Chapter 2. Solutions of Equations in One Variable

2.1 The Bisection Method

INPUT endpoints a, b; tolerance TOL; maximum number of iterations N_0.

OUTPUT approximate solution p or message of failure.

Step 1 Set $i = 1$; FA = $f(a)$

Step 2 While $i \le N_0$ do Step 3-6.

Step 3 Set $p = a + (b - a)/2$; (Compute p_i.)

FP $= f(p)$.

Step 4 If FP = 0 or $(b - a)/2 < TOL$ then

OUTPUT (p); STOP.

Step 5 Set $i = i + 1$.

Step 6 If FA $\cdot$ FP > 0 then set $a = p$; (Compute a_i, b_i.)

FA $=$ FP

else set $b = p$. (FA is unchanged.)

Step 7 OUTPUT ('Method failed after N_0 iterations, $N_0 =$', N_0); (The procedure was unsuccessful.)

STOP.

Example

Show that $f(x) = x^3 + 4x^2 - 10 = 0$ has a root in $[1, 2]$, and use the Bisection method to determine an approximation to the root that is accurate to at least within 10^{-4}.

```
f = @(x) x^3 + 4*x^2 - 10;
a = 1;
b = 2;
TOL = 1e-4;
N0 = 30;
p = bisection(a,b,TOL,N0,f);
sprintf('%.8f',p)
```

```
ans = '1.36517334'
```

```
bisection_relative_error(a,b,TOL,N0,f);
```

```
ans = 'iter    a_n         b_n         p_n         f(a_n)    f(p_n)     RelErr'
ans = '1       1.000000    2.000000    1.500000    -5.000    2.375      0.33333'
ans = '2       1.000000    1.500000    1.250000    -5.000    -1.797     0.20000'
ans = '3       1.250000    1.500000    1.375000    -1.797    0.162      0.09091'
ans = '4       1.250000    1.375000    1.312500    -1.797    -0.848     0.04762'
ans = '5       1.312500    1.375000    1.343750    -0.848    -0.351     0.02326'
ans = '6       1.343750    1.375000    1.359375    -0.351    -0.096     0.01149'
ans = '7       1.359375    1.375000    1.367188    -0.096    0.032      0.00571'
ans = '8       1.359375    1.367188    1.363281    -0.096    -0.032     0.00287'
ans = '9       1.363281    1.367188    1.365234    -0.032    0.000      0.00143'
ans = '10      1.363281    1.365234    1.364258    -0.032    -0.016     0.00072'
ans = '11      1.364258    1.365234    1.364746    -0.016    -0.008     0.00036'
ans = '12      1.364746    1.365234    1.364990    -0.008    -0.004     0.00018'
ans = '13      1.364990    1.365234    1.365112    -0.004    -0.002     0.00009'
```

2.2 Fixed-Point Iteration

INPUT initial approximation p_0; tolerance TOL; maximum number of iterations N_0.

OUTPUT approximate solution p or message of failure.

Step 1 Set $i = 1$.

Step 2 While $i \le N_0$ do Step 3–6.

Step 3 Set $p = g(p_0)$; (Compute p_i.)

Step 4 If $|p - p_0| < TOL$ then

OUTPUT (p); (The procedure was successful.)

STOP.

Step 5 Set $i = i + 1$.

Step 6 Set $p_0 = p$; (Update p_0.)

Step 7 OUTPUT ('The method failed after N_0 iterations, $N_0 =$', N_0);

(The procedure was unsuccessful.)

STOP.

Example

The equation $x^3 + 4x^2 - 10 = 0$ has a unique root in [1,2]. Its value is approximately 1.365230013.

