO JUMP TO STEP 18, NOT STEP 20 (APRIL 1989)
C  STEP 16

```

```

        IFN=IFN+1
        IF(IFN.GT.LIFN)GOTO 210
        NOCOM=.FALSE.
        P=FUNS(B,NOCOM)
        IF(NOCOM)GOTO 180
        IF(IPR.GT.0)WRITE(IPR,965)IFN,B,P
C   STEP 17
        IF(P.LT.S1)GOTO 190
C   STEP 18
180    B=BMIN+X1
        P=S1
        GOTO 200
C   STEP 19
190    X1=X2
C   STEP 20
200    ST=A2*ST
        GOTO 20
210    IFN=LIFN
220    B=BMIN
        ST=S1
        RETURN
        END

```

Example output

```

gfortran ../fortran/dr18.f
mv ./a.out ../fortran/dr18f.run
../fortran/dr18f.run < ../fortran/dr18f.in

```

```

## TEST- COUNT=    5 NBIS=    5 U=          0.00000 V=          3.00000 TOL=    0.0000010000
##    2 EVALNS, F(  0.00000000E+00)= -5.00000000E+00 F(  3.00000000E+00)=  1.60000000E+01
##    3 EVALNS, F(  7.14285731E-01)= -6.06413984E+00 F(  3.00000000E+00)=  1.60000000E+01
##    4 EVALNS, F(  1.34249473E+00)= -5.26542187E+00 F(  3.00000000E+00)=  1.60000000E+01
##    5 EVALNS, F(  1.75290096E+00)= -3.11973000E+00 F(  3.00000000E+00)=  1.60000000E+01
## FAILURE
## ROOT U=  1.75290096E+00 F(U)= -3.11973000E+00 AFTER    5 EVALNS
## TEST- COUNT=   40 NBIS=    5 U=          0.00000 V=          3.00000 TOL=    0.0000000000
##    2 EVALNS, F(  0.00000000E+00)= -5.00000000E+00 F(  3.00000000E+00)=  1.60000000E+01
##    3 EVALNS, F(  7.14285731E-01)= -6.06413984E+00 F(  3.00000000E+00)=  1.60000000E+01
##    4 EVALNS, F(  1.34249473E+00)= -5.26542187E+00 F(  3.00000000E+00)=  1.60000000E+01
##    5 EVALNS, F(  1.75290096E+00)= -3.11973000E+00 F(  3.00000000E+00)=  1.60000000E+01
##    6 EVALNS, F(  1.95638776E+00)= -1.42479300E+00 F(  3.00000000E+00)=  1.60000000E+01
## BISECTION AT EVALN #    7
##    7 EVALNS, F(  2.04172206E+00)= -5.72261810E-01 F(  3.00000000E+00)=  1.60000000E+01
##    8 EVALNS, F(  2.04172206E+00)= -5.72261810E-01 F(  2.52086115E+00)=  5.97769737E+00
##    9 EVALNS, F(  2.08358383E+00)= -1.21660233E-01 F(  2.52086115E+00)=  5.97769737E+00
##   10 EVALNS, F(  2.09230590E+00)= -2.50315666E-02 F(  2.52086115E+00)=  5.97769737E+00
##   11 EVALNS, F(  2.09409308E+00)= -5.11503220E-03 F(  2.52086115E+00)=  5.97769737E+00
## BISECTION AT EVALN #   12
##   12 EVALNS, F(  2.09445810E+00)= -1.04284286E-03 F(  2.52086115E+00)=  5.97769737E+00
##   13 EVALNS, F(  2.09445810E+00)= -1.04284286E-03 F(  2.30765963E+00)=  2.67364454E+00
##   14 EVALNS, F(  2.09454131E+00)= -1.13964081E-04 F(  2.30765963E+00)=  2.67364454E+00
##   15 EVALNS, F(  2.09455061E+00)= -1.00135803E-05 F(  2.30765963E+00)=  2.67364454E+00
##   16 EVALNS, F(  2.09455132E+00)= -2.38418579E-06 F(  2.30765963E+00)=  2.67364454E+00

```



