3.4 How to Search an Ordered Table

Suppose that you have decided to use some particular interpolation scheme, such as fourth-order polynomial interpolation, to compute a function \( f(x) \) from a set of tabulated \( x_i \)'s and \( f_i \)'s. Then you will need a fast way of finding your place in the table of \( x_i \)'s, given some particular value \( x \) at which the function evaluation is desired. This problem is not properly one of numerical analysis, but it occurs so often in practice that it would be negligent of us to ignore it.

Formally, the problem is this: Given an array of abscissas \( xx[j], j=1,2,\ldots,n \), with the elements either monotonically increasing or monotonically decreasing, and given a number \( x \), find an integer \( j \) such that \( x \) lies between \( xx[j] \) and \( xx[j+1] \). For this task, let us define fictitious array elements \( xx[0] \) and \( xx[n+1] \) equal to plus or minus infinity (in whichever order is consistent with the monotonicity of the table). Then \( j \) will always be between 0 and \( n \), inclusive; a value of 0 indicates “off-scale” at one end of the table, \( n \) indicates off-scale at the other end.

In most cases, when all is said and done, it is hard to do better than bisection, which will find the right place in the table in about \( \log_2 n \) tries. We already did use bisection in the spline evaluation routine \texttt{splint} of the preceding section, so you might glance back at that. Standing by itself, a bisection routine looks like this:

```c
void locate(float xx[], unsigned long n, float x, unsigned long *j)
{
    unsigned long ju,jm,jl; int ascnd;
    jl=0; ju=n+1;           /* Initialize lower */
    ascnd=(xx[n] >= xx[1]); /* and upper limits. */
    while (ju-jl > 1) {
        jm=(ju+jl) >> 1;     /* If we are not yet done, */
        if (x >= xx[jm] == ascnd) { /* compute a midpoint, */
            jl=jm;            /* if \( x \) is between \( xx[j] \) */
            else ju=jm;       /* and \( xx[j+1] \), \( xx \) */
                            /* must be monotonic, either increasing */
                            /* or decreasing. */
        }                    /* \( j=0 \) or \( j=n \) is */
                            /* returned to indicate that */
                            /* \( x \) is out of range. */
        if (x == xx[1]) *j=1;    /* \texttt{locate} with a zero-offset */
        else if(x == xx[n]) *j=n-1;    /* array, remember to subtract */
        else *j=jl;             /* 1 from the address of \( xx \), */
                               /* and also from the returned */
                               /* value \( j \). */
    }
}
```

Sometimes you will be in the situation of searching a large table many times, and with nearly identical abscissas on consecutive searches. For example, you may be generating a function that is used on the right-hand side of a differential equation: Most differential-equation integrators, as we shall see in Chapter 16, call
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Figure 3.4.1. (a) The routine locate finds a table entry by bisection. Shown here is the sequence of steps that converge to element 51 in a table of length 64. (b) The routine hunt searches from a previous known position in the table by increasing steps, then converges by bisection. Shown here is a particularly unfavorable example, converging to element 32 from element 7. A favorable example would be convergence to an element near 7, such as 9, which would require just three “hops.”

for right-hand side evaluations at points that hop back and forth a bit, but whose trend moves slowly in the direction of the integration.

In such cases it is wasteful to do a full bisection, *ab initio*, on each call. The following routine instead starts with a guessed position in the table. It first “hunts,” either up or down, in increments of 1, then 2, then 4, etc., until the desired value is bracketed. Second, it then bisects in the bracketed interval. At worst, this routine is about a factor of 2 slower than locate above (if the hunt phase expands to include the whole table). At best, it can be a factor of $\log_2 n$ faster than locate, if the desired point is usually quite close to the input guess. Figure 3.4.1 compares the two routines.

```c
void hunt(float xx[], unsigned long n, float x, unsigned long *jlo)
{
    unsigned long jm, jhi, inc;
    int ascnd;

    ascnd=(xx[n] >= xx[1]);
    if (*jlo <= 0 || *jlo > n) {
        *jlo=0;
        jhi=n+1;
    } else {
        inc=1;
        if (x >= xx[*jlo] == ascnd) {  // True if ascending order of table, false otherwise.
            jhi=*jlo+1;
            Set the hunting increment.
            if (*jlo == n) return;  // Input guess not useful. Go immediately to bisection.
        } else if (x >= xx[*jlo] == ascnd) {  // Input guess not useful. Go immediately to bisection.
            while (x >= xx[jhi] == ascnd) {  // Not done hunting.
                inc *= inc;
                *jlo=jhi;
                so double the increment
                jhi=*jlo+inc;
                if (jhi > n) {  // Done hunting, since off end of table.
                    jhi=n+1;
                    break;
                }
            }
            Hunt up:
            if (*jlo == n) return;
        }
        while (x >= xx[jhi] == ascnd) {  // Not done hunting.
            *jlo=jhi;
            so double the increment
            inc *= inc;
            jhi=*jlo+inc;
            if (jhi > n) {  // Done hunting, since off end of table.
                jhi=n+1;
                break;
            }
            Try again.
        }
    }
}
```
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```c
} else {
    if (*jlo == 1) {
        *jlo = 0;
        return;
    }
    jhi = (*jlo) - 1;
    while (x < xx[*jlo] == ascnd) {
        Not done hunting,
    jhi = (*jlo);
        inc <<= 1;
        if (inc >= jhi) {
            Done hunting, since off end of table.
            *jlo = 0;
            break;
        } else *
            jlo = jhi - inc;
    }
    \*jlo = jhi - inc;
    \}
}