$(a)\quad x = g_1(x) = x - x^3 - 4x^2 + 10$

$(b)\quad x = g_2(x) = \left(\frac{10}{x} - 4x\right)^{\frac{1}{2}}$

$(c)\quad x = g_3(x) = \frac{1}{2}(10 - x^3)^{\frac{1}{2}}$

$(d)\quad x = g_4(x) = \left(\frac{10}{4+x}\right)^{\frac{1}{2}}$

$(e)\quad x = g_5(x) = x - \frac{x^3 + 4x^2 - 10}{3x^2 + 8x}$

```
p0 = 1.5;
TOL = 1e-9;
N0 = 50;
```

(a)

```
g1 = @(x) x - x^3 - 4*x^2 + 10;
fixed_point(p0,TOL,N0,g1);
```

```
ans = 'iteration 0: 1.500000000'
ans = 'iteration 1: -0.875000000'
ans = 'iteration 2: 6.732421875'
ans = 'iteration 3: -469.720012002'
ans = 'iteration 4: 102754555.187385112'
ans = 'iteration 5: -1084933870531746486812672.000000000'
ans = 'iteration 6: 1277055591444378466573438322982097922987374859897466271890545849990643712.000000000'
ans = 'iteration 7: -20827129085810271407186275962151251982335668349556937381863593783721160572922598903112264111685864739907372172734018438167522806806721619 8
ans = 'iteration 8: NaN'
ans = 'iteration 9: NaN'
ans = 'iteration 10: NaN'
ans = 'iteration 11: NaN'
ans = 'iteration 12: NaN'
ans = 'iteration 13: NaN'
ans = 'iteration 14: NaN'
ans = 'iteration 15: NaN'
ans = 'iteration 16: NaN'
ans = 'iteration 17: NaN'
ans = 'iteration 18: NaN'
ans = 'iteration 19: NaN'
ans = 'iteration 20: NaN'
ans = 'iteration 21: NaN'
ans = 'iteration 22: NaN'
ans = 'iteration 23: NaN'
ans = 'iteration 24: NaN'
ans = 'iteration 25: NaN'
ans = 'iteration 26: NaN'
ans = 'iteration 27: NaN'
ans = 'iteration 28: NaN'
ans = 'iteration 29: NaN'
ans = 'iteration 30: NaN'
ans = 'iteration 31: NaN'
ans = 'iteration 32: NaN'
```

```
ans = 'iteration 33: NaN'
ans = 'iteration 34: NaN'
ans = 'iteration 35: NaN'
ans = 'iteration 36: NaN'
ans = 'iteration 37: NaN'
ans = 'iteration 38: NaN'
ans = 'iteration 39: NaN'
ans = 'iteration 40: NaN'
ans = 'iteration 41: NaN'
ans = 'iteration 42: NaN'
ans = 'iteration 43: NaN'
ans = 'iteration 44: NaN'
ans = 'iteration 45: NaN'
ans = 'iteration 46: NaN'
ans = 'iteration 47: NaN'
ans = 'iteration 48: NaN'
ans = 'iteration 49: NaN'
ans = 'iteration 50: NaN'
ans = 'Method failed after N0 iterations, N0 = 50'
```