```

## BISECTION AT EVALN # 17
## ROOT U= 2.09455156E+00 F(U)= 1.43051147E-06 AFTER 17 EVALNS
## TEST- COUNT= 80 NBIS= 1 U= 0.00000 V= 3.00000 TOL= 0.0000000000
## 2 EVALNS, F( 0.00000000E+00)= -5.00000000E+00 F( 3.00000000E+00)= 1.60000000E+01
## BISECTION AT EVALN # 3
## 3 EVALNS, F( 7.14285731E-01)= -6.06413984E+00 F( 3.00000000E+00)= 1.60000000E+01
## BISECTION AT EVALN # 4
## 4 EVALNS, F( 1.85714281E+00)= -2.30903840E+00 F( 3.00000000E+00)= 1.60000000E+01
## BISECTION AT EVALN # 5
## 5 EVALNS, F( 1.85714281E+00)= -2.30903840E+00 F( 2.42857146E+00)= 4.46647263E+00
## BISECTION AT EVALN # 6
## 6 EVALNS, F( 1.85714281E+00)= -2.30903840E+00 F( 2.14285707E+00)= 5.53935051E-01
## BISECTION AT EVALN # 7
## 7 EVALNS, F( 2.00000000E+00)= -1.00000000E+00 F( 2.14285707E+00)= 5.53935051E-01
## BISECTION AT EVALN # 8
## 8 EVALNS, F( 2.07142854E+00)= -2.54737854E-01 F( 2.14285707E+00)= 5.53935051E-01
## BISECTION AT EVALN # 9
## 9 EVALNS, F( 2.07142854E+00)= -2.54737854E-01 F( 2.10714293E+00)= 1.41536236E-01
## BISECTION AT EVALN # 10
## 10 EVALNS, F( 2.08928585E+00)= -5.85985184E-02 F( 2.10714293E+00)= 1.41536236E-01
## BISECTION AT EVALN # 11
## 11 EVALNS, F( 2.08928585E+00)= -5.85985184E-02 F( 2.09821439E+00)= 4.09674644E-02
## BISECTION AT EVALN # 12
## 12 EVALNS, F( 2.09375000E+00)= -8.94165039E-03 F( 2.09821439E+00)= 4.09674644E-02
## BISECTION AT EVALN # 13
## 13 EVALNS, F( 2.09375000E+00)= -8.94165039E-03 F( 2.09598207E+00)= 1.59802437E-02
## BISECTION AT EVALN # 14
## 14 EVALNS, F( 2.09375000E+00)= -8.94165039E-03 F( 2.09486604E+00)= 3.51095200E-03
## BISECTION AT EVALN # 15
## 15 EVALNS, F( 2.09430790E+00)= -2.71844864E-03 F( 2.09486604E+00)= 3.51095200E-03
## BISECTION AT EVALN # 16
## 16 EVALNS, F( 2.09430790E+00)= -2.71844864E-03 F( 2.09458685E+00)= 3.95298004E-04
## BISECTION AT EVALN # 17
## 17 EVALNS, F( 2.09444737E+00)= -1.16205215E-03 F( 2.09458685E+00)= 3.95298004E-04
## BISECTION AT EVALN # 18
## 18 EVALNS, F( 2.09451723E+00)= -3.82423401E-04 F( 2.09458685E+00)= 3.95298004E-04
## BISECTION AT EVALN # 19
## 19 EVALNS, F( 2.09451723E+00)= -3.82423401E-04 F( 2.09455204E+00)= 6.67572021E-06
## BISECTION AT EVALN # 20
## 20 EVALNS, F( 2.09453464E+00)= -1.87873840E-04 F( 2.09455204E+00)= 6.67572021E-06
## BISECTION AT EVALN # 21
## 21 EVALNS, F( 2.09454346E+00)= -9.01222229E-05 F( 2.09455204E+00)= 6.67572021E-06
## BISECTION AT EVALN # 22
## 22 EVALNS, F( 2.09454775E+00)= -4.14848328E-05 F( 2.09455204E+00)= 6.67572021E-06
## BISECTION AT EVALN # 23
## 23 EVALNS, F( 2.09454989E+00)= -1.76429749E-05 F( 2.09455204E+00)= 6.67572021E-06
## BISECTION AT EVALN # 24
## 24 EVALNS, F( 2.09455109E+00)= -4.76837158E-06 F( 2.09455204E+00)= 6.67572021E-06
## BISECTION AT EVALN # 25
## 25 EVALNS, F( 2.09455109E+00)= -4.76837158E-06 F( 2.09455156E+00)= 1.43051147E-06
## BISECTION AT EVALN # 26
## ROOT U= 2.09455156E+00 F(U)= 1.43051147E-06 AFTER 26 EVALNS
## TEST- COUNT= 40 NBIS= 5 U= 0.00000 V= 3.00000 TOL= 0.0010000000
## 2 EVALNS, F( 0.00000000E+00)= -5.00000000E+00 F( 3.00000000E+00)= 1.60000000E+01

```

```

##      3 EVALNS, F( 7.14285731E-01)= -6.06413984E+00 F( 3.00000000E+00)= 1.60000000E+01
##      4 EVALNS, F( 1.34249473E+00)= -5.26542187E+00 F( 3.00000000E+00)= 1.60000000E+01
##      5 EVALNS, F( 1.75290096E+00)= -3.11973000E+00 F( 3.00000000E+00)= 1.60000000E+01
##      6 EVALNS, F( 1.95638776E+00)= -1.42479300E+00 F( 3.00000000E+00)= 1.60000000E+01
##      BISECTION AT EVALN #      7
##      7 EVALNS, F( 2.04172206E+00)= -5.72261810E-01 F( 3.00000000E+00)= 1.60000000E+01
##      8 EVALNS, F( 2.04172206E+00)= -5.72261810E-01 F( 2.52086115E+00)= 5.97769737E+00
##      9 EVALNS, F( 2.08358383E+00)= -1.21660233E-01 F( 2.52086115E+00)= 5.97769737E+00
##     10 EVALNS, F( 2.09230590E+00)= -2.50315666E-02 F( 2.52086115E+00)= 5.97769737E+00
##     11 EVALNS, F( 2.09409308E+00)= -5.11503220E-03 F( 2.52086115E+00)= 5.97769737E+00
##     BISECTION AT EVALN #     12
##     12 EVALNS, F( 2.09445810E+00)= -1.04284286E-03 F( 2.52086115E+00)= 5.97769737E+00
##     13 EVALNS, F( 2.09445810E+00)= -1.04284286E-03 F( 2.30765963E+00)= 2.67364454E+00
##     14 EVALNS, F( 2.09454131E+00)= -1.13964081E-04 F( 2.30765963E+00)= 2.67364454E+00
##     15 EVALNS, F( 2.09455061E+00)= -1.00135803E-05 F( 2.30765963E+00)= 2.67364454E+00
##     16 EVALNS, F( 2.09455132E+00)= -2.38418579E-06 F( 2.30765963E+00)= 2.67364454E+00
##     ROOT U= 2.09455132E+00 F(U)= -2.38418579E-06 AFTER 17 EVALNS
##     TEST- COUNT= 40 NBIS= 5 U= 0.00000 V= 1.00000 TOL= 0.0010000000
##     FAILURE
##     ROOT U= 0.00000000E+00 F(U)= 1.00000000E+00 AFTER 2 EVALNS
##     TEST- COUNT= 0 NBIS= 0 U= 0.00000 V= 0.00000 TOL= 0.0000000000

```

BASIC

The code used here was edited from one dated August 30, 1976. Changes were needed to adapt to the changed syntax of the PRINT statement and to allow us to run the program inside a scripted environment, but the logic is unchanged. For example, we have artificially inserted a working set of values to start the Bisection / False Position rootfinder after the grid search. The original program was designed to present the grid search so that the user could interactively choose an interval for which the endpoints had different function values to start the rootfinder.

Listing