While (jhi - (*jlo) != 1) \{
    jm = (jhi + (*jlo)) >> 1;
    if (x >= xx[jm] == ascnd)
        *jlo = jm;
    else
        jhi = jm;
    if (x == xx[n]) *jlo = n - 1;
    if (x == xx[1]) *jlo = 1;
}
```

Done hunting, value bracketed.
Hunt down:

Hunt down:

```c
if (*jlo == 1) {
    *jlo = 0;
    return;
}
```

Not done hunting.

```c
jhi = (*jlo);
inc <<= 1;
if (inc >= jhi) {
    Done hunting, since off end of table.
    *jlo = 0;
    break;
} else *
    jlo = jhi - inc;
}
```

and try again.

Done hunting, value bracketed.

Hunt done, so begin the final bisection phase:

```c
jhi = (*jlo) - 1;
```

Hunt is done, so begin the final bisection phase:

If your array xx is zero-offset, read the comment following locate, above.

**After the Hunt**

The problem: Routines locate and hunt return an index \( j \) such that your desired value lies between table entries \( xx[j] \) and \( xx[j+1] \), where \( xx[1..n] \) is the full length of the table. But, to obtain an \( m \)-point interpolated value using a routine like \texttt{polint} (§3.1) or \texttt{ratint} (§3.2), you need to supply much shorter \( xx \) and \( yy \) arrays, of length \( m \). How do you make the connection?

The solution: Calculate

\[
k = \text{IMIN}(\text{IMAX}(j-(m-1)/2,1),n+1-m)
\]

(The macros \texttt{IMIN} and \texttt{IMAX} give the minimum and maximum of two integer arguments; see §1.2 and Appendix B.) This expression produces the index of the leftmost member of an \( m \)-point set of points centered (insofar as possible) between \( j \) and \( j+1 \), but bounded by 1 at the left and \( n \) at the right. \( C \) then lets you call the interpolation routine with array addresses offset by \( k \), e.g.,

\[
\texttt{polint}(\&xx[k-1],\&yy[k-1],m,...)
\]

CITED REFERENCES AND FURTHER READING:

### 3.5 Coefficients of the Interpolating Polynomial

Occasionally you may wish to know not the value of the interpolating polynomial that passes through a (small!) number of points, but the coefficients of that polynomial. A valid use of the coefficients might be, for example, to compute simultaneous interpolated values of the function and of several of its derivatives (see §5.3), or to convolve a segment of the tabulated function with some other function, where the moments of that other function (i.e., its convolution with powers of \(x\)) are known analytically.

However, please be certain that the coefficients are what you need. Generally the coefficients of the interpolating polynomial can be determined much less accurately than its value at a desired abscissa. Therefore it is not a good idea to determine the coefficients only for use in calculating interpolating values. Values thus calculated will not pass exactly through the tabulated points, for example, while values computed by the routines in §§3.1–§3.3 will pass exactly through such points.

Also, you should not mistake the interpolating polynomial (and its coefficients) for its cousin, the best fit polynomial through a data set. Fitting is a smoothing process, since the number of fitted coefficients is typically much less than the number of data points. Therefore, fitted coefficients can be accurately and stably determined even in the presence of statistical errors in the tabulated values. (See §14.8.) Interpolation, where the number of coefficients and number of tabulated points are equal, takes the tabulated values as perfect. If they in fact contain statistical errors, these can be magnified into oscillations of the interpolating polynomial in between the tabulated points.

As before, we take the tabulated points to be \(y_i = y(x_i)\). If the interpolating polynomial is written as

\[
y = c_0 + c_1 x + c_2 x^2 + \cdots + c_N x^N
\]

then the \(c_i\)'s are required to satisfy the linear equation

\[
\begin{bmatrix}
1 & x_0 & x_0^2 & \cdots & x_0^N \\
1 & x_1 & x_1^2 & \cdots & x_1^N \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
1 & x_N & x_N^2 & \cdots & x_N^N
\end{bmatrix}
\begin{bmatrix}
c_0 \\
c_1 \\
\vdots \\
c_N
\end{bmatrix}
= \begin{bmatrix}
y_0 \\
y_1 \\
\vdots \\
y_N
\end{bmatrix}
\]

This is a Vandermonde matrix, as described in §2.8. One could in principle solve equation (3.5.2) by standard techniques for linear equations generally (§2.3); however the special method that was derived in §2.8 is more efficient by a large factor, of order \(N\), so it is much better.

Remember that Vandermonde systems can be quite ill-conditioned. In such a case, no numerical method is going to give a very accurate answer. Such cases do not, please note, imply any difficulty in finding interpolated values by the methods of §3.1, but only difficulty in finding coefficients.

Like the routine in §2.8, the following is due to G.B. Rybicki. Note that the arrays are all assumed to be zero-offset.