6.1 Gamma Function, Beta Function, Factorials, Binomial Coefficients

The gamma function is defined by the integral

\[ \Gamma(z) = \int_0^\infty t^{z-1}e^{-t}dt \]  \hspace{1cm} (6.1.1)

When the argument \( z \) is an integer, the gamma function is just the familiar factorial function, but offset by one,

\[ n! = \Gamma(n+1) \]  \hspace{1cm} (6.1.2)

The gamma function satisfies the recurrence relation

\[ \Gamma(z+1) = z\Gamma(z) \]  \hspace{1cm} (6.1.3)

If the function is known for arguments \( z > 1 \) or, more generally, in the half complex plane \( \text{Re}(z) > 1 \) it can be obtained for \( z < 1 \) or \( \text{Re}(z) < 1 \) by the reflection formula

\[ \Gamma(1-z) = \frac{\pi}{\Gamma(z)\sin(\pi z)} = \frac{\pi z}{\Gamma(1+z)\sin(\pi z)} \]  \hspace{1cm} (6.1.4)

Notice that \( \Gamma(z) \) has a pole at \( z = 0 \), and at all negative integer values of \( z \).

There are a variety of methods in use for calculating the function \( \Gamma(z) \) numerically, but none is quite as neat as the approximation derived by Lanczos [1]. This scheme is entirely specific to the gamma function, seemingly plucked from thin air. We will not attempt to derive the approximation, but only state the resulting formula: For certain integer choices of \( \gamma \) and \( N \), and for certain coefficients \( c_1, c_2, \ldots, c_N \), the gamma function is given by

\[ \Gamma(z+1) = (z + \gamma + \frac{1}{2})^{z+\frac{1}{2}}e^{-(z+\gamma+\frac{1}{2})} \times \sqrt{2\pi} \left[ c_0 + \frac{c_1}{z+1} + \frac{c_2}{z+2} + \cdots + \frac{c_N}{z+N} + \epsilon \right] \]  \hspace{1cm} (z > 0) \hspace{1cm} (6.1.5)

You can see that this is a sort of take-off on Stirling's approximation, but with a series of corrections that take into account the first few poles in the left complex plane. The constant \( c_0 \) is very nearly equal to 1. The error term is parametrized by \( \epsilon \). For \( \gamma = 5 \), \( N = 6 \), and a certain set of \( c \)'s, the error is smaller than \( |\epsilon| < 2 \times 10^{-10} \).

Impressed? If not, then perhaps you will be impressed by the fact that (with these
same parameters) the formula (6.1.5) and bound on $\epsilon$ apply for the complex gamma function, everywhere in the half complex plane $\text{Re} \ z > 0$.

It is better to implement $\ln \Gamma(x)$ than $\Gamma(x)$, since the latter will overflow many computers’ floating-point representation at quite modest values of $x$. Often the gamma function is used in calculations where the large values of $\Gamma(x)$ are divided by other large numbers, with the result being a perfectly ordinary value. Such operations would normally be coded as subtraction of logarithms. With (6.1.5) in hand, we can compute the logarithm of the gamma function with two calls to a logarithm and 25 or so arithmetic operations. This makes it not much more difficult than other built-in functions that we take for granted, such as $\sin x$ or $e^x$:

```fortran
FUNCTION gammln(xx)
REAL gammln,xx
   Returns the value $\ln[\Gamma(xx)]$ for $xx > 0$.
INTEGER j
DOUBLE PRECISION ser,stp,tmp,x,y,cof(6)
   Internal arithmetic will be done in double precision, a nicety that you can omit if five-figure accuracy is good enough.
SAVE cof,stp
DATA cof,stp/76.18009172947146d0,-86.50532032941677d0,
   24.01409824083091d0,-1.231739572450155d0,.1208650973866179d-2,
   -.5395239384953d-5,2.5066282746310005d0/
   x=xx
   y=x
   tmp=x+5.5d0
   tmp=(x+0.5d0)*log(tmp)-tmp
   ser=1.000000000190015d0
   do 11 j=1,6
      y=y+1.d0
      ser=ser+cof(j)/y
   enddo
   gammln=tmp+log(stp*ser/x)
   return
END
```