```

5 PRINT "ENHROO AUG 30 76"
10 PRINT "GRID SEARCH"
20 READ U
30 REM PRINT "U=";U
40 READ V
50 PRINT "U=";U;" V=";V
70 READ N9
80 PRINT "# OF POINTS";N9
100 LET H=(V-U)/N9
110 FOR I=0 TO N9
120 LET B=U+I*H
130 GOSUB 2000
140 PRINT "F(",B,")=",P
150 NEXT I
160 REM STOP
200 PRINT "ROOTFINDER"
210 READ U
220 REM PRINT "U=";U
230 READ V
240 PRINT "U=";U;" V=";V
250 REM PRINT

```

```

260 READ N9
270 PRINT "BISECTION EVERY";N9
280 REM PRINT
290 READ E3
300 PRINT "TOLERANCE";E3
310 REM PRINT
320 GOSUB 1000
330 PRINT "ROOT: F(",B,")=",P
335 PRINT "Done!" : rem stop
340 QUIT
1000 REM BISECTION/FALSE POSITION ROOT-FINDER
1010 LET B=U
1020 GOSUB 2000
1030 LET F1=P
1040 LET B=V
1050 GOSUB 2000
1060 LET F2=P
1070 IF F1*F2<=0 THEN GOTO 1090
1075 PRINT "FUNCTIONS HAVE SAME SIGN AT BOTH ENDS OF INTERVAL"
1080 QUIT
1090 PRINT "F(";U,")=";F1;" F(";V,")=";F2
1100 LET I9=0
1110 REM FALSE POSITION
1115 PRINT "FP ";
1120 LET B=(U*F2-V*F1)/(F2-F1)
1130 IF B>U THEN GOTO 1160
1140 LET B=U
1145 LET P=F1
1150 GOTO 1320
1160 IF B<V THEN GOTO 1190
1170 LET B=V
1175 LET P=F2
1180 GOTO 1320
1190 LET I9=I9+1
1200 GOSUB 2000
1210 PRINT "ITN";I9;" U=";U;" V=";V;" F(";B,")=";P
1220 IF P*F1>0 THEN GOTO 1260
1230 LET F2=P
1240 LET V=B
1250 GOTO 1280
1260 LET F1=P
1270 LET U=B
1280 IF (V-U)<E3 THEN GOTO 1320
1290 IF N9*INT(I9/N9)<>I9 THEN GOTO 1110
1295 PRINT "BI ";
1300 LET B=(U+V)/2 : REM BETTER IS U+(V-U)*0.5
1310 GOTO 1130
1320 PRINT "CONVERGED"
1330 RETURN
2000 REM CUBIC FUNCTION TEST
2010 LET P=B*(B*B-2.0)-5.0
2020 REM NOTE USE ARGUMENT B AND RETURNED VALUE P
2090 RETURN

```

