Numerical Methods for Differential Equations

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Rectangular Rule

The approximation uses Euler’s idea of replacing the integrand by a constant. The value of the integral is approximately the area of a rectangle of width $b - a$ and height $F(a)$.

$$\int_{a}^{b} F(x) \, dx \approx (b - a) F(a)$$

Figure 1. Rectangular Rule
Trapezoidal Rule

The rule replaces the integrand $F(x)$ by a linear function $L(x)$ which connects the planar points $(a, F(a)), (b, F(b))$. The value of the integral is approximately the area under the curve $L$, which is the area of a trapezoid.

$$\int_{a}^{b} F(x) \, dx \approx \frac{b - a}{2} (F(a) + F(b))$$

Figure 2. Trapezoidal Rule
Simpson’s Rule

The rule replaces the integrand $F(x)$ by a quadratic polynomial $Q(x)$ which connects the planar points $(a, F(a))$, $((a + b)/2, F((a + b)/2))$, $(b, F(b))$. Then the integral of $F$ is approximately the area under the quadratic curve $Q$.

$$
\int_a^b F(x) \, dx \approx (b - a) \left( \frac{F(a) + 4F \left( \frac{a+b}{2} \right) + F(b)}{6} \right)
$$

Figure 3. Simpson’s Rule
How to make a connect-the-dots graphic

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>2.000</td>
</tr>
<tr>
<td>0.1</td>
<td>1.901</td>
</tr>
<tr>
<td>0.2</td>
<td>1.808</td>
</tr>
<tr>
<td>0.3</td>
<td>1.727</td>
</tr>
<tr>
<td>0.4</td>
<td>1.664</td>
</tr>
<tr>
<td>0.5</td>
<td>1.625</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>1.616</td>
</tr>
<tr>
<td>0.7</td>
<td>1.643</td>
</tr>
<tr>
<td>0.8</td>
<td>1.712</td>
</tr>
<tr>
<td>0.9</td>
<td>1.829</td>
</tr>
<tr>
<td>1.0</td>
<td>2.000</td>
</tr>
</tbody>
</table>

The table consists of $xy$-values for $y = x^3 - x + 2$. The graphic represents the table’s rows, which are pairs $(x, y)$, as dots. Joined dots make the *connect-the-dots* graphic.

**Maple code**

A connect-the-dots graphic can be made in *maple* by supplying a list $L$ of pairs to be connected. An example:

```maple
L:=[[1,3],[2,1],[3,5]]: plot(L);
```
Numerical Methods for $y' = F(x)$

Quadrature applies to give $y(x) = y_0 + \int_{x_0}^{x} F(x) \, dx$. Numerical solution methods amount to approximating the integral on the right by Rectangular, Trapezoidal and Simpson methods.

The methods replace the exact value of an integral $\int_{x_0}^{x_0+h} F(x) \, dx$ by a numerical approximation value which is useful for graphics when $h$ is small. Larger intervals are broken into smaller intervals of length $h$, then the approximation is applied.

**Table 1. Three numerical integration methods.**

<table>
<thead>
<tr>
<th>Method</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rect</td>
<td>$Y = y_0 + hF(x_0)$</td>
</tr>
<tr>
<td>Trap</td>
<td>$Y = y_0 + \frac{h}{2}(F(x_0) + F(x_0 + h))$</td>
</tr>
<tr>
<td>Simp</td>
<td>$Y = y_0 + \frac{h}{6}(F(x_0) + 4F(x_0 + h/2) + F(x_0 + h))$</td>
</tr>
</tbody>
</table>
Maple code for the Rectangular and Trapezoid Rules

# Rectangular algorithm
# Group 1, initialize.
F:=x->evalf(cos(x) + 2*x):
x0:=0:y0:=0:h:=0.1*Pi:
Dots1:=[x0,y0]:

# Group 2, repeat 10 times
Y:=y0+h*F(x0):
x0:=x0+h:y0:=evalf(Y):
Dots1:=Dots1,[x0,y0]:

# Group 3, plot.
plot([Dots1]);

# Trapezoidal algorithm
# Group 1, initialize.
F:=x->evalf(cos(x) + 2*x):
x0:=0:y0:=0:h:=0.1*Pi:
Dots2:=[x0,y0]:

# Group 2, repeat 10 times
Y:=y0+h*(F(x0)+F(x0+h))/2:
x0:=x0+h:y0:=evalf(Y):
Dots2:=Dots2,[x0,y0]:

# Group 3, plot.
plot([Dots2]);
Maple code for Rectangular and Simpson Rules

# Rectangular algorithm
# Group 1, initialize.
F:=x->evalf(exp(-x*x)):
x0:=0:y0:=0:h:=0.1:
Dots1:=[x0,y0]:

# Group 2, repeat 10 times
Y:=evalf(y0+h*F(x0)):
x0:=x0+h:y0:=Y:
Dots1:=Dots1,[x0,y0]:

# Group 3, plot.
plot([Dots1]);

# Simpson algorithm
# Group 1, initialize.
F:=x->evalf(exp(-x*x)):
x0:=0:y0:=0:h:=0.1:
Dots3:=[x0,y0]:

# Group 2, repeat 10 times
Y:=evalf(y0+h*(F(x0)+4*F(x0+h/2)+F(x0+h))/6):
x0:=x0+h:y0:=Y:
Dots3:=Dots3,[x0,y0]:

# Group 3, plot.
plot([Dots3]);
Numerical Methods for $y' = f(x, y)$

The methods replace the exact value of

$$y(x_0 + h) = y_0 + \int_{x_0}^{x_0 + h} f(x, y(x)) \, dx$$

by a numerical approximation $Y$. The value is useful for graphics when $h$ is small.

