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Basic Searching, Interpolating, and Curve-Fitting Algorithms in C++

Robert J Yager
Weapons and Materials Research Directorate, ARL
**REPORT DOCUMENTATION PAGE**

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I would also like to thank Dr Douglas Chapman, Professor of Chemistry at Southern Oregon University, for the concepts he taught me in his “Computer Applications in Chemistry” class. Dr Chapman taught me that it’s possible to use very simple computer code to solve complex problems. At the time, I didn’t realize how valuable that lesson was.
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1. Introduction

This report documents a set of functions, written in C++, that can be used to perform interpolations (nearest-neighbor, linear, and cubic) and to find coefficients for best-fit equations. Functions for working with periodic equations are included.

Measurements can be taken and stored using a variety of schemes. The interpolations described in this report are designed to work with data sets where measured values for all independent and dependent variables are explicitly stored. Furthermore, for data that has more than 1 independent variable, the measurements must all lie on some type of rectangular grid, where all grid locations are populated.

When measurements do not lie on some type of rectangular grid, interpolations become more difficult. For those types of data sets, KD-trees can be used to perform efficient nearest-neighbor searches, which can act as interpolations. The yKDTree namespace\(^1\) can be used to work with KD-trees using C++.

The yBilinear namespace\(^2\) can be used for the special case of data sets with 2 independent variables, where all measurements lie on a rectangular grid, all grid locations are populated, and all grid lines are evenly spaced.

The functions that are described in this report have been grouped into the yInterp namespace, which is summarized at the end of this report. The yInterp namespace relies exclusively on standard C++ operations and functions. However, example code that is included in this report makes use of the yRandom namespace\(^3\) for generating pseudorandom numbers, the yBmp namespace\(^4\) for creating images, and the yIo2\(^5\) namespace for reading and parsing text files.

2. Background

My motivation for this project began with a task that involved interpolating a look-up table with 8 independent variables, some of which were periodic. Prior to this project, I had always written interpolators on an ad hoc basis. However, the thought of having to deal with an array that requires 8 indices to access a particular element (something like A[i][j][k][l][m][n][o][p]) convinced me that I needed a more formal set of tools.

The task required that all code be written in C++. To maximize portability, the code had to be written without the use of any platform-specific or C++11 tools. Performance was a priority. In addition, I wanted a versatile set of tools that I could use for future projects. The tools needed to
be simple to use and well-tested so that I could feel comfortable sharing them with other programmers.

3. Searching Sorted Arrays: The BinarySearch() Function

The BinarySearch() function uses a binary search algorithm to search arrays that are sorted into ascending order. For arrays that do not contain duplicate entries, the BinarySearch() function can be used to find a pointer \( c \) such that

\[
*c \leq k < *(c+1),
\]

where \( k \) is key on which the search is based.

For arrays that contain duplicate entries, Eq. 1 needs to be slightly modified:

\[
*c \leq k \leq *(c+1).
\]

Thus, if \( k \) is equal to an element that has one or more duplicates, \( c \) may point to any one of the duplicates.

Performance for the BinarySearch() function is \( O(\log(n)) \), which is demonstrated in Section 3.7.

3.1 BinarySearch() Code

```cpp
template<class T>
T*BinarySearch(T*a, T*b, T k){
    if(k<*a)
        return a-1; // note that a-1 may point to an invalid address
    for(T*c; k--; c+=a+b-a/2)
        return b;
}
```

3.2 BinarySearch() Template Class

- **T** must be a sortable data type.

3.3 BinarySearch() Parameters

- **a** points to the beginning of the array that will be searched. The array should be sorted into ascending order.
- **b** points to one element past the end of the array that will be searched. Thus, \( b \) is used to define the end of the search region but is not included in the search. \( b \) should be greater than \( a \).
- **k** is the key on which the search is based.
3.4 BinarySearch() Return Value

For arrays that do not contain duplicate entries, the BinarySearch() function returns a pointer to the greatest array element that is less than or equal to \( k \). If \( k \) is less than the least array element, then \( a-1 \) is returned. Care needs to be taken when accessing the return pointer, since \( a-1 \) may not point to a valid address.

3.5 BinarySearch() Simple Example

The following example uses the BinarySearch() function to search a small sorted array that contains duplicates.

```c
#include <stdio.h>
#include "y_interp.h"

int main(){
    printf("X={");
    for(int i=0;i<11;++i)printf("%d%s",X[i],i!=10?",":"\n");
    printf(" | KEY | *(c+1) | INDEX\n---------------------------
");    
    for(int k=28;k<52;++k){
        int*c=yInterp::BinarySearch(X,X+11,k);
        if(c<X)printf("--| %4d |%5d   |%4d\n",k,*(c+1),c-X);
        else if(c==X+10)printf("%3d |%4d |--|%4d\n",*c,k,c-X);
        else printf("%3d |%4d |%5d   |%4d\n",*c,k,*(c+1),c-X);
    }
}
```

OUTPUT:

```
X={30,40,41,42,42,42,42,43,44,45,50}

<table>
<thead>
<tr>
<th>*c</th>
<th>KEY</th>
<th>*(c+1)</th>
<th>INDEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>--</td>
<td>28</td>
<td>30</td>
<td>-1</td>
</tr>
<tr>
<td>--</td>
<td>29</td>
<td>30</td>
<td>-1</td>
</tr>
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<td>50</td>
<td>--</td>
<td>10</td>
</tr>
<tr>
<td>50</td>
<td>51</td>
<td>--</td>
<td>10</td>
</tr>
</tbody>
</table>
```
3.6 BinarySearch() Text Example

The following example uses the BinarySearch() function to determine where a word should be inserted into a sorted list.

```cpp
#include <iostream>
#include <string>
#include "y_interp.h"

int main()
{
    std::string S[6]="defective","defend","defendant","defender","defense","defensive"},s="defenestrate";
    for(int i=0;i<6;++i)std::cout<<S[i]<<(i==5?"\n\n":" ");
    std::string*c=yInterp::BinarySearch(S,S+6,s);
    std::cout<<"The word "<<s<<" should be between "<<*c<<" and "<<*(c+1)<<".\n";
} // ~~~~~YAGENAUT@GMAIL.COM~~~~~~~~~~~~~~~~~~~~~~~~~LAST~UPDATED~21JUL2014~~~~~~
```

OUTPUT:

defective, defend, defendant, defender, defense, defensive

The word defenestrate should be between defender and defense.