```
2200 DATA 0, 5, 10, 2, 2.5, 5, 1e-12
2300 END
```

Example output

```
bwbasic ../BASIC/a18roo.bas
```

```
## Bywater BASIC Interpreter/Shell, version 2.20 patch level 2
## Copyright (c) 1993, Ted A. Campbell
## Copyright (c) 1995-1997, Jon B. Volkoff
##
## ENHROO AUG 30 76
## GRID SEARCH
## U= 0 V= 5
## # OF POINTS 10
## F(      0      )=      -5
## F(      0.500000 )=     -5.8750000
## F(      1      )=      -6
## F(      1.500000 )=     -4.6250000
## F(      2      )=      -1
## F(      2.500000 )=      5.6250000
## F(      3      )=      16
## F(      3.500000 )=     30.8750000
## F(      4      )=      51
## F(      4.500000 )=     77.1250000
## F(      5      )=     110
## ROOTFINDER
## U= 2 V= 2.5000000
## BISECTION EVERY 5
## TOLERANCE 0
## F( 2)= -1 F( 2.5000000)= 5.6250000
## FP ITN 1 U= 2 V= 2.5000000 F( 2.0754717)= -0.2106773
## FP ITN 2 U= 2.0754717 V= 2.5000000 F( 2.0907978)= -0.0418075
## FP ITN 3 U= 2.0907978 V= 2.5000000 F( 2.0938168)= -0.0081969
## FP ITN 4 U= 2.0938168 V= 2.5000000 F( 2.0944078)= -0.0016033
## FP ITN 5 U= 2.0944078 V= 2.5000000 F( 2.0945234)= -0.0003135
## BI ITN 6 U= 2.0945234 V= 2.5000000 F( 2.2972617)= 2.5290715
## FP ITN 7 U= 2.0945234 V= 2.2972617 F( 2.0945485)= -0.000033
## FP ITN 8 U= 2.0945485 V= 2.2972617 F( 2.0945512)= -0.0000035
## FP ITN 9 U= 2.0945512 V= 2.2972617 F( 2.0945514)= -0.0000004
## FP ITN 10 U= 2.0945514 V= 2.2972617 F( 2.0945515)= -0
## BI ITN 11 U= 2.0945515 V= 2.2972617 F( 2.1959066)= 1.196861
## FP ITN 12 U= 2.0945515 V= 2.1959066 F( 2.0945515)= -0
## FP ITN 13 U= 2.0945515 V= 2.1959066 F( 2.0945515)= -0
## FP ITN 14 U= 2.0945515 V= 2.1959066 F( 2.0945515)= -0
## FP ITN 15 U= 2.0945515 V= 2.1959066 F( 2.0945515)= -0
## BI ITN 16 U= 2.0945515 V= 2.1959066 F( 2.145229)= 0.5819023
## FP ITN 17 U= 2.0945515 V= 2.145229 F( 2.0945515)= -0
## FP ITN 18 U= 2.0945515 V= 2.145229 F( 2.0945515)= 0
## CONVERGED
## ROOT: F(      2.0945515      )=      0
## Done!
```

Pascal

Listing

Note that in this routine, we use bisection every 5 function evaluations. That is, we fix the `nbis` variable at 5. This could easily be changed to make it an input quantity.

?? Do we want to discuss why this may be useful?

```
procedure root1d(var lbound, ubound: real;
                 var ifn: integer;
                 tol : real;
                 var noroot: boolean );

var
  nbis: integer;
  b, fb, flow, fup : real;
  notcomp: boolean;

begin
  writeln('alg18.pas -- root of a function of one variable');

  notcomp := false;
  ifn := 2;
  nbis := 5;
  fup := fn1d(ubound, notcomp);
  if notcomp then halt;
  flow := fn1d(lbound, notcomp);
  if notcomp then halt;
  writeln('f(', lbound:8:5, ')=' , flow, '  f(', ubound:8:5, ')=' , fup);
  if fup*flow>0 then noroot := true else noroot := false;
  while (not noroot) and ((ubound-lbound)>tol) do
    begin
      if (nbis * ((ifn - 2) div nbis) = (ifn - 2)) then
        begin
          write('Bisect ');
          b := lbound + 0.5*(ubound - lbound)
        end
      else
        begin
          write('False P ');
          b := (lbound*fup-ubound*flow)/(fup-flow);
        end;

      if b<=lbound then
        begin
          b := lbound;
          ubound := lbound;
        end;
      if b>=ubound then
        begin
          b := ubound; lbound := ubound;
        end;
      ifn := ifn+1;
      fb := fn1d(b, notcomp);
```

```

if notcomp then halt;
write(ifn, ' evalns: f(',b:16,')=' ,fb:10);
write(confile,ifn, ' evalns: f(',b:16,')=' ,fb:10);
writeln(' width interval= ',(ubound-lbound):10);
writeln(confile,' width interval= ',(ubound-lbound):10);
if (ubound-lbound)>tol then
begin
  if fb*flow<0.0 then
  begin
    fup := fb; ubound := b;
  end
  else
  begin
    flow := fb; lbound := b;
  end;
end;
end;
writeln('Converged to f(',b,')=' ,fb);
writeln(' Final interval width =',ubound-lbound);
end;

```

Example output

First we compile the codes.

```

fpc ../Pascal2021/dr1618.pas
# copy to run file
mv ../Pascal2021/dr1618 ../Pascal2021/dr1618p.run

```

```

## Free Pascal Compiler version 3.0.4+dfsg-23 [2019/11/25] for x86_64
## Copyright (c) 1993-2017 by Florian Klaempfl and others
## Target OS: Linux for x86-64
## Compiling ../Pascal2021/dr1618.pas
## Linking ../Pascal2021/dr1618
## /usr/bin/ld.bfd: warning: link.res contains output sections; did you forget -T?
## 205 lines compiled, 0.1 sec

```

Then we run the grid search (Algorithm 16) followed by the Bisection / False position routine (Algorithm 18).

```

../Pascal2021/dr1618p.run <../Pascal2021/dr1618a.in >../Pascal2021/dr1618a.out

```

```

Enter lower bound for search 0.000000000000000E+000
Enter upper bound for search 5.000000000000000E+000
Enter the number of intervals for grid search (0 for none) 10
Enter a tolerance for root search interval width 1.000000000000000E-010
alg16.pas -- one-dimensional grid search
In gridsrch lbound= 0.000000000000000E+000 ubound= 5.000000000000000E+000
lb f( 0.000000000000000E+000)=-5.000000000000000E+000
f( 5.000000000000000E-001)=-5.875000000000000E+000
f( 1.000000000000000E+000)=-6.000000000000000E+000
f( 1.500000000000000E+000)=-4.625000000000000E+000
f( 2.000000000000000E+000)=-1.000000000000000E+000
f( 2.500000000000000E+000)= 5.625000000000000E+000 *** sign change ***
f( 3.000000000000000E+000)= 1.600000000000000E+001
f( 3.500000000000000E+000)= 3.087500000000000E+001
f( 4.000000000000000E+000)= 5.100000000000000E+001

```

