NAG C Library Function Document

nag_1d_quad_brkpts (d01alc)

1 Purpose

nag_1d_quad_brkpts (d01alc) is a general purpose integrator which calculates an approximation to the integral of a function $f(x)$ over a finite interval $[a, b]$:

$$I = \int_a^b f(x)\, dx.$$

where the integrand may have local singular behaviour at a finite number of points within the integration interval.

2 Specification

```
#include <nag.h>
#include <nagd01.h>
```

```
void nag_1d_quad_brkpts (double (*f)(double x),
          double a, double b, Integer nbrkpts, double brkpts[], double epsabs,
          double epsrel, Integer max_num_subint, double *result,
          double *abserr, Nag_QuadProgress *qp, NagError *fail)
```

3 Description

This function is based upon the QUADPACK routine QAGP (Piessens *et al.* (1983)). It is very similar to nag_1d_quad_gen (d01ajc), but allows the user to supply 'break-points', points at which the function is known to be difficult. It is an adaptive routine, using the Gauss 10-point and Kronrod 21-point rules. The algorithm described by De Doncker (1978), incorporates a global acceptance criterion (as defined by Malcolm and Simpson (1976)) together with the ϵ-algorithm (Wynn (1956)) to perform extrapolation. The user-supplied 'break-points' always occur as the end-points of some sub-interval during the adaptive process. The local error estimation is described by Piessens *et al.* (1983).

4 Parameters

1: **f** – function supplied by user *Function*

The function **f**, supplied by the user, must return the value of the integrand f at a given point.

The specification of **f** is:

```
double f(double x)
```

1: **x** – double *Input*

On entry: the point at which the integrand f must be evaluated.

2: **a** – double *Input*

On entry: the lower limit of integration, a.

3: **b** – double *Input*

On entry: the upper limit of integration, b. It is not necessary that $a < b$.

4: **nbrkpts** – Integer *Input*

On entry: the number of user-supplied break-points within the integration interval.

Constraint: **nbrkpts** ≥ 0.

5: **brkpts[nbrkpts]** – double *Input*

On entry: the user-specified break-points.

Constraint: the break-points must all lie within the interval of integration (but may be supplied in any order).

6: **epsabs** – double *Input*

On entry: the absolute accuracy required. If **epsabs** is negative, the absolute value is used. See Section 6.1.

7: **epsrel** – double *Input*

On entry: the relative accuracy required. If **epsrel** is negative, the absolute value is used. See Section 6.1.

8: **max_num_subint** – Integer *Input*

On entry: the upper bound on the number of sub-intervals into which the interval of integration may be divided by the function. The more difficult the integrand, the larger **max_num_subint** should be.

Suggested values: a value in the range 200 to 500 is adequate for most problems.

Constraint: **max_num_subint** ≥ 1.

9: **result** – double * *Output*

On exit: the approximation to the integral I.

10: **abserr** – double * *Output*

On exit: an estimate of the modulus of the absolute error, which should be an upper bound for $|I-$**result**$|$.

11: **qp** – Nag_QuadProgress *

Pointer to structure of type **Nag_QuadProgress** with the following members:

num_subint – Integer *Output*

On exit: the actual number of sub-intervals used.

fun_count – Integer *Output*

On exit: the number of function evaluations performed by nag_1d_quad_brkpts.

sub_int_beg_pts – double * *Output*
sub_int_end_pts – double * *Output*
sub_int_result – double * *Output*
sub_int_error – double * *Output*

On exit: these pointers are allocated memory internally with **max_num_subint** elements. If an error exit other than **NE_INT_ARG_LT**, **NE_2_INT_ARG_LE** or **NE_ALLOC_FAIL** occurs, these arrays will contain information which may be useful. For details, see Section 6.

Before a subsequent call to nag_1d_quad_brkpts is made, or when the information contained in these arrays is no longer useful, the user should free the storage allocated by these pointers using the NAG macro **NAG_FREE**.

12: **fail** – NagError * *Input/Output*

The NAG error parameter (see the Essential Introduction).

Users are recommended to declare and initialise **fail** and set **fail.print** = **TRUE** for this function.