3.7 BinarySearch() Performance

The following example begins by using the yRandom namespace to populate an array with $2^{14}$ pseudorandom numbers using the Mersenne twister 19937 algorithm. The array is then sorted using the sort() function. Average search times are calculated for searches performed using a linear search algorithm and the BinarySearch() function. Figure 1 presents a graph of the results.

The average search time for the LinearSearch() function is $O(n)$. The average search time for the BinarySearch() function is $O(\log(n))$. 
```cpp
#include <algorithm>
#include <cstdio>
#include <ctime>
#include "y_interp.h"
#include "y_random.h"

template <class T>
T*LinearSearch(T*a,T*b,T k){
if(k<*a)
return a-1;
while(k<*--b);
return b;
}

int main(){
const int N=16384,M=10000000;
unsigned I[625];
yRandom::Initialize(I,1);
double*X=new double[N];
for(int i=0;i<M;++i)X[i]=yRandom::RandU(I,0,N);
std::sort(X,X+N);

printf("          |     linear  search     |    binary  search\n");
printf("    size  |------------------------|------------------------\n");
printf(" of   |  search  |    index    |  search  |    index \n");
printf("   array  | time (s) |   average   | time (s) |   average \n");
for(int m=2;m<16385;m*=2){
    printf("%8d  |",m),yRandom::Initialize(I,1);
    double y=.0,z=0,t=clock();
    for(int i=0;i<;i++)y+=LinearSearch(X,X+m,yRandom::RandU(I,0,m))-X;
    t=clock();
    printf("%8.3f  |%12.6f |\n",(clock()-t)/CLOCKS_PER_SEC,y/M),t=clock();
    yRandom::Initialize(I,1);
    for(int i=0;i<;i++)z+=yInterp::BinarySearch(X,X+m,yRandom::RandU(I,0,m))-X;
    printf("%8.3f  |%12.6f \n",(clock()-t)/CLOCKS_PER_SEC,z/M);}
```

**OUTPUT:**

<table>
<thead>
<tr>
<th>size of array</th>
<th>linear search</th>
<th>binary search</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.140</td>
<td>-0.731079</td>
</tr>
<tr>
<td>4</td>
<td>0.140</td>
<td>0.555495</td>
</tr>
<tr>
<td>8</td>
<td>0.203</td>
<td>1.833760</td>
</tr>
<tr>
<td>16</td>
<td>0.244</td>
<td>5.133788</td>
</tr>
<tr>
<td>32</td>
<td>0.312</td>
<td>13.015384</td>
</tr>
<tr>
<td>64</td>
<td>0.390</td>
<td>31.287311</td>
</tr>
<tr>
<td>128</td>
<td>0.531</td>
<td>66.159459</td>
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<td>16384</td>
<td>43.945</td>
<td>8193.415153</td>
</tr>
</tbody>
</table>
4. Searching Sorted Arrays: The PeriodicSearch() Function

The PeriodicSearch() function uses the BinarySearch() function to search arrays that are associated with periodic functions, such as $f$, where

$$f(x + np) = f(x).$$

Thus, the PeriodicSearch() function can be used to find a pointer $c$ such that

$$*c \leq k + np < *(c+1),$$

where $k$ and $p$ are user supplied values and the integer $n$ is chosen such that

$$*a \leq k + np < *a+p.$$

4.1 PeriodicSearch() Code

```cpp
template<class T>T*PeriodicSearch(
    //<=======FOR ARRAYS WITH PERIODIC VARIABLES
    T*a,T*b,///<STARTING & ENDING POINTS (ARRAY MUST BE SORTED IN INC. ORDER)
    T&k, ///<---KEY (WILL BE SET TO k'=k+np)
    T p){///<---PERIOD (p>0)
    return BinarySearch(a,b,k=fmod(k-a,p)+a+(k-a<0?p:0));
}
```

4.2 PeriodicSearch() Template Class

T must be a sortable data type.

4.3 PeriodicSearch() Parameters

a points to the beginning of the array that will be searched. The array should be sorted into ascending order.
\textbf{b} \quad \text{points to one element past the end of the array that will be searched. Thus, b is used to define the end of the search region but is not included in the search. b should be greater than a.}

\textbf{k} \quad \text{k is the key on which the search is based. Note that before the function returns, k is set to } k' = k + n p.\textbf{p} \quad \text{is the period of the function associated with the array. Values for p are typically chosen such that } p > *(b-1) - *a. \text{ In no case should p be equal to zero.}

\subsection*{4.4 \textbf{PeriodicSearch()} Return Value}

The \textbf{PeriodicSearch()} function returns a pointer that satisfies the requirements for \textbf{c} in Eq. 4.