```

f( 4.500000000000000E+000)= 7.712500000000000E+001
f( 5.000000000000000E+000)= 1.100000000000000E+002
Minimum so far is f( 1.000000000000000E+000)=-6.000000000000000E+000
Sign change observed last in interval
[ 2.000000000000000E+000, 2.500000000000000E+000]
Now try rootfinder
alg18.pas -- root of a function of one variable
f( 2.000000)=-1.000000000000000E+000 f( 2.500000)= 5.625000000000000E+000
Bisect 3 evalns: f( 2.25000000E+000)= 1.89E+000 width interval= 5.00E-001
False P 4 evalns: f( 2.08648649E+000)=-8.96E-002 width interval= 2.50E-001
False P 5 evalns: f( 2.09388573E+000)=-7.43E-003 width interval= 1.64E-001
False P 6 evalns: f( 2.09449668E+000)=-6.12E-004 width interval= 1.56E-001
False P 7 evalns: f( 2.09454697E+000)=-5.03E-005 width interval= 1.56E-001
Bisect 8 evalns: f( 2.17227349E+000)= 9.06E-001 width interval= 1.55E-001
False P 9 evalns: f( 2.09455129E+000)=-2.14E-006 width interval= 7.77E-002
False P 10 evalns: f( 2.09455147E+000)=-9.06E-008 width interval= 7.77E-002
False P 11 evalns: f( 2.09455148E+000)=-3.84E-009 width interval= 7.77E-002
False P 12 evalns: f( 2.09455148E+000)=-1.63E-010 width interval= 7.77E-002
Bisect 13 evalns: f( 2.13341248E+000)= 4.43E-001 width interval= 7.77E-002
False P 14 evalns: f( 2.09455148E+000)=-3.51E-012 width interval= 3.89E-002
False P 15 evalns: f( 2.09455148E+000)=-7.55E-014 width interval= 3.89E-002
False P 16 evalns: f( 2.09455148E+000)=-1.78E-015 width interval= 3.89E-002
False P 17 evalns: f( 2.09455148E+000)=-1.78E-015 width interval= 0.00E+000
Converged to f( 2.0945514815423265E+000)=-1.7763568394002505E-015
Final interval width = 0.000000000000000E+000

```

Let us try WITHOUT grid search first.

```

../Pascal2021/dr1618p.run <../Pascal2021/dr1618b.in >../Pascal2021/dr1618b.out

```

```

Enter lower bound for search 0.000000000000000E+000
Enter upper bound for search 5.000000000000000E+000
Enter the number of intervals for grid search (0 for none) 0
Enter a tolerance for root search interval width 1.000000000000000E-010
Now try rootfinder
alg18.pas -- root of a function of one variable
f( 0.000000)=-5.000000000000000E+000 f( 5.000000)= 1.100000000000000E+002
Bisect 3 evalns: f( 2.50000000E+000)= 5.63E+000 width interval= 5.00E+000
False P 4 evalns: f( 1.17647059E+000)=-5.72E+000 width interval= 2.50E+000
False P 5 evalns: f( 1.84404318E+000)=-2.42E+000 width interval= 1.32E+000
False P 6 evalns: f( 2.04121344E+000)=-5.78E-001 width interval= 6.56E-001
False P 7 evalns: f( 2.08393696E+000)=-1.18E-001 width interval= 4.59E-001
Bisect 8 evalns: f( 2.29196848E+000)= 2.46E+000 width interval= 4.16E-001
False P 9 evalns: f( 2.09345558E+000)=-1.22E-002 width interval= 2.08E-001
False P 10 evalns: f( 2.09443873E+000)=-1.26E-003 width interval= 1.99E-001
False P 11 evalns: f( 2.09453989E+000)=-1.29E-004 width interval= 1.98E-001
False P 12 evalns: f( 2.09455029E+000)=-1.33E-005 width interval= 1.97E-001
Bisect 13 evalns: f( 2.19325938E+000)= 1.16E+000 width interval= 1.97E-001
False P 14 evalns: f( 2.09455142E+000)=-7.11E-007 width interval= 9.87E-002
False P 15 evalns: f( 2.09455148E+000)=-3.80E-008 width interval= 9.87E-002
False P 16 evalns: f( 2.09455148E+000)=-2.03E-009 width interval= 9.87E-002
False P 17 evalns: f( 2.09455148E+000)=-1.08E-010 width interval= 9.87E-002
Bisect 18 evalns: f( 2.14390543E+000)= 5.66E-001 width interval= 9.87E-002
False P 19 evalns: f( 2.09455148E+000)=-2.95E-012 width interval= 4.94E-002
False P 20 evalns: f( 2.09455148E+000)=-7.99E-014 width interval= 4.94E-002

```

