

## 17.2 Shooting to a Fitting Point

The shooting method described in §17.1 tacitly assumed that the “shots” would be able to traverse the entire domain of integration, even at the early stages of convergence to a correct solution. In some problems it can happen that, for very wrong starting conditions, an initial solution can’t even get from  $x_1$  to  $x_2$  without encountering some incalculable, or catastrophic, result. For example, the argument of a square root might go negative, causing the numerical code to crash. Simple shooting would be stymied.

A different, but related, case is where the endpoints are both singular points of the set of ODEs. One frequently needs to use special methods to integrate near the singular points, analytic asymptotic expansions, for example. In such cases it is feasible to integrate in the direction *away* from a singular point, using the special method to get through the first little bit and then reading off “initial” values for further numerical integration. However it is usually not feasible to integrate *into* a singular point, if only because one has not usually expended the same analytic effort to obtain expansions of “wrong” solutions near the singular point (those not satisfying the desired boundary condition).

The solution to the above mentioned difficulties is *shooting to a fitting point*. Instead of integrating from  $x_1$  to  $x_2$ , we integrate first from  $x_1$  to some point  $x_f$  that is *between*  $x_1$  and  $x_2$ ; and second from  $x_2$  (in the opposite direction) to  $x_f$ .

If (as before) the number of boundary conditions imposed at  $x_1$  is  $n_1$ , and the number imposed at  $x_2$  is  $n_2$ , then there are  $n_2$  freely specifiable starting values at  $x_1$  and  $n_1$  freely specifiable starting values at  $x_2$ . (If you are confused by this, go back to §17.1.) We can therefore define an  $n_2$ -vector  $\mathbf{V}_{(1)}$  of starting parameters at  $x_1$ , and a prescription  $\text{load1}(x_1, \mathbf{v}_1, \mathbf{y})$  for mapping  $\mathbf{V}_{(1)}$  into a  $\mathbf{y}$  that satisfies the boundary conditions at  $x_1$ ,

$$y_i(x_1) = y_i(x_1; V_{(1)1}, \dots, V_{(1)n_2}) \quad i = 1, \dots, N \quad (17.2.1)$$

Likewise we can define an  $n_1$ -vector  $\mathbf{V}_{(2)}$  of starting parameters at  $x_2$ , and a prescription  $\text{load2}(x_2, \mathbf{v}_2, \mathbf{y})$  for mapping  $\mathbf{V}_{(2)}$  into a  $\mathbf{y}$  that satisfies the boundary conditions at  $x_2$ ,

$$y_i(x_2) = y_i(x_2; V_{(2)1}, \dots, V_{(2)n_1}) \quad i = 1, \dots, N \quad (17.2.2)$$

We thus have a total of  $N$  freely adjustable parameters in the combination of  $\mathbf{V}_{(1)}$  and  $\mathbf{V}_{(2)}$ . The  $N$  conditions that must be satisfied are that there be agreement in  $N$  components of  $\mathbf{y}$  at  $x_f$  between the values obtained integrating from one side and from the other,

$$y_i(x_f; \mathbf{V}_{(1)}) = y_i(x_f; \mathbf{V}_{(2)}) \quad i = 1, \dots, N \quad (17.2.3)$$

In some problems, the  $N$  matching conditions can be better described (physically, mathematically, or numerically) by using  $N$  different functions  $F_i$ ,  $i = 1 \dots N$ , each possibly depending on the  $N$  components  $y_i$ . In those cases, (17.2.3) is replaced by

$$F_i[\mathbf{y}(x_f; \mathbf{V}_{(1)})] = F_i[\mathbf{y}(x_f; \mathbf{V}_{(2)})] \quad i = 1, \dots, N \quad (17.2.4)$$

In the program below, the user-supplied function  $\text{score}(x_f, y, f)$  is supposed to map an input  $N$ -vector  $y$  into an output  $N$ -vector  $F$ . In most cases, you can dummy this function as the identity mapping.