\subsection*{4.5 \textbf{PeriodicSearch()} Example}

The following example begins by creating a pair of arrays that are used to store independent and dependent variables that approximate Eq. 6.

\begin{equation}
y(x) = \sin(2\pi x/5) + 1. \quad (6)
\end{equation}

The \textbf{BinarySearch()} and \textbf{PeriodicSearch()} functions are then used to retrieve dependent variables based on a selection of independent variables. Figure 2 presents a pair of graphs that display the results of the searches.

```
#include <cstdio> //..................freopen(),printf(),stdout
#include "y_interp.h" //..................yInterp,<cmath>{sin()}

int main(){
    //<==============COMPARISON BETWEEN BinarySearch() & PeriodicSearch()
    freopen("sine.csv","w",stdout);
    double X[20];/*<*/for(int i=0;i<20;++i)X[i]=5*i/20.+5;
    double Y[20];/*<*/for(int i=0;i<20;++i)Y[i]=sin(2*3.14159*X[i]/5)+1;
    printf("x,y - BinarySearch()\n");
    for(double x=-5,k;x<15;x+=.1){
        printf("%f,%f\n",x,Y[yInterp::BinarySearch(X+1,X+20,x)-X]);
        printf("%f\n",Y[yInterp::PeriodicSearch(X,X+20,k,x,5.0)-X]);
    }
}
```

//~~~~~~~~~~~~~~~~~YAGENAUT@GMAIL.COM~~~~~~~~~~~~~~~~~~~~~~~~~~~LAST~UPDATED~21JUL2014~~~~~~~
5. Performing Nearest-Neighbor Interpolations: The NNInterp() Function

Suppose that some function \( y(x) \) is represented by a finite set of points \( (x_i, y_i) \), such as is shown in Fig. 3.

![Fig. 3](image)

Fig. 3 \( y(x) \) represented by a finite number of points, with nearest-neighbor interpolation shown in red

The NNInterp() function uses Eq. 7, represented by the solid red line in Fig. 3, to approximate \( y(x) \):
\[
y(x) = \begin{cases} 
y_{i+1} & \text{for } x > \frac{x_i + x_{i+1}}{2} \\
y_i & \text{otherwise}
\end{cases}
\]  \hspace{1cm} (7)

5.1 NNInterp() Code

```
template<class T>
NNInterp(const T* X, // <------------------------NEAREST-NEIGHBOR INTERPOLATOR
const T* Y, // <------------------------BRACKETING VALUES (*X AND X[1] MUST BE VALID)
T x) { // <------------------------VALUE TO INTERPOLATE AT (TYPICALLY, *X <= x <= x[1])
  return x>(*X+X[1])/2?Y[1]:*Y;
}
```

5.2 NNInterp() Template Class

T is typically a floating-point data type.

5.3 NNInterp() Parameters

- **X**: X points to an array that is used to store values for \( x_i \) from Eq. 7. Specifically, \( *X = x_i \) and \( X[1] = x_{i+1} \). Thus, both X and X+1 must point to valid addresses.

- **Y**: Y points to an array that is used to store values for \( y_i \) from Eq. 7. Specifically, \( *Y = y_i \) and \( Y[1] = y_{i+1} \). Thus, both Y and Y+1 must point to valid addresses.

- **x**: x represents the independent variable \( x \) from Eq. 7.

5.4 NNInterp() Return Value

The NNInterp() function returns \( y \) from Eq. 7.

5.5 NNInterp() Simple Example

The following example begins by creating a pair of arrays that are used to store independent and dependent variables that approximate Eq. 6. Next, the BinarySearch() function is used to find a pointer that conforms to Eq. 1, which is then converted to an index. Finally, the NNInterp() function is used to approximate \( y(7.180) \).

Note that the value for the BinarySearch() parameter \( a \) is set to X+1 to avoid the possibility of accessing the X-1 element. Similarly, the value for the BinarySearch() parameter \( b \) is set to X+19 to avoid the possibility of accessing the X+20 element.
#include <cstdio>
#include "y_interp.h"

int main(){
    // A SIMPLE EXAMPLE FOR THE yInterp::NNInterp() FUNCTION
    double X[20]; /*<*/
    for (int i=0;i<20;++i) X[i]=5*i/20.+5;
    double Y[20]; /*<*/
    for (int i=0;i<20;++i) Y[i]=sin(2*3.14159*X[i]/5)+1;
    double x=7.18;
    int i=yInterp::BinarySearch(X, X+19, x) - X;
    double y=yInterp::NNInterp(X+i, Y+i, x);
    printf("At x=%.3f, y is approximately %.3f.\n", x, y);
}

OUTPUT:
At x=7.180, y is approximately 1.309.

6. Performing Linear Interpolations: The LinInterp() Function

Suppose that some function \( y(x) \) is represented by a finite set of points \((x_i, y_i)\), such as is shown in Fig. 4.

The LinInterp() function uses Eq. 8, represented by the solid red line in Fig. 4, to approximate \( y(x) \):
\[ y(x) = y_i + (y_{i+1} - y_i) \frac{x-x_i}{x_{i+1}-x_i}. \] (8)

6.1 LinInterp() Code

```
template<class T>
T LinInterp()
{ //***********************************************************
    T x);
    return*Y+(Y[1]-*Y)*(x-*X)/(X[1]-*X);
);

//~~~YAGENAUT@GMAIL.COM~~~~~~~~~~~~~~~~~~~~~~~~~LAST~UPDATED~21JUL2014~~~~~~
```

6.2 LinInterp() Template Class

T T is typically a floating-point data type.

6.3 LinInterp() Parameters

X X points to an array that is used to store values for \( x_i \) from Eq. 8. Specifically, *X = x_i and X[1] = x_{i+1}. Thus, both X and X+1 must point to valid addresses.

Y Y points to an array that is used to store values for \( y_i \) from Eq. 8. Specifically, *Y = y_i and Y[1] = y_{i+1}. Thus, both Y and Y+1 must point to valid addresses.

x x represents the independent variable \( x \) from Eq. 8.

6.4 LinInterp() Return Value

The LinInterp() function returns \( y \) from Eq. 8.

6.5 LinInterp() Simple Example

The following example begins by creating a pair of arrays that are used to store independent and dependent variables that approximate Eq. 6. Next, the BinarySearch() function is used to find a pointer that conforms to Eq. 1, which it then converted to an index. Finally, the LinInterp() function is used to approximate \( y(7.180) \).