5 Error Indicators and Warnings

NE_INT_ARG_LT

On entry, **max_num_subint** must not be less than 1: **max_num_subint** = <*value*>.
On entry, **nbrkpts** must not be less than 0: **nbrkpts** = <*value*>.

NE_2_INT_ARG_LE

On entry, **max_num_subint** = <*value*> while **nbrkpts** = <*value*>. These parameters must satisfy **max_num_subint** > **nbrkpts**.

NE_ALLOC_FAIL

Memory allocation failed.

NE_QUAD_MAX_SUBDIV

The maximum number of subdivisions has been reached: **max_num_subint** = <*value*>.
The maximum number of subdivisions has been reached without the accuracy requirements being achieved. Look at the integrand in order to determine the integration difficulties. If the position of a local difficulty within the interval can be determined (e.g., a singularity of the integrand or its derivative, a peak, a discontinuity, etc.) you will probably gain from splitting up the interval at this point and calling the integrator on the sub-intervals. If necessary, another integrator, which is designed for handling the type of difficulty involved, must be used. Alternatively, consider relaxing the accuracy requirements specified by **epsabs** and **epsrel**, or increasing the value of **max_num_subint**.

NE_QUAD_ROUNDOFF_TOL

Round-off error prevents the requested tolerance from being achieved: **epsabs** = <*value*>, **epsrel** = <*value*>.
The error may be underestimated. Consider relaxing the accuracy requirements specified by **epsabs** and **epsrel**.

NE_QUAD_BAD_SUBDIV

Extremely bad integrand behaviour occurs around the sub-interval (<*value*>, <*value*>).
The same advice applies as in the case of **NE_QUAD_MAX_SUBDIV**.

NE_QUAD_ROUNDOFF_EXTRAPL

Round-off error is detected during extrapolation.
The requested tolerance cannot be achieved, because the extrapolation does not increase the accuracy satisfactorily; the returned result is the best that can be obtained.
The same advice applies as in the case of **NE_QUAD_MAX_SUBDIV**.

NE_QUAD_NO_CONV

The integral is probably divergent, or slowly convergent.
Please note that divergence can occur with any error exit other than **NE_INT_ARG_LT**, **NE_2_INT_ARG_LE** and **NE_ALLOC_FAIL**.

NE_QUAD_BRKPTS_INVAL

On entry, break points outside (**a**, **b**): **a** = <*value*>, **b** = <*value*>.

6 Further Comments

The time taken by nag_1d_quad_brkpts depends on the integrand and the accuracy required.

If the function fails with an error exit other than **NE_INT_ARG_LT**, **NE_2_INT_ARG_LE** or **NE_ALLOC_FAIL**, then the user may wish to examine the contents of the structure **qp**. These contain the end-points of the sub-intervals used by nag_1d_quad_brkpts along with the integral contributions and error estimates over the sub-intervals.

Specifically, for $i = 1, 2, \ldots, n$, let r_i denote the approximation to the value of the integral over the sub-interval $[a_i, b_i]$ in the partition of $[a, b]$ and e_i be the corresponding absolute error estimate.

Then, $\int_{a_i}^{b_i} f(x)dx \simeq r_i$ and **result** $= \sum_{i=1}^{n} r_i$ unless the function terminates while testing for divergence of the integral (see Section 3.4.3 of Piessens *et al.* (1983)). In this case, **result** (and **abserr**) are taken to be the values returned from the extrapolation process. The value of n is returned in **num_subint**, and the values a_i, b_i, r_i and e_i are stored in the structure **qp** as

a_i = **sub_int_beg_pts**$[i-1]$,

b_i = **sub_int_end_pts**$[i-1]$,

r_i = **sub_int_result**$[i-1]$ and

e_i = **sub_int_error**$[i-1]$.