Shooting to a fitting point uses globally convergent Newton-Raphson exactly as in §17.1. Comparing closely with the routine `shoot` of the previous section, you should have no difficulty in understanding the following routine `shootf`. The main differences in use are that you have to supply both `load1` and `load2`. Also, in the calling program you must supply initial guesses for  $v_1[1..n_2]$  and  $v_2[1..n_1]$ . Once again a sample program illustrating shooting to a fitting point is given in §17.4.

```
#include "nrutil.h"
#define EPS 1.0e-6

extern int nn2,nvar;          Variables that you must define and set in your main program.
extern float x1,x2,xf;

int kmax,kount;             Communicates with odeint.
float *xp,**yp,dxsav;

void shootf(int n, float v[], float f[])
Routine for use with newt to solve a two point boundary value problem for nvar coupled
ODEs by shooting from x1 and x2 to a fitting point xf. Initial values for the nvar ODEs at
x1 (x2) are generated from the n2 (n1) coefficients v1 (v2), using the user-supplied routine
load1 (load2). The coefficients v1 and v2 should be stored in a single array v[1..n1+n2]
in the main program by statements of the form v1=v; and v2 = &v[n2];. The input parameter
n = n1 + n2 = nvar. The routine integrates the ODEs to xf using the Runge-Kutta
method with tolerance EPS, initial stepsize h1, and minimum stepsize hmin. At xf it calls the
user-supplied routine score to evaluate the nvar functions f1 and f2 that ought to match
at xf. The differences f are returned on output. newt uses a globally convergent Newton's
method to adjust the values of v until the functions f are zero. The user-supplied routine
derivs(x,y,dydx) supplies derivative information to the ODE integrator (see Chapter 16).
The first set of global variables above receives its values from the main program so that shoot
can have the syntax required for it to be the argument vecfunc of newt. Set nn2 = n2 in
the main program.
{
    void derivs(float x, float y[], float dydx[]);
    void load1(float x1, float v1[], float y[]);
    void load2(float x2, float v2[], float y[]);
    void odeint(float ystart[], int nvar, float x1, float x2,
                float eps, float h1, float hmin, int *nok, int *nbad,
                void (*derivs)(float, float [], float []),
                void (*rkqs)(float [], float [], int, float *, float, float,
                float [], float *, float *, void (*)(float, float [], float [])));
    void rkqs(float y[], float dydx[], int n, float *x,
              float htry, float eps, float yscal[], float *hdid, float *hnext,
              void (*derivs)(float, float [], float []));
    void score(float xf, float y[], float f[]);
    int i,nbad,nok;
    float h1,hmin=0.0,*f1,*f2,*y;

    f1=vector(1,nvar);
    f2=vector(1,nvar);
    y=vector(1,nvar);
    kmax=0;
    h1=(x2-x1)/100.0;
    load1(x1,v,y);          Path from x1 to xf with best trial values v1.
    odeint(y,nvar,x1,xf,EPS,h1,hmin,&nok,&nbad,derivs,rkqs);
    score(xf,y,f1);
    load2(x2,&v[nn2],y);    Path from x2 to xf with best trial values v2.
    odeint(y,nvar,x2,xf,EPS,h1,hmin,&nok,&nbad,derivs,rkqs);
    score(xf,y,f2);
}
```

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```

for (i=1;i<=n;i++) f[i]=f1[i]-f2[i];
free_vector(y,1,nvar);
free_vector(f2,1,nvar);
free_vector(f1,1,nvar);
}

```

There are boundary value problems where even shooting to a fitting point fails — the integration interval has to be partitioned by several fitting points with the solution being matched at each such point. For more details see [1].

#### CITED REFERENCES AND FURTHER READING:

- Acton, F.S. 1970, *Numerical Methods That Work*; 1990, corrected edition (Washington: Mathematical Association of America).
- Keller, H.B. 1968, *Numerical Methods for Two-Point Boundary-Value Problems* (Waltham, MA: Blaisdell).
- Stoer, J., and Bulirsch, R. 1980, *Introduction to Numerical Analysis* (New York: Springer-Verlag), §§7.3.5–7.3.6. [1]

## 17.3 Relaxation Methods

In *relaxation methods* we replace ODEs by approximate *finite-difference equations* (FDEs) on a grid or mesh of points that spans the domain of interest. As a typical example, we could replace a general first-order differential equation

$$\frac{dy}{dx} = g(x, y) \quad (17.3.1)$$

with an algebraic equation relating function values at two points  $k, k - 1$ :

$$y_k - y_{k-1} - (x_k - x_{k-1}) g \left[ \frac{1}{2}(x_k + x_{k-1}), \frac{1}{2}(y_k + y_{k-1}) \right] = 0 \quad (17.3.2)$$

The form of the FDE in (17.3.2) illustrates the idea, but not uniquely: There are many ways to turn the ODE into an FDE. When the problem involves  $N$  coupled first-order ODEs represented by FDEs on a mesh of  $M$  points, a solution consists of values for  $N$  dependent functions given at each of the  $M$  mesh points, or  $N \times M$  variables in all. The relaxation method determines the solution by starting with a guess and improving it, iteratively. As the iterations improve the solution, the result is said to *relax* to the true solution.

While several iteration schemes are possible, for most problems our old standby, multi-dimensional Newton's method, works well. The method produces a matrix equation that must be solved, but the matrix takes a special, "block diagonal" form, that allows it to be inverted far more economically both in time and storage than would be possible for a general matrix of size  $(MN) \times (MN)$ . Since  $MN$  can easily be several thousand, this is crucial for the feasibility of the method.

Our implementation couples at most pairs of points, as in equation (17.3.2). More points can be coupled, but then the method becomes more complex. We will provide enough background so that you can write a more general scheme if you have the patience to do so.

Let us develop a general set of algebraic equations that represent the ODEs by FDEs. The ODE problem is exactly identical to that expressed in equations (17.0.1)–(17.0.3) where we had  $N$  coupled first-order equations that satisfy  $n_1$  boundary conditions at  $x_1$  and  $n_2 = N - n_1$  boundary conditions at  $x_2$ . We first define a mesh or grid by a set of  $k = 1, 2, \dots, M$  points at which we supply values for the independent variable  $x_k$ . In particular,  $x_1$  is the initial boundary, and  $x_M$  is the final boundary. We use the notation  $\mathbf{y}_k$  to refer to the entire set of