Note that the value for the BinarySearch() parameter a is set to X+1 to avoid the possibility of accessing the X-1 element. Similarly, the value for the BinarySearch() parameter b is set to X+19 to avoid the possibility of accessing the X+20 element.
#include <cstdio>
#include "y_interp.h"
#include <cmath>

int main()
{
  double X[20];
  for (int i=0;i<20;++i) X[i]=5*i/20.+5;
  double Y[20];
  for (int i=0;i<20;++i) Y[i]=sin(2*3.14159*X[i]/5)+1;

  double x=7.18;
  int i=yInterp::BinarySearch(X+1,X+19,x)-X;
  double y=yInterp::LinInterp(X+i,Y+i,x);
  printf("At x=%.3f, y is approximately %.3f.\n",x,y);
}

OUTPUT:
At x=7.180, y is approximately 1.387.

7. Performing Cubic Interpolations: The CubeInterp() Function

A cubic Hermite spline is a third-degree-polynomial interpolating function that is uniquely determined by 2 endpoint positions (\( \tilde{p}_0 \) and \( \tilde{p}_1 \)) and tangent vectors at the 2 endpoint positions (\( \tilde{m}_0 \) and \( \tilde{m}_1 \), respectively):

\[
\tilde{p}(t) = H_0(t)\tilde{p}_0 + H_1(t)\tilde{m}_0 + H_2(t)\tilde{p}_1 + H_3(t)\tilde{m}_1.
\]

\( H_0(t), H_1(t), H_2(t), \) and \( H_3(t) \) are known as Hermite basis functions and are given by Eqs. 10–13. \( t \) is the linearly scaled distance from \( \tilde{p}_0 \) to \( \tilde{p}_1 \) such that at \( \tilde{p}_0, t = 0 \) and at \( \tilde{p}_1, t = 1 \).

\[
H_0(t) \equiv 2t^3 - 3t^2 + 1.
\]

\[
H_1(t) \equiv t^3 - 2t^2 + t.
\]

\[
H_2(t) \equiv -2t^3 + 3t^2.
\]

\[
H_3(t) \equiv t^3 - t^2.
\]

Suppose that some function \( y(x) \) is represented by a finite set of points \( (x_i, y_i) \), such as is shown in Fig. 5.
From Eq. 9 (and noting that $H_0(t) = 1 - H_2(t)$),

$$y(t) = H_1(t)\frac{dy}{dt}_{t=0} + H_2(t)(y_{i+1} - y_i) + H_3(t)\frac{dy}{dt}_{t=1} + y_i,$$

(14)

Eq. 15 can be used to convert from the scaled independent variable $t$ to the general independent variable $x$.

$$t = \frac{x - x_i}{x_{i+1} - x_i}.$$  

(15)

Eq. 16, along with the chain rule, can be used to convert the derivatives.

$$\frac{dt}{dx} = \frac{1}{x_{i+1} - x_i}.$$  

(16)

Thus,

$$\frac{dy}{dt}_{t=0} = (x_{i+1} - x_i)m_i,$$

(17)

and

$$\frac{dy}{dt}_{t=1} = (x_{i+1} - x_i)m_{i+1},$$

(18)
where

\[
  m_i = \frac{dy}{dx}\bigg|_{x=x_i}.
\]  \hspace{1cm} (19)

Substituting Eqs. 11–13, 17, and 18 into Eq. 14, then regrouping terms, results in the form of the cubic interpolating function that is used by the CubeInterp() function:

\[
y = y_i + (x - x_i)[\{(m_i + m_{i+1})t - (2m_i + m_{i+1})t + m_i\} + (y_{i+1} - y_i)(3 - 2t)t^2].
\]  \hspace{1cm} (20)

### 7.1 CubeInterp() Code

```cpp
template<class T>
T CubeInterp()
{
    const T*Y, //=-----------------BRACKETING Y VALUES (*Y AND Y[1] MUST BE VALID)
    T x, //=-----------------VALUE TO INTERPOLATE AT (TYPICALLY, *X <= x <= X[1])
    T m0, T m1);//<---------------------------SLOPES AT *X AND X[1]
    T t=(x-*X)/(X[1]-*X);
    return*Y+((x-*X)*((m0+m1)*t-(2*m0+m1)*t+m0)+(Y[1]-*Y)*(3-2*t)*t*t;
}
```

#### 7.2 CubeInterp() Template Class

* T is typically a floating-point data type.

#### 7.3 CubeInterp() Parameters

* X \( \Rightarrow \) points to an array that is used to store values for \( x_i \) from Eq. 20. Specifically, 
  \( *X = x_i \) and \( X[1] = x_{i+1} \). Thus, both X and X+1 must point to valid addresses.
* Y \( \Rightarrow \) points to an array that is used to store values for \( y_i \) from Eq. 20. Specifically, 
  \( *Y = y_i \) and \( Y[1] = y_{i+1} \). Thus, both Y and Y+1 must point to valid addresses.
* m0 \( \Rightarrow \) represents \( m_i \), the slope of the interpolating function at \( x_i \).
* m1 \( \Rightarrow \) represents \( m_{i+1} \), the slope of the interpolating function at \( x_{i+1} \).
* x \( \Rightarrow \) represents the independent variable \( x \) from Eq. 20.

#### 7.4 CubeInterp() Return Value

The CubeInterp() function returns \( y \) from Eq. 20.

#### 7.5 CubeInterp() Simple Example

The following example begins by creating a pair of arrays that are used to store independent and dependent variables that approximate Eq. 6. Next, the BinarySearch() function is used to find a pointer that conforms to Eq. 1, which is then converted to an index. Finally, the CubeInterp()
function is used to approximate \( y(7.180) \). For simplicity, \( m_i \) and \( m_{i+1} \) have been set to zero. Section 8 presents a function that can be used to find values for \( m_i \) and \( m_{i+1} \).