How shall we write a routine for the factorial function $n!$? Generally the factorial function will be called for small integer values (for large values it will overflow anyway!), and in most applications the same integer value will be called for many times. It is a profligate waste of computer time to call $\exp(\text{gammln}(n+1.0))$ for each required factorial. Better to go back to basics, holding $\text{gammln}$ in reserve for unlikely calls:

```fortran
FUNCTION factrl(n)
INTEGER n
REAL factrl
   USES gammln
   Returns the value $n!$ as a floating-point number.
INTEGER j,ntop
SAVE ntop,a
DATA ntop,a(33)/0,1./
   Table to be filled in only as required.
if (n.lt.0) then
   pause 'negative factorial in factrl'
else if (n.le.ntop) then
   Already in table.
   factrl=a(n+1)
else if (n.le.32) then
   Fill in table up to desired value.
   do ii j=ntop+1,n
   END
```

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a(j+1)=j*a(j)
enddo ::
ntop=n
factrl=a(n+1)
else
    Larger value than size of table is required. Actually, this big
    a value is going to overflow on many computers, but no
    harm in trying.
factrl=exp(gammln(n+1.))
endif
return
END

A useful point is that factrl will be *exact* for the smaller values of n, since
floating-point multiplies on small integers are exact on all computers. This exactness
will not hold if we turn to the logarithm of the factorials. For binomial coefficients,
however, we must do exactly this, since the individual factorials in a binomial
coefficient will overflow long before the coefficient itself will.

The binomial coefficient is defined by

\[
\binom{n}{k} = \frac{n!}{k!(n-k)!} \quad 0 \leq k \leq n
\]

(6.1.6)

FUNCTION bico(n,k)
INTEGER k,n
REAL bico
C USES factln
Returns the binomial coefficient \( \binom{n}{k} \) as a floating-point number.
REAL factln
bico=nint(exp(factln(n)-factln(k)-factln(n-k)))
return
END

which uses

FUNCTION factln(n)
INTEGER n
REAL factln
C USES gammln
Returns \( \ln(n!) \).
REAL a(100),gammln
SAVE a
DATA a/100*-1./
if (n.lt.0) pause 'negative factorial in factln'
if (n.le.99) then
    if (a(n+1).lt.0.) a(n+1)=gammln(n+1.)
    factln=a(n+1)
else
    factln=gammln(n+1.)
endif
return
END
If your problem requires a series of related binomial coefficients, a good idea is to use recurrence relations, for example

\[
\binom{n+1}{k} = \frac{n+1}{n-k+1} \binom{n}{k} = \binom{n}{k} + \binom{n}{k-1}
\]

Finally, turning away from the combinatorial functions with integer valued arguments, we come to the beta function,

\[
B(z, w) = B(w, z) = \int_0^1 t^{z-1}(1 - t)^{w-1} dt
\]

which is related to the gamma function by

\[
B(z, w) = \frac{\Gamma(z)\Gamma(w)}{\Gamma(z + w)}
\]

hence

\[
\text{FUNCTION beta}(z, w) \\
\text{REAL beta, w, z} \\
\text{C USES gammln} \\
\text{Returns the value of the beta function } B(z, w). \\
\text{REAL gammln} \\
\beta = \exp(\text{gammln}(z) + \text{gammln}(w) - \text{gammln}(z + w)) \\
\text{return} \\
\text{END}
\]

CITED REFERENCES AND FURTHER READING:

### 6.2 Incomplete Gamma Function, Error Function, Chi-Square Probability Function, Cumulative Poisson Function

The incomplete gamma function is defined by

\[
P(a, x) = \frac{\gamma(a, x)}{\Gamma(a)} = \frac{1}{\Gamma(a)} \int_0^x e^{-t} t^{a-1} dt 
\quad (a > 0) 
\]