**Table 2. Three numerical methods for $y' = f(x, y)$.**

<table>
<thead>
<tr>
<th>Method</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euler</td>
<td>$Y = y_0 + hf(x_0, y_0)$</td>
</tr>
</tbody>
</table>
| Heun | $y_1 = y_0 + hf(x_0, y_0)$  
$Y = y_0 + \frac{h}{2}(f(x_0, y_0) + f(x_0 + h, y_1))$ |
| RK4 | $k_1 = hf(x_0, y_0)$  
$k_2 = hf(x_0 + h/2, y_0 + k1/2)$  
$k_3 = hf(x_0 + h/2, y_0 + k2/2)$  
$k_4 = hf(x_0 + h, y_0 + k3)$  
$Y = y_0 + \frac{k_1 + 2k_2 + 2k_3 + k_4}{6}$ |
Maple code for Euler and Heun methods

# Euler algorithm
# Group 1, initialize.
f:=(x,y)->-y+1-x:
x0:=0:y0:=3:h:=0.1:L:=[x0,y0]:

# Group 2, repeat 10 times
Y:=y0+h*f(x0,y0):
x0:=x0+h:y0:=Y:L:=L,[x0,y0];

# Group 3, plot.
plot([L]);

# Heun algorithm
# Group 1, initialize.
f:=(x,y)->-y+1-x:
x0:=0:y0:=3:h:=0.1:L:=[x0,y0]:

# Group 2, repeat 10 times
Y:=y0+h*(f(x0,y0)+f(x0+h,Y))/2:
x0:=x0+h:y0:=Y:L:=L,[x0,y0];

# Group 3, plot.
plot([L]);
Maple code for Heun and RK4 methods

# Heun algorithm
# Group 1, initialize.
f:=(x,y)->-y+1-x:
x0:=0:y0:=3:h:=0.1:L:=[x0,y0]:

# Group 2, repeat 10 times
Y:=y0+h*f(x0,y0):
Y:=y0+h*(f(x0,y0)+f(x0+h,Y))/2:
x0:=x0+h:y0:=Y:L:=L,[x0,y0]:

# Group 3, plot.
plot([L]);

# RK4 algorithm
# Group 1, initialize.
f:=(x,y)->-y+1-x:
x0:=0:y0:=3:h:=0.1:L:=[x0,y0]:

# Group 2, repeat 10 times.
k1:=h*f(x0,y0):
k2:=h*f(x0+h/2,y0+k1/2):
k3:=h*f(x0+h/2,y0+k2/2):
k4:=h*f(x0+h,y0+k3):
Y:=y0+(k1+2*k2+2*k3+k4)/6:
x0:=x0+h:y0:=Y:L:=L,[x0,y0]:

# Group 3, plot.
plot([L]);
Numerical Algorithms: Planar Case

Notation. Let $t_0, x_0, y_0$ denote the entries of the dot table on a particular line. Let $h$ be the increment for the dot table and let $t_0 + h, x, y$ stand for the dot table entries on the next line.

Planar Euler Method

\[
x = x_0 + hf(t_0, x_0, y_0),
\]
\[
y = y_0 + hg(t_0, x_0, y_0).
\]

Planar Heun Method

\[
x_1 = x_0 + hf(t_0, x_0, y_0),
\]
\[
y_1 = y_0 + hg(t_0, x_0, y_0),
\]
\[
x = x_0 + h(f(t_0, x_0, y_0) + f(t_0 + h, x_1, y_1))/2
\]
\[
y = y_0 + h(g(t_0, x_0, y_0) + g(t_0 + h, x_1, y_1))/2.
\]
Planar RK4 Method

\[
\begin{align*}
    k_1 &= hf(t_0, x_0, y_0), \\
    m_1 &= hg(t_0, x_0, y_0), \\
    k_2 &= hf(t_0 + h/2, x_0 + k_1/2, y_0 + m_1/2), \\
    m_2 &= hg(t_0 + h/2, x_0 + k_1/2, y_0 + m_1/2), \\
    k_3 &= hf(t_0 + h/2, x_0 + k_2/2, y_0 + m_2/2), \\
    m_3 &= hg(t_0 + h/2, x_0 + k_2/2, y_0 + m_2/2), \\
    k_4 &= hf(t_0 + h, x_0 + k_3, y_0 + m_3), \\
    m_4 &= hg(t_0 + h, x_0 + k_3, y_0 + m_3), \\
    x &= x_0 + \frac{1}{6} (k_1 + 2k_2 + 2k_3 + k_4), \\
    y &= y_0 + \frac{1}{6} (m_1 + 2m_2 + 2m_3 + m_4).
\end{align*}
\]
Consider a vector initial value problem

\[ u'(t) = F(t, u(t)), \quad u(t_0) = u_0. \]

**Vector Euler Method**

\[ u = u_0 + hF(t_0, u_0) \]

**Vector Heun Method**

\[ w = u_0 + hF(t_0, u_0), \]

\[ u = u_0 + \frac{h}{2} (F(t_0, u_0) + F(t_0 + h, w)) \]
Vector RK4 Method

\[
\begin{align*}
  k_1 &= h F(t_0, u_0), \\
  k_1 &= h F(t_0 + h/2, u_0 + k_1/2), \\
  k_1 &= h F(t_0 + h/2, u_0 + k_2/2), \\
  k_1 &= h F(t_0 + h, u_0 + k_3), \\
  u &= u_0 + \frac{1}{6} (k_1 + 2k_2 + 2k_3 + k_4).
\end{align*}
\]