Note that the value for the BinarySearch() parameter \( a \) is set to \( X+1 \) to avoid the possibility of accessing the \( X-1 \) element. Similarly, the value for the BinarySearch() parameter \( b \) is set to \( X+19 \) to avoid the possibility of accessing the \( X+20 \) element.

```c
#include <cstdio>
#include "y_interp.h"
int main()
{
    double X[20]; /*<
        */for (int i=0;i<20;++i)X[i]=5*i/20.+5;
    double Y[20]; /*<
        */for (int i=0;i<20;++i)Y[i]=sin(2*3.14159*X[i]/5)+1;
    double x=7.18;
    int i=yInterp::BinarySearch(X+1,X+19,x)-X;
    double y=yInterp::CubeInterp(X+i,Y+i,x,0.,0.);
    printf("At x=%.3f, y is approximately %.3f.\n",x,y);
}
```

**OUTPUT:**

At \( x=7.180 \), \( y \) is approximately 1.362.

---

### 8. Cardinal Splines: The CardinalSlope() Function

The CardinalSlope() function uses Eq. 21 to calculate the CubeInterp()-function input parameters \( m_0 \) and \( m_1 \).

\[
m_i = (1-t) \frac{y_{i+1}-y_{i-1}}{x_{i+1}-x_{i-1}}.
\]  \((21)\)

\( t \) is sometimes referred to as a tension parameter and is typically limited to the interval \([0,1]\).

#### 8.1 CardinalSlope() Code

```c
template<T>T CardinalSlope() //<========CALCULATES SLOPES FOR CubeInterp()
{
    const T*X; //<--------BRACKETING X VALUES (X[-1] AND X[1] MUST BE VALID)
    const T*Y; //<--------BRACKETING Y VALUES (Y[-1] AND Y[1] MUST BE VALID)
    T t); //<-------------------------------TENSION PARAMETER
    return(1-t)*(Y[1]-Y[-1])/(X[1]-X[-1]);
}
```

#### 8.2 CardinalSlope() Template Class

\( T \quad T \) is typically a floating-point data type.
8.3 CardinalSlope() Parameters

**X**

X points to an array that is used to store values for \( x_i \) from Eq. 21. Specifically, \( X[-1] = x_{i-1} \) and \( X[1] = x_{i+1} \). Thus, both \( X-1 \) and \( X+1 \) must point to valid addresses.

**Y**

Y points to an array that is used to store values for \( y_i \) from Eq. 21. Specifically, \( Y[-1] = y_{i-1} \) and \( Y[1] = y_{i+1} \). Thus, both \( Y-1 \) and \( Y+1 \) must point to valid addresses.

**t**

\( t \) represents \( t \), the tension parameter from Eq. 21.

Because the CardinalSlope() function looks at points to either side of the bracketing points, extra care needs to be taken when selecting \( X \) and \( Y \).

8.4 CardinalSlope() Return Value

The CardinalSlope() function returns \( m_i \) from Eq. 21.

8.5 CardinalSlope() Simple Example

The following example begins by creating a pair of arrays that are used to store independent and dependent variables that approximate Eq. 6. Next, the BinarySearch() function is used to find a pointer that conforms to Eq. 1, which is then converted to an index. Finally, the CubeInterp() function is used to approximate \( y(7.180) \).

Note that the value for the BinarySearch() parameter \( a \) has been set to \( X+1 \) to avoid the possibility of accessing the \( X-1 \) element. Similarly, the value for the BinarySearch() parameter \( b \) has been set to \( X+19 \) to avoid the possibility of accessing the \( X+20 \) element.

```
#include <cstdio>
#include "y_interp.h"

int main(){
  //<========A SIMPLE EXAMPLE FOR THE yInterp::CardinalSlope() FUNCTION
  double X[20];/*<*/for(int i=0;i<20;++i)X[i]=5*i/20.+5;
  double Y[20];/*<*/for(int i=0;i<20;++i)Y[i]=sin(2*3.14159*X[i]/5)+1;
  double x=7.18;
  int i=yInterp::BinarySearch(X+1,X+19,x)-X;
  double m0=i==0||i>17?0:yInterp::CardinalSlope(X+i,Y+i,0.),
                m1=i==0||i>17?0:yInterp::CardinalSlope(X+i+1,Y+i+1,0.);
  double y=yInterp::CubeInterp(X+i,Y+i,x,m0,m1);
  printf("At x=%.3f, y is approximately %.3f\n",x,y);
} //~~~~~~YAGENAUT@GMAIL.COM~~~~~~~~~~~~~~~~~~~~~~~~~LAST~UPDATED~21JUL2014~~~~~~
```

OUTPUT:

At x=7.180, y is approximately 1.391.
9. Example: Comparing Interpolating Functions

The following example code creates a comma-separated text file that can be used to create the graph shown in Fig. 6. The plot relating to the CubeInterp() function relies on slopes that are calculated using the CardinalSlope() function (except for the endpoints, where the slopes are set to zero).

```
#include <cstdio>
#include "y_interp.h"

int main(){
    freopen("interp.csv","w",stdout);// redirect output to a file
    double X[8]={2,7,13,19,22,23,28,37},Y[8]={2,6,6,2,9,5,4,7};
    double m[8]={0};/*
        */
    for(int i=1;i<7;++i)
        m[i]=yInterp::CardinalSlope(X+i,Y+i,0.);
    printf("#x,y,x,y1,y2,y3
        \n");
    for(int k=0,n=20000;k<n;++k){
        double x=50/(n-1.)*k;
        int i=yInterp::BinarySearch(X+1,X+8-1,x)-X;\\
            \note \theta>=i<=6
        double y1=yInterp::NNInterp(X+i,Y+i,x);
        double y2=yInterp::LinInterp(X+i,Y+i,x);
        double y3=yInterp::CubeInterp(X+i,Y+i,x,m[i],m[i+1]);
        k<8?printf("%f,%f,"\n,x,Y[k]):printf("-,-,\n);
        printf("%f,%f,%f\n",x,y1,y2,y3);
    }
}
```