```
False P 21 evalns: f( 2.09455148E+000)=-6.22E-015 width interval= 4.94E-002
False P 22 evalns: f( 2.09455148E+000)=-1.78E-015 width interval= 4.94E-002
Bisect 23 evalns: f( 2.11922846E+000)= 2.79E-001 width interval= 4.94E-002
False P 24 evalns: f( 2.09455148E+000)= 3.55E-015 width interval= 2.47E-002
Converged to f( 2.0945514815423270E+000)= 3.5527136788005009E-015
Final interval width = 4.4408920985006262E-016
```

But we can run just the minimizer. Note that above we use only 13 function evaluations in the minimizer, but now use 17 (for the input used in this example). However, the grid search used 11 function evaluations prior to the call to the minimizer for a total of 24.

Algorithm 27 – Hooke and Jeeves pattern search minimization

Pascal

Listing

```
procedure hjmin(n: integer;
  var B,X: rvector;
  var Fmin: real;
  Workdata: probdata;
  var fail: boolean;
  intol: real);

var
  i: integer;
  stepsize: real;
  fold: real;
  fval: real;
  notcomp: boolean;
  temp: real;
  samepoint: boolean;
  ifn: integer;

begin
  if intol<0.0 then intol := calceps;
  ifn := 1;
  fail := false;

  stepsize := 0.0;
  for i := 1 to n do
    if stepsize < stepredn*abs(B[i]) then stepsize := stepredn*abs(B[i]);
  if stepsize=0.0 then stepsize := stepredn;

  for i := 1 to n do X[i] := B[i];

  fval := fminfn(n, B,Workdata,notcomp);
  if notcomp then
    begin
      writeln('*** FAILURE *** Function not computable at initial point');
      fail := true;
    end
  else
    begin
      writeln('Initial function value =',fval);
      for i := 1 to n do
        begin
          write(B[i]:10:5,' ');
          if (7 * (i div 7) = i) and (i<n) then writeln;
        end;
      writeln;
      fold := fval; Fmin := fval;
      while stepsize>intol do
        begin
```

```

for i := 1 to n do
begin
  temp := B[i]; B[i] := temp+stepsize;
  fval := fminfn(n, B,Workdata,notcomp); ifn := ifn+1;
  if notcomp then fval := big;
  if fval<Fmin then
    Fmin := fval
  else
    begin
      B[i] := temp-stepsize;
      fval := fminfn(n, B,Workdata,notcomp); ifn := ifn+1;
      if notcomp then fval := big;
      if fval<Fmin then
        Fmin := fval
      else
        B[i] := temp;
    end;
end;
if Fmin<fold then
begin
  for i := 1 to n do
  begin
    temp := 2.0*B[i]-X[i];
    X[i] := B[i]; B[i] := temp;
  end;
  fold := Fmin;
end
else
begin
  samepoint := true;
  i := 1;
  repeat
    if B[i]<>X[i] then samepoint := false;
    i := i+1;
  until (not samepoint) or (i>n);
  if samepoint then
  begin
    stepsize := stepsize*stepredn;

    write('stepsize now ',stepsize:10,' Best fn value=',Fmin);
    writeln(' after ',ifn);
    for i := 1 to n do
    begin
      write(B[i]:10:5,' ');
      if (7 * (i div 7) = i) and (i<n) then writeln;
    end;
    writeln;
  end
  else
  begin
    for i := 1 to n do B[i] := X[i];
    writeln('Return to old base point');
  end
end

```

```

        end;
    end;
end;
writeln('Converged to Fmin=',Fmin,' after ',ifn,' evaluations');
end;
end;

```

Example output

Example output

Use Rosenbrock banana-shaped valley problem in 2 dimensions.

```

fpc ../Pascal2021/dr27.pas
# copy to run file
mv ../Pascal2021/dr27 ../Pascal2021/dr27.run
../Pascal2021/dr27.run >../Pascal2021/dr27p.out

## Free Pascal Compiler version 3.0.4+dfsg-23 [2019/11/25] for x86_64
## Copyright (c) 1993-2017 by Florian Klaempfl and others
## Target OS: Linux for x86-64
## Compiling ../Pascal2021/dr27.pas
## Linking ../Pascal2021/dr27
## /usr/bin/ld.bfd: warning: link.res contains output sections; did you forget -T?
## 303 lines compiled, 0.1 sec

Function: Rosenbrock Banana Valley
Classical starting point (-1.2,1)
Initial function value = 2.4199999999999996E+001
-1.20000 1.00000
Return to old base point
stepsize now 4.80E-002 Best fn value= 4.4562559999999998E+000 after 12
-0.96000 1.00000
Return to old base point
stepsize now 9.60E-003 Best fn value= 4.0578692096000006E+000 after 24
-1.00800 1.00000
Return to old base point
Return to old base point
Return to old base point
stepsize now 1.92E-003 Best fn value= 1.0707319193525812E-003 after 161
0.98880 0.98080
Return to old base point
stepsize now 3.84E-004 Best fn value= 1.3884319308353293E-004 after 172
0.99072 0.98080
Return to old base point
stepsize now 7.68E-005 Best fn value= 9.3512661164573335E-005 after 184
0.99034 0.98080
Return to old base point
stepsize now 1.54E-005 Best fn value= 1.1312841503153136E-007 after 387
0.99978 0.99954
Return to old base point
stepsize now 3.07E-006 Best fn value= 5.6836523263813657E-008 after 399
0.99977 0.99954
Return to old base point
stepsize now 6.14E-007 Best fn value= 5.2964452813167824E-008 after 410

```