(b)

```
g2 = @(x) sqrt(10/x - 4*x);
fixed_point(p0,TOL,N0,g2)
```

```
ans = 'iteration 0: 1.500000000'
ans = 'iteration 1: 0.816496581'
ans = 'iteration 2: 2.996908806'
ans = 'iteration 3: 0.000000000'
ans = 'iteration 4: 2.753622388'
ans = 'iteration 5: 1.814991519'
ans = 'iteration 6: 2.384265848'
ans = 'iteration 7: 2.182771900'
ans = 'iteration 8: 2.296997587'
ans = 'iteration 9: 2.256510286'
ans = 'iteration 10: 2.279179049'
ans = 'iteration 11: 2.271142587'
ans = 'iteration 12: 2.275631311'
ans = 'iteration 13: 2.274039927'
ans = 'iteration 14: 2.274928362'
ans = 'iteration 15: 2.274613384'
ans = 'iteration 16: 2.274789213'
ans = 'iteration 17: 2.274726876'
ans = 'iteration 18: 2.274761673'
ans = 'iteration 19: 2.274749337'
ans = 'iteration 20: 2.274756223'
ans = 'iteration 21: 2.274753782'
ans = 'iteration 22: 2.274755145'
ans = 'iteration 23: 2.274754661'
ans = 'iteration 24: 2.274754931'
ans = 'iteration 25: 2.274754835'
ans = 'iteration 26: 2.274754889'
ans = 'iteration 27: 2.274754870'
ans = 'iteration 28: 2.274754880'
ans = 'iteration 29: 2.274754877'
ans = 'iteration 30: 2.274754879'
ans = 'iteration 31: 2.274754878'
ans = 'iteration 32: 2.274754878'
ans = 'iteration 33: 2.274754878'
ans = 'iteration 34: 2.274754878'
ans = 'iteration 35: 2.274754878'
ans = 'iteration 36: 2.274754878'
ans = 'iteration 37: 2.274754878'
ans = 'iteration 38: 2.274754878'
ans = 'iteration 39: 2.274754878'
ans = 'iteration 40: 2.274754878'
ans = 'iteration 41: 2.274754878'
ans = 'iteration 42: 2.274754878'
ans = 'iteration 43: 2.274754878'
ans = 'iteration 44: 2.274754878'
ans = 'iteration 45: 2.274754878'
ans = 'iteration 46: 2.274754878'
ans = 'iteration 47: 2.274754878'
ans = 'iteration 48: 2.274754878'
ans = 'iteration 49: 2.274754878'
ans = 'iteration 50: 2.274754878'
ans = 'Method failed after N0 iterations, N0 = 50'
ans = 2.2748 - 3.6088i
```

(c)

```
g3 = @(x) 0.5 * sqrt(10 - x^3);
fixed_point(p0,TOL,N0,g3);
```

```
ans = 'iteration 0: 1.500000000'
ans = 'iteration 1: 1.286953768'
ans = 'iteration 2: 1.402540804'
ans = 'iteration 3: 1.345458374'
ans = 'iteration 4: 1.375170253'
ans = 'iteration 5: 1.360094193'
ans = 'iteration 6: 1.367846968'
ans = 'iteration 7: 1.363887004'
ans = 'iteration 8: 1.365916733'
```

```
ans = 'iteration 9: 1.364878217'
ans = 'iteration 10: 1.365410061'
ans = 'iteration 11: 1.365137821'
ans = 'iteration 12: 1.365277209'
ans = 'iteration 13: 1.365205850'
ans = 'iteration 14: 1.365242384'
ans = 'iteration 15: 1.365223680'
ans = 'iteration 16: 1.365233256'
ans = 'iteration 17: 1.365228353'
ans = 'iteration 18: 1.365230863'
ans = 'iteration 19: 1.365229578'
ans = 'iteration 20: 1.365230236'
ans = 'iteration 21: 1.365229899'
ans = 'iteration 22: 1.365230072'
ans = 'iteration 23: 1.365229984'
ans = 'iteration 24: 1.365230029'
ans = 'iteration 25: 1.365230006'
ans = 'iteration 26: 1.365230017'
ans = 'iteration 27: 1.365230011'
ans = 'iteration 28: 1.365230014'
ans = 'iteration 29: 1.365230013'
ans = 'iteration 30: 1.365230014'
```

(d)

```
g4 = @(x) sqrt(10/(4+x));
fixed_point(p0,TOL,N0,g4);
```

```
ans = 'iteration 0: 1.500000000'
ans = 'iteration 1: 1.348399725'
ans = 'iteration 2: 1.367376372'
ans = 'iteration 3: 1.364957015'
ans = 'iteration 4: 1.365264748'
ans = 'iteration 5: 1.365225594'
ans = 'iteration 6: 1.365230576'
ans = 'iteration 7: 1.365229942'
ans = 'iteration 8: 1.365230023'
ans = 'iteration 9: 1.365230012'
ans = 'iteration 10: 1.365230014'
ans = 'iteration 11: 1.365230013'
```