Fig. 6 Comparison of the NNInterp(), LinInterp(), and CubeInterp() functions

10. Example: Performing Periodic Interpolations

The following example code begins by setting up a set of points that are used to represent a periodic function with a period equal to 10.0. Next, the NNInterp(), LinInterp(), and CubInterp() functions are used to create values for a comma-separated text file. The graph shown in Fig. 7 represents the contents of the output file.
#include <cstdio>
#include "y_interp.h"

int main() {
    freopen("interp_periodic.csv","w",stdout);........redirect output to a file

double XP[7]={X[3]-10,X[0],X[1],X[2],X[3],X[0]+10,X[1]+10};
double YP[7]={Y[3],Y[0],Y[1],Y[2],Y[3],Y[0],Y[1]};
double m[5];/*<for(int i=0;i<5;++i)
    m[i]=yInterp::CardinalSlope(XP+1+i,YP+1+i,0.);
printf("#x,y,x,y1,y2,y3
n");int j=0;
for(double x=-10,k;x<70;x+=.1,++j){
    int i=yInterp::PeriodicSearch(X,X+4,k=x,10.)-X;
double y1=yInterp::NNInterp(XP+1+i,YP+1+i,k);
double y2=yInterp::LinInterp(XP+1+i,YP+1+i,k);
double y3=yInterp::CubeInterp(XP+1+i,YP+1+i,k,m[i],m[i+1]);
j<4?printf("%f,%f,",X[j],Y[j]):printf("-,-");
printf("%f,%f,%f%n",x,y1,y2,y3);}}

Fig. 7 NNInterp(), LinInterp(), and CubeInterp() functions used to create periodic plots

11. Example: Determining Interpolation Performance

The following example can be used to test the performance of the NNInterp(), LinInterp(), and CubeInterp() functions.

The output was generated by compiling the code using Microsoft's Visual Studio C++ 2010 Express compiler, with the output set to “release” mode. Surprisingly, for this scenario, the LinInterp() and CubeInterp() functions outperform the NNInterp() function.
#include <cstdio>
#include <ctime>
#include "y_interp.h"
#include "y_random.h"

int main(){
    const int N=10000000;
    unsigned I[625];
    double R[N];
    for(int i=0;i<N;++i)R[i]=yRandom::RandU(I,0,1);
    double S=0,t=clock();
    for(int i=0;i<N;++i)S+=yInterp::NNInterp(X,Y,R[i]);
    printf("Using NNInterp(): y_avg= %.6f, t_avg= %.2f ns\n",S/N,(clock()-t)/CLOCKS_PER_SEC/N*1E9),t=clock(),S=0;
    yRandom::Initialize(I,1);
    for(int i=0;i<N;++i)S+=yInterp::LinInterp(X,Y,R[i]);
    printf("Using LinInterp(): y_avg= %.6f, t_avg= %.2f ns\n",S/N,(clock()-t)/CLOCKS_PER_SEC/N*1E9),t=clock(),S=0;
    yRandom::Initialize(I,1);
    for(int i=0;i<N;++i)S+=yInterp::CubeInterp(X,Y,R[i],10.,10.);
    printf("Using CubeInterp(): y_avg= %.6f, t_avg= %.2f ns\n",S/N,(clock()-t)/CLOCKS_PER_SEC/N*1E9);
}

OUTPUT:

Using NNInterp():
    y_avg=4.999344, t_avg=4.52 ns

Using LinInterp():
    y_avg=4.999774, t_avg=2.50 ns

Using CubeInterp():
    y_avg=4.99709, t_avg=3.43 ns

12. Example: Interpolating in Two Dimensions

The NNInterp(), LinInterp(), and CubeInterp() functions can be used to perform interpolations in 2 (and higher) dimensions.