6.1 Accuracy

The function cannot guarantee, but in practice usually achieves, the following accuracy:

$$|I - \textbf{result}| \leq tol$$

where

$$tol = \max\{|\textbf{epsabs}|, |\textbf{epsrel}| \times |I|\}$$

and **epsabs** and **epsrel** are user-specified absolute and relative error tolerances. Moreover it returns the quantity **abserr** which, in normal circumstances, satisfies

$$|I - \textbf{result}| \leq \textbf{abserr} \leq tol.$$

6.2 References

De Doncker E (1978) An adaptive extrapolation algorithm for automatic integration *ACM SIGNUM Newsl.* **13 (2)** 12–18

Malcolm M A and Simpson R B (1976) Local versus global strategies for adaptive quadrature *ACM Trans. Math. Software* **1** 129–146

Piessens R, De Doncker-Kapenga E, Überhuber C and Kahaner D (1983) *QUADPACK, A Subroutine Package for Automatic Integration* Springer-Verlag

Wynn P (1956) On a device for computing the $e_m(S_n)$ transformation *Math. Tables Aids Comput.* **10** 91–96

7 See Also

nag_1d_quad_gen (d01ajc)
nag_1d_quad_osc (d01akc)

8 Example

To compute

$$\int_0^1 \frac{1}{\sqrt{|x - \frac{1}{7}|}}\, dx.$$

8.1 Program Text

```
/* nag_1d_quad_brkpts(d01alc) Example Program
 *
 * Copyright 1991 Numerical Algorithms Group.
 *
 * Mark 2, 1991.
 *
 * Mark 6 revised, 2000.
 */

#include <nag.h>
#include <stdio.h>
#include <nag_stdlib.h>
#include <math.h>
#include <nagd01.h>

static double f(double x);

main()
{
  double a, b;
  double epsabs, abserr, epsrel, brkpts[1], result;
  Integer nbrkpts;
  Nag_QuadProgress qp;
  Integer max_num_subint;
  static NagError fail;

  Vprintf("d01alc Example Program Results\n");
  nbrkpts = 1;
  epsabs = 0.0;
  epsrel = 0.001;
  a = 0.0;
  b = 1.0;
  max_num_subint = 200;
  brkpts[0] = 1.0/7.0;
  d01alc(f, a, b, nbrkpts, brkpts, epsabs, epsrel, max_num_subint,
         &result, &abserr, &qp, &fail);

  Vprintf("a      - lower limit of integration = %10.4f\n", a);
  Vprintf("b      - upper limit of integration = %10.4f\n", b);
  Vprintf("epsabs - absolute accuracy requested = %9.2e\n", epsabs);
  Vprintf("epsrel - relative accuracy requested = %9.2e\n\n", epsrel);
  Vprintf("brkpts[0] - given break-point = %10.4f\n", brkpts[0]);

  if (fail.code != NE_NOERROR)
    Vprintf("%s\n", fail.message);

  if (fail.code != NE_INT_ARG_LT && fail.code != NE_2_INT_ARG_LE &&
      fail.code != NE_ALLOC_FAIL)
    {
      /* Free memory used by qp pointers */
      NAG_FREE(qp.sub_int_beg_pts);
      NAG_FREE(qp.sub_int_end_pts);
      NAG_FREE(qp.sub_int_result);
      NAG_FREE(qp.sub_int_error);
    }
  if (fail.code != NE_INT_ARG_LT && fail.code != NE_2_INT_ARG_LE
      && fail.code != NE_QUAD_BRKPTS_INVAL && fail.code != NE_ALLOC_FAIL)
```

```
    {
      Vprintf("result - approximation to the integral = %9.5f\n", result);
      Vprintf("abserr - estimate of the absolute error = %9.2e\n", abserr);
      Vprintf("qp.fun_count  - number of function evaluations = %4ld\n",
              qp.fun_count);
      Vprintf("qp.num_subint  - number of subintervals used = %4ld\n",
              qp.num_subint);
      exit(EXIT_SUCCESS);
    }
  exit(EXIT_FAILURE);
}

static double f(double x)
{
  double a;
  a = FABS(x-1.0/7.0);
  return (a != 0.0) ? pow(a, -0.5): 0.0;
}
```

8.2 Program Data

None.

8.3 Program Results

```
d01alc Example Program Results
a      - lower limit of integration =     0.0000
b      - upper limit of integration =     1.0000
epsabs - absolute accuracy requested =  0.00e+00
epsrel - relative accuracy requested =  1.00e-03

brkpts[0] - given break-point =     0.1429
result - approximation to the integral =   2.60757
abserr - estimate of the absolute error =  5.46e-14
qp.fun_count  - number of function evaluations =  462
qp.num_subint  - number of subintervals used =   12
```