```

    0.99977    0.99954
Return to old base point
stepsize now 1.23E-007 Best fn value= 1.4270706145809712E-011 after 506
    1.00000    0.99999
Return to old base point
stepsize now 2.46E-008 Best fn value= 9.4796228739601164E-012 after 517
    1.00000    0.99999
Return to old base point
stepsize now 4.92E-009 Best fn value= 9.4690619892340589E-012 after 529
    1.00000    0.99999
Return to old base point
Return to old base point
stepsize now 9.83E-010 Best fn value= 4.4567065650768205E-015 after 661
    1.00000    1.00000
Return to old base point
stepsize now 1.97E-010 Best fn value= 4.0727302462025689E-015 after 673
    1.00000    1.00000
Return to old base point
stepsize now 3.93E-011 Best fn value= 5.5957365459244406E-019 after 1084
    1.00000    1.00000
Return to old base point
stepsize now 7.86E-012 Best fn value= 1.7697158812184515E-019 after 1096
    1.00000    1.00000
Return to old base point
stepsize now 1.57E-012 Best fn value= 1.5428882521329409E-019 after 1107
    1.00000    1.00000
Return to old base point
stepsize now 3.15E-013 Best fn value= 2.9714142551459652E-023 after 1190
    1.00000    1.00000
Return to old base point
stepsize now 6.29E-014 Best fn value= 3.6918757417520296E-024 after 1201
    1.00000    1.00000
Return to old base point
stepsize now 1.26E-014 Best fn value= 2.5495050765906063E-024 after 1213
    1.00000    1.00000
Return to old base point
stepsize now 2.52E-015 Best fn value= 4.7610344079933319E-027 after 1293
    1.00000    1.00000
Return to old base point
stepsize now 5.03E-016 Best fn value= 3.9955928108960689E-027 after 1304
    1.00000    1.00000
Converged to Fmin= 3.9955928108960689E-027 after 1304 evaluations

Minimum function value found = 3.9955928108960689E-027
At parameters
B[1]= 9.9999999999993683E-001
B[2]= 9.999999999987343E-001

```

R

Listing

```

# hjn.R -- R implementation of J Nash BASIC HJG.BAS 20160705
hjn <- function(par, fn, lower=-Inf, upper=Inf, bdmsk=NULL, control=list(trace=0), ...){
  n <- length(par) # number of parameters
  if (! is.null(control$maximize) && control$maximize)
    stop("Do NOT try to maximize with hjn()")
  if (is.null(control$trace)) control$trace <- 0 # just in case
  if (is.null(control$stepsize)) {
    stepsize <- 1 # initial step size (could put in control())
  } else { stepsize <- control$stepsize }
  # Want stepsize positive or bounds get messed up
  if (is.null(control$stepredn)) {
    stepredn <- .1 # defined step reduction (again in control()??)
  } else { stepredn <- control$stepredn }
  if (is.null(control$maxfeval)) control$maxfeval<-2000*n
  if (is.null(control$seps)) control$sepsl<-1e-07
  steptol <- control$seps
  # Hooke and Jeeves with bounds and masks
  if (length(upper) == 1) upper <- rep(upper, n)
  if (length(lower) == 1) lower <- rep(lower, n)
  if (is.null(bdmsk)) {
    bdmsk <- rep(1,n)
    idx <- 1:n
  } else { idx <- which(bdmsk != 0) } # define masks
  if (any(lower >= upper)){
    warning("hjn: lower >= upper for some parameters -- set masks")
    bdmsk[which(lower >= upper)] <- 0
    idx <- which(bdmsk != 0)
  }
  if (control$trace > 0) {
    cat("hjn:bdmsk:")
    print(bdmsk)
  }
  # cat("idx:")
  # print(idx)
  }
  nac <- length(idx)
  offset = 100. # get from control() -- used for equality check
  if (any(par < lower) || any(par > upper)) stop("hjn: initial parameters out of bounds")
  pbase <- par # base parameter set (fold is function value)
  f <- fn(par, ...) # fn at base point
  fmin <- fold <- f # "best" function so far
  pbest <- par # Not really needed
  fcount <- 1 # count function evaluations, compare with maxfeval
  # cat(fcount, " f=",fold," at ")
  # print(par)
  # tmp <- readline("cont.")
  keepgoing <- TRUE
  ccode <- 1 # start assuming won't get to solution before feval limit
  while (keepgoing) {
    # exploratory search -- fold stays same for whole set of axes
    if (control$trace > 0) cat("Exploratory move - stepsize = ",stepsize,"\n")
    if (control$trace > 1) {
      cat("p-start:")
      print(par)
    }

```

```

}
for (jj in 1:nac){ # possibly could do this better in R
  # use unmasked parameters
  j <- idx[jj]
  ptmp <- par[j]
  doneg <- TRUE # assume we will do negative step
  if (ptmp + offset < upper[j] + offset) { # Not on upper bound so do pos step
    par[j] <- min(ptmp+stepsize, upper[j])
    if ((par[j] + offset) != (ptmp + offset)) {
      fcount <- fcount + 1
      f <- fn(par, ...)
      #      cat(fcount, " f=",f," at ")
      #      print(par)
      if (f < fmin) {
        fmin <- f
        pbest <- par
        #      cat("*")
        doneg <- FALSE # only case where we don't do neg
        resetpar <- FALSE
      }
      #      tmp <- readline("cont>")
    }
  } # end not on upper bound
  if (fcount >= control$maxfeval) break
  if (doneg) {
    resetpar <- TRUE # going to reset the parameter unless we improve
    if ((ptmp + offset) > (lower[j] + offset)) { # can do negative step
      par[j] <- max((ptmp - stepsize), lower[j])
      if ((par[j] + offset) != (ptmp + offset)) {
        fcount <- fcount + 1
        f <- fn(par, ...)
        #      cat(fcount, " f=",f," at ")
        #      print(par)
        if (f < fmin) {
          fmin <- f
          pbest <- par
          #      cat("*")
          resetpar <- FALSE # don't reset parameter
        }
        #      tmp <- readline("cont<")
      }
    } # neg step possible
  } # end doneg
  if (resetpar) { par[j] <- ptmp }
} # end loop on axes
if (fcount >= control$maxfeval) {
  ccode <- 1
  if (control$trace > 0) cat("Function count limit exceeded\n")
  ans <- list(par=pbest, value=fmin, counts=c(fcount, NA), convergence=ccode)
  return(ans)
}
if (control$trace > 0) {
  cat("axial search with stepsize =",stepsize," fn value = ",fmin," after ",fcount," maxfeval =

```