Suppose that \( z_{i,j} \equiv z(x_i, y_j) \). To interpolate in 2 dimensions, begin by performing 2 interpolations in the \( \hat{y} \) direction, 1 at \( x_i \) and 1 at \( x_{i+1} \) (shown in green in Fig. 8). Define \( z_a \) to be the interpolation at \( x_i \) and \( z_b \) to be the interpolation at \( x_{i+1} \). Complete the interpolation by interpolating between \( z_a \) and \( z_b \) in the \( \hat{x} \) direction (shown in red in Fig. 8).
The following example code uses the yBmp namespace to create 3 images (presented in Fig. 9) that show the results of using the NNInterp(), LinInterp(), and CubeInterp() functions to interpolate in 2 dimensions.

```cpp
#include "y_interp.h"
#include "y_bmp.h"

inline void Rainbow(){
    unsigned char C[3];
    double x;
    double min, max;
    if(x<min){C[0]=C[1]=C[2]=0; return;}
    if(x>max){C[0]=C[1]=C[2]=255; return;}
    x=(1-(x-min)/(max-min))*8;
    C[0]=int((3<x&&x<5||x>7 ? -fabs(x/2-3)+1.5:5<=x&&x<=7?1:0)*255);
    C[1]=int((1<x&&x<3||5<x&&x<7? -fabs(x/2-2)+1.5:3<=x&&x<=5?1:0)*255);
    C[2]=int(( x<1|3<x&&x<5? -fabs(x/2-1)+1.5:1<=x&&x<=3?1:0)*255);
}

int main(){
    const int m=4,n=4,r=250;
    double X[4]={0,1,2,3},Y[4]={0,1,2,3};
    double Z[m][n]={1,1,1,0 , 1,0,0,1 ; 0,0,0,0 , 0,0,0,0};
    unsigned char*I=yBmp::NewImage(m*r,n*r,255);
    for(int q=0;q<m*r;++q)for(int p=0;p<n*r;++p){
```
double x=q*(m-1)*1.)/(m*r-1), y=p*(n-1)*1.)/(n*r-1);
int i=yInterp::BinarySearch(X+1,X+m-1,x)-X,
      j=yInterp::BinarySearch(Y+1,Y+n-1,y)-Y;
double Z[2]={yInterp::NNInterp(Y+j,Z[i]+j,y),
            yInterp::NNInterp(Y+j,Z[i+1]+j,y)};
double z=yInterp::NNInterp(X+i,ZI,x);
Rainbow(yBmp::GetPixel(I,q,p),z,-.2,1.2);
}
yBmp::WriteBmpFile("nearest_neighbor.bmp",I);
for(int q=0;q<m*r;++q)
  for(int p=0;p<n*r;++p){
    double x=q*(m-1)*1.)/(m*r-1), y=p*(n-1)*1.)/(n*r-1);
    int i=yInterp::BinarySearch(X+1,X+m-1,x)-X,
      j=yInterp::BinarySearch(Y+1,Y+n-1,y)-Y;
    double Z[2]={yInterp::LinInterp(Y+j,Z[i]+j,y),
                   yInterp::LinInterp(Y+j,Z[i+1]+j,y)};
    double z=yInterp::LinInterp(X+i,ZI,x);
    Rainbow(yBmp::GetPixel(I,q,p),z,-.2,1.2);
  }
yBmp::WriteBmpFile("linear.bmp",I);
for(int q=0;q<m*r;++q)
  for(int p=0;p<n*r;++p){
    double x=q*(m-1)*1.)/(m*r-1), y=p*(n-1)*1.)/(n*r-1);
    int i=yInterp::BinarySearch(X+1,X+m-1,x)-X,
       j=yInterp::BinarySearch(Y+1,Y+n-1,y)-Y;
    double Z[2]={yInterp::CubeInterp(Y+j,Z[i]+j,y,0.,0.),
                  yInterp::CubeInterp(Y+j,Z[i+1]+j,y,0.,0.)};
    double z=yInterp::CubeInterp(X+i,ZI,x,0.,0.);
    Rainbow(yBmp::GetPixel(I,q,p),z,-.2,1.2);
  }
yBmp::WriteBmpFile("cubic.bmp",I);
}  //~~~~~~YAGENAUT@GMAIL.COM~~~~~~~~~~~~~~~~~~~~~~~~~LAST~UPDATED~21JUL2014~~~~~~

Fig. 9  2-dimensional interpolations using NNInterp() (left), LinInterp() (center), and CubeInterp() (right)

13. Polynomial Curve Fitting: The PolyFit() Function

Suppose that some set of \( n \) ordered pairs \((x_k, y_k)\) represents a set of measurements, with \( x_k \)
being a value for an independent variable and \( y_k \) being a value for a dependent variable.
Furthermore, suppose that Eq. 22 represents a best-fit equation for the ordered pairs, where the coefficients \( c_i \) are unknown.

\[
y(x) = c_0 + c_1 x + c_2 x^2 + \cdots + c_r x^r.
\]  

(22)

Eq. 23 can be used to find the coefficients for Eq. 22:

\[
\begin{bmatrix}
  n \\
  k < n \\
  k \leq n \\
  k = 0 \\
  k = 0 \\
  k = 0 \\
  k = 0
\end{bmatrix}
\begin{bmatrix}
  \sum x_k \\
  \sum x_k^2 \\
  \sum x_k^3 \\
  \vdots \\
  \sum x_k^d \\
  \vdots \\
  \sum x_k^{d+1}
\end{bmatrix}
= \begin{bmatrix}
  \sum y_k \\
  \sum y_k x_k \\
  \vdots \\
  \vdots \\
  \sum y_k x_k^d
\end{bmatrix}
\]  

(23)

The PolyFit() function uses Gaussian elimination with backward substitution to solve Eq. 23.

13.1 PolyFit() Code

```cpp
template<typename T> void PolyFit(Vec x, Vec y, const T* X, const T* Y, T n, int m, int i, int j)
{
    for (int k = 0; k < n; ++k) A[i][j] += pow(X[k], i + j);
}
```

13.2 PolyFit() Template Classes

T T is typically a floating-point data type.

13.3 PolyFit() Parameters

X X points to an array that is used to store the \( n \) \( x_k \) values that are specified in Eq. 23, where \( X = \{ x_0, x_1, \ldots, x_k, \ldots, x_{n-1} \} \). Each \( x_k \) value must be unique.

Y Y points to an array that is used to store the \( n \) \( y_k \) values that are specified in Eq. 23, where \( Y = \{ y_0, y_1, \ldots, y_k, \ldots, y_{n-1} \} \).

n n specifies \( n \), the number of \( x_k \) (or \( y_k \)) values.
\( m \) specifies the number of coefficients in the array that is pointed to by \( C \). Thus, \( m = d + 1 \), where \( d \) is the degree of the fitting polynomial (see Eq. 22).

\( C \) points to storage for an array that is used to store the \( c_i \) coefficients \((C = \{c_0, c_1, \ldots , c_i, \ldots, c_d\})\). \( C \) must point to an array with storage for at least \( m \) elements. The elements pointed to by \( C \) are calculated by the PolyFit() function.

Note that if \( m \) is too large, or if the values pointed to by \( X \) are too close together, then the PolyFit() function may return coefficients that do not accurately describe a best-fit curve. It is always best to plot the best-fit curve against measured data to verify the quality of the fit. It is also a good idea to calculate the coefficient of determination \((R^2)\), which is a measurement of the quality of the fit.

\[
R^2 \equiv 1 - \frac{\sum_{k=0}^{k<q} (y_k - f(x_k))^2}{\sum_{k=0}^{k<q} (y_k - \bar{y})^2},
\]

where

\[
\bar{y} \equiv \frac{1}{n} \sum_{k=0}^{k<q} y_i.
\]

\( R^2 \) values are typically in the interval \([0,1]\), with 1 indicating a perfect fit.