(e)

```
g5 = @(x) x - (x^3 + 4*x^2 - 10)/(3*x^2 + 8*x);
fixed_point(p0,TOL,N0,g5);
```

```
ans = 'iteration 0: 1.500000000'
ans = 'iteration 1: 1.373333333'
ans = 'iteration 2: 1.365262015'
ans = 'iteration 3: 1.365230014'
ans = 'iteration 4: 1.365230013'
```

2.3 Newton's Method and Its Extensions

Newton's Method

INPUT initial approximation p_0; tolerance TOL; maximum number of iterations N_0.

OUTPUT approximate solution p or message of failure.

Step 1 Set $i = 1$.

Step 2 While $i \leq N_0$ do Step 3–6.

- **Step 3** Set $p = p_0 - f(p_0)/f'(p_0)$; (Compute p_i.)
- **Step 4** If $|p - p_0| < TOL$ then
  - OUTPUT (p); (The procedure was successful.)
  - STOP.
- **Step 5** Set $i = i + 1$.
- **Step 6** Set $p_0 = p$; (Update p_0.)

Step 7 OUTPUT ('The method failed after N_0 iterations, $N_0 =$', N_0);
(The procedure was unsuccessful.)
STOP.

Example

Consider the function $f(x) = \cos x - x = 0$. Approximate a root of f using Newton's Method.

```
f = @(x) cos(x) - x;
fp = @(x) -sin(x) - 1;
p0 = pi/4;
TOL = 1e-8;
N0 = 10;

newton(p0, TOL, N0, f, fp);
```

```
ans = 'iteration 1: p = 0.73953613       |p - p0| = 0.04586203'
ans = 'iteration 2: p = 0.73908518       |p - p0| = 0.00045096'
ans = 'iteration 3: p = 0.73908513       |p - p0| = 0.00000004'
ans = 'iteration 4: p = 0.73908513       |p - p0| = 0.00000000'
```

Secant Method

INPUT initial approximation $p_0,\ p_1$; tolerance TOL; maximum number of iterations N_0.

OUTPUT approximate solution p or message of failure.

Step 1 Set $i = 2$; $q_0 = f(p_0)$; $q_1 = f(p_1)$.

Step 2 While $i \leq N_0$ do Step 3–6.

Step 3 Set $p = p_1 - q_1(p_1 - p_0)/(q_1 - q_0)$; (Compute p_i.)

Step 4 If $|p - p_1| < TOL$ then

OUTPUT (p); (The procedure was successful.)

STOP.

Step 5 Set $i = i + 1$.

Step 6 Set $p_0 = p_1$; $q_0 = q_1$; $p_1 = p$; $q_1 = f(p)$. (Update $p_0,\ q_0,\ p_1,\ q_1$.)

Step 7 OUTPUT ('The method failed after N_0 iterations, $N_0 =$', N_0);

(The procedure was unsuccessful.)

STOP.

Example

Consider the function $f(x) = \cos x - x = 0$. Approximate a root of f using the Secant Method.

```
f = @(x) cos(x) - x;
p0 = 0.5;
p1 = pi/4;
TOL = 1e-8;
N0 = 10;

secant(p0, p1, TOL, N0, f);
```

```
ans = 'iteration 2: p = 0.736384139      |p - p1| = 0.0490140246'
ans = 'iteration 3: p = 0.739058139      |p - p1| = 0.0026740004'
ans = 'iteration 4: p = 0.739085149      |p - p1| = 0.0000270101'
ans = 'iteration 5: p = 0.739085133      |p - p1| = 0.0000000161'
ans = 'iteration 6: p = 0.739085133      |p - p1| = 0.0000000000'
```