```

}
if (fmin < fold) { # success -- do pattern move (control$trace > 0) cat("Pattern move \n")
  if (control$trace > 1) {
    cat("PM from:")
    print(par)
    cat("pbest:")
    print(pbest)
  }
  for (jj in 1:nac) { # Note par is best set of parameters
    j <- idx[jj]
    ptmp <- 2.0*par[j] - pbase[j]
    if (ptmp > upper[j]) ptmp <- upper[j]
    if (ptmp < lower[j]) ptmp <- lower[j]
    pbase[j] <- par[j]
    par[j] <- ptmp
  }
  fold <- fmin
  if (control$trace > 1) {
    cat("PM to:")
    print(par)
  }
  # Addition to HJ -- test new base
  #   fcount <- fcount + 1
  #   f <- fn(par, ...)
  #   cat(fcount, " f=",f," at ")
  #   print(par)
  #   tmp <- readline("PM point")
  #   if (f < fmin) {
  #     if (control$trace > 0) {cat("Use PM point as new base\n")}
  #     pbest <- pbase <- par
  #   }
} else { # no success in Axial Seart, so reduce stepsize
  if (fcount >= control$maxfeval) {
    ccode <- 1
    if (control$trace > 0) cat("Function count limit exceeded\n")
    ans <- list(par=pbest, value=fmin, counts=c(fcount, NA), convergence=ccode)
    return(ans)
  }
  # first check if point changed
  samepoint <- identical((par + offset),(pbase + offset))
  if (samepoint) {
    stepsize <- stepsize*stepredn
    if (control$trace > 1) cat("Reducing step to ",stepsize,"\n")
    if (stepsize <= steptol) keepgoing <- FALSE
    ccode <- 0 # successful convergence
  } else { # return to old base point
    if (control$trace > 1) {
      cat("return to base at:")
      print(pbase)
    }
    par <- pbase
  }
}
}

```

```

    if (fcount >= control$maxfeval) {
      ccode <- 1
      if (control$trace > 0) cat("Function count limit exceeded\n")
      ans <- list(par=pbest, value=fmin, counts=c(fcount, NA), convergence=ccode)
      return(ans)
    }
  } # end keepgoing loop
  if ( control$trace > 1 ) {
    if (identical(pbest, pbase)) {cat("pbase = pbest\n") }
    else { cat("BAD!: pbase != pbest\n") }
  }

  ans <- list(par=pbest, value=fmin, counts=c(fcount, NA), convergence=ccode)
}

```

Example output

We use the Rosenbrock banana-shaped valley problem in 2 dimensions.

```

source("../R/hjn.R")
fminfn <-function(x){
  val<-((x[2]-x[1]^2)^2)*100.0+(1.0-x[1])^2
  val
}
x0<-c(-1.2,1)
cat("Check fn at c(-1.2,1)=",fminfn(x0),"\n")

```

```
## Check fn at c(-1.2,1)= 24.2
```

```

rslt <- hjn(par=x0, fn=fminfn, control=list(trace=0))
print(rslt)

```

```

## $par
## [1] 1.000001 1.000002
##
## $value
## [1] 6.399999e-13
##
## $counts
## [1] 1996    NA
##
## $convergence
## [1] 0

```

Cleanup of working files

The following script is included to remove files created during compilation or execution of the examples.

```

## remove object and run files
cd ../fortran/
echo `pwd`
rm *.o
rm *.run
rm *.out
cd ../Pascal2021/

```



```

echo `pwd`
rm *.o
rm *.run
rm *.out
cd ../BASIC
echo `pwd`
rm *.out
cd ../Documentation
## ?? others

## /j19z/j19store/versioned/Nash-Compact-Numerical-Methods/fortran
## rm: cannot remove '*.o': No such file or directory
## rm: cannot remove '*.out': No such file or directory
## /j19z/j19store/versioned/Nash-Compact-Numerical-Methods/Pascal2021
## /j19z/j19store/versioned/Nash-Compact-Numerical-Methods/BASIC
## rm: cannot remove '*.out': No such file or directory

```

References

- Brent, R. 1973. *Algorithms for Minimization Without Derivatives*. Englewood Cliffs, NJ: Prentice-Hall.
- Maechler, Martin. 2020. *Rmpfr: R Mpfr - Multiple Precision Floating-Point Reliable*. <https://CRAN.R-project.org/package=Rmpfr>.
- Nash, John C. 1979. *Compact Numerical Methods for Computers : Linear Algebra and Function Minimisation*. Book. Hilger: Bristol.