### 13.4 PolyFit() Simple Example

The following example first defines a polynomial, then uses that polynomial to calculate a set of \((x_k, y_k)\) ordered pairs. The PolyFit() function is used to calculate the coefficients for a polynomial that best fits the set of ordered pairs. The calculated coefficients are shown to be identical (at least to 6 decimal places) to the coefficients of the original polynomial.

```c
#include <cstdio>
#include "y_interp.h"

int main(){
    //<==============A SIMPLE EXAMPLE FOR THE yInterp::PolyFit() FUNCTION
    double a=-308,b=177,c=-33,d=2;
    double X[10],Y[10];
    for(int i=0;i<10;++i){
        X[i]=i,Y[i]=a+b*i+c*i*i+d*i*i*i;
        printf("%f,%f\n",X[i],Y[i]);}
    double C[4];/*<*/yInterp::PolyFit(X,Y,10,4,C);
    printf("\n");
    for(int i=0;i<4;++i)printf("%f\n",C[i]);
} //~~~~~~YAGENAUT@GMAIL.COM~~~~~~~~~~~~~~~~~~~~~~~~~LAST~UPDATED~21JUL2014~~~~~~
```
The PolyFit() function can be used to fit nonpolynomial equations to measured data. Suppose Eq. 26 is suspected to be a good fit for some set of data points \((x_k, y_k)\).

\[ y = Ae^{Bx} \quad \text{(26)} \]

The PolyFit() function can be used to find the parameters \(A\) and \(B\).

Begin by defining \(y' = \ln(y)\). Next, use the PolyFit() function to find \(c_0\) and \(c_1\) (the parameters for a straight line) for the data set \((x_k, y'_k)\). Thus,

\[ y' = \ln(y) = c_0 + c_1x. \quad \text{(27)} \]

Solving for \(y\),

\[ y = e^{c_0 + c_1x} = e^{c_0} e^{c_1x}. \quad \text{(28)} \]

Thus,

\[ A = e^{c_0} \quad \text{and} \quad B = c_1. \quad \text{(29)} \]

The following example code uses the PolyFit() function to fit Eq. 26 to beginning-of-year values for the Dow Jones Industrial Average for the decade 1986–1995. Values were obtained from the file “dji_d.csv,” which was downloaded from http://stooq.com. The yIo2 namespace was used to read and parse the data file. The results are presented in Fig. 10.
```c
#include <cstdio>
#include <vector>
#include "y_interp.h"
#include "y_io_2.h"

int main(){
    //FITTING AN EXPONENTIAL EQUATION USING THE PolyFit() FUNCTION
    char*s=yIo2::ReadTextFile("^dji_d.csv");
    std::vector<std::vector<char*>> S=yIo2::Parse2D(s,"/ \t-,");
    std::vector<double> X,Y;
    for(int i=2,y;i<S.size();++i)
        if(y!=atoi(S[i-1][0])&&y>1984)X.push_back(y),Y.push_back(atof(S[i][6]));
    delete[]s;
    std::vector<double> Yp(X.size());
    for(int i=0,m=X.size();i<m;++i)Yp[i]=log(Y[i]);
    double*a=&X[0],*b=&Yp[0];
    double C[2];
    yInterp::PolyFit(a,b,X.size(),2,C);
    double y_bar=0;
    for(int k=0;k<10;++k)y_bar+=Y[k];
y_bar/=10;
    double SS_res=0,SS_tot=0;
    for(int k=0;k<10;++k)
        SS_res+=pow(Y[k]-exp(C[0]+C[1]*X[k]),2.),SS_tot+=pow(Y[k]-y_bar,2.);
    printf("A=%E\nB=%f\nR^2=%f\n",exp(C[0]),C[1],1-SS_res/SS_tot);
    freopen("exponential_fit.csv","w",stdout);
    for(int i=1,n=X.size();i<n;++i)
        printf("%f,%f,%f\n",X[i],Y[i],exp(C[0]+C[1]*X[i]));
}
```

Fig. 10  Best-fit line calculated by the PolyFit() function

$$y = 1.524582 \times 10^{-22} e^{0.110156 x}$$

$$R^2 = 0.956466$$
15. Code Summary

The following summary sheet presents the yInterp namespace, which contains the BinarySearch(), PeriodicSearch(), NNInterp(), LinInterp(), CubeInterp(), CardinalSlope(), and PolyFit() functions.
**yInterp Summary**

- **BinarySearch()**
  - **Performance**
  - **Example**

- **PeriodicSearch()**

- **Interpolation Comparison**

- **Polyfit()**

- **BinarySearch() / PeriodicSearch() Example**

**Include std::cmath;**

```cpp
#include <cmath>
#include <iostream>

namespace yInterp {

// BinarySearch() Example

int main() {
    int n = 100000000;
    double x = 5.1;
    double y = 0.1;
    double z = 0.1;
    double t = clock();
    // Timer
    double T = (long)(clock() - t) / CLOCKS_PER_SEC; // Time in seconds
    for (int i = 0; i < n; ++i) {
        // BinarySearch
        y = yInterp::BinarySearch(x, y, z, T);
    }
    double T1 = (long)(clock() - t) / CLOCKS_PER_SEC;
    // Timer
    return T1;
}
```

---

**PeriodicSearch()**

```cpp
#include <cmath>
#include <iostream>

namespace yInterp {

// PeriodicSearch() Example

int main() {
    int n = 100000000;
    double x = 5.1;
    double y = 0.1;
    double z = 0.1;
    double t = clock();
    // Timer
    double T = (long)(clock() - t) / CLOCKS_PER_SEC; // Time in seconds
    for (int i = 0; i < n; ++i) {
        // PeriodicSearch
        y = yInterp::PeriodicSearch(x, y, z, T);
    }
    double T2 = (long)(clock() - t) / CLOCKS_PER_SEC;
    // Timer
    return T2;
}
```
16. References


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