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GALAHAD

BQP

USER DOCUMENTATION

GALAHAD Optimization Library version 5.0

1 SUMMARY

This package uses a preconditioned, projected-gradient method to solve the **convex bound-constrained quadratic programming problem**

$$\text{minimize } q(\mathbf{x}) = \frac{1}{2}\mathbf{x}^T\mathbf{H}\mathbf{x} + \mathbf{g}^T\mathbf{x} + f$$

subject to the simple bound constraints

$$x_j^l \leq x_j \leq x_j^u, \quad j = 1, \dots, n,$$

where the n by n symmetric, positive-definite matrix \mathbf{H} , the vectors \mathbf{g} , \mathbf{x}^l , \mathbf{x}^u and the scalar f are given. Any of the constraint bounds x_j^l and x_j^u may be infinite. Full advantage is taken of any zero coefficients in the matrix \mathbf{H} ; the matrix need not be provided as there are options to obtain matrix-vector products involving \mathbf{H} either by reverse communication or from a user-provided subroutine.

ATTRIBUTES — Versions: GALAHAD_BQP_single, GALAHAD_BQP_double. **Uses:** GALAHAD_CPU_time, GALAHAD_SYMBOLS, GALAHAD_SPACE, GALAHAD_SBLS, GALAHAD_QPT, GALAHAD_SPECFILE. **Date:** November 2009. **Origin:** N. I. M. Gould, Rutherford Appleton Laboratory. **Language:** Fortran 95 + TR 15581 or Fortran 2003.

2 HOW TO USE THE PACKAGE

The package is available using both single and double precision reals, and either 32-bit or 64-bit integers. Access to the 32-bit integer, single precision version requires the `USE` statement

```
USE GALAHAD_BQP_single
```

with the obvious substitution `GALAHAD_BQP_double`, `GALAHAD_BQP_single_64` and `GALAHAD_BQP_double_64` for the other variants.

If it is required to use more than one of the modules at the same time, the derived types `SMT_type`, `QPT_problem_type`, `NLPT_userdata_type`, `BQP_time_type`, `BQP_control_type`, `BQP_inform_type` and `BQP_data_type` (Section 2.3) and the subroutines `BQP_initialize`, `BQP_solve`, `BQP_terminate`, (Section 2.4) and `BQP_read_specfile` (Section 2.8) must be renamed on one of the `USE` statements.

2.1 Matrix storage formats

When it is explicitly available, the Hessian matrix \mathbf{H} may be stored in a variety of input formats.

2.1.1 Dense storage format

Since \mathbf{H} is symmetric, only the lower triangular part (that is the part h_{ij} for $1 \leq j \leq i \leq n$) need be held. The lower-triangular part of \mathbf{H} is stored as a compact dense matrix by rows, that is, the values of the entries that occur before or on the diagonal of each row in turn are stored in order within an appropriate real one-dimensional array. That is component $i*(i-1)/2 + j$ of the storage array `H%val` will hold the value h_{ij} (and, by symmetry, h_{ji}) for $1 \leq j \leq i \leq n$.

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2.1.2 Sparse co-ordinate storage format

Only the nonzero entries of the lower triangular part of \mathbf{H} is stored. For the l -th entry of the lower triangular part of \mathbf{H} , its row index i , column index j and value h_{ij} are stored in the l -th components of the integer arrays `H%row`, `H%col` and real array `H%val`, respectively. The order is unimportant, but the total number of entries `H%ne` is also required.

2.1.3 Sparse row-wise storage format

Again only the nonzero entries of the lower triangular part of \mathbf{H} is stored, but this time they are ordered so that those that occur before or on the diagonal in row i appear directly before those in row $i + 1$. For the i -th row of \mathbf{H} , the i -th component of a integer array `H%ptr` holds the position of the first entry in this row, while `H%ptr(n + 1)` holds the total number of entries plus one. The column indices j and values h_{ij} of the entries occurring before or on the diagonal in the i -th row are stored in components $l = \text{H\%ptr}(i), \dots, \text{H\%ptr}(i + 1) - 1$ of the integer array `H%col`, and real array `H%val`, respectively.

For sparse matrices, this scheme almost always requires less storage than its predecessor.

2.1.4 Diagonal storage format

If \mathbf{H} is diagonal (i.e., $h_{ij} = 0$ for all $1 \leq i \neq j \leq n$) only the diagonal entries h_{ii} , $1 \leq i \leq n$, need be stored, and the first n components of the array `H%val` may be used for the purpose.

2.2 Real and integer kinds

We use the terms integer and real to refer to the fortran keywords `REAL(rp_)` and `INTEGER(ip_)`, where `rp_` and `ip_` are the relevant kind values for the real and integer types employed by the particular module in use. The former are equivalent to default `REAL` for the single precision versions and `DOUBLE PRECISION` for the double precision cases, and correspond to `rp_ = real32` and `rp_ = real64`, respectively, as supplied by the fortran `iso_fortran_env` module. The latter are default (32-bit) and long (64-bit) integers, and correspond to `ip_ = int32` and `ip_ = int64`, respectively, again from the `iso_fortran_env` module.

2.3 The derived data types

Ten derived data types are accessible from the package.

2.3.1 The derived data type for holding matrices

The derived data type `SMT_TYPE` is used to hold the matrix \mathbf{H} . The components of `SMT_TYPE` used here are:

- `n` is a scalar component of type `INTEGER(ip_)`, that holds the number of columns in the matrix.
- `ne` is a scalar variable of type `INTEGER(ip_)`, that holds the number of matrix entries.
- `type` is a rank-one allocatable array of type default `CHARACTER`, that is used to indicate the matrix storage scheme used. Its precise length and content depends on the type of matrix to be stored (see §2.3.2).
- `val` is a rank-one allocatable array of type `REAL(rp_)` and dimension at least `ne`, that holds the values of the entries. Each pair of off-diagonal entries $h_{ij} = h_{ji}$ of a *symmetric* matrix \mathbf{H} is represented as a single entry (see §2.1.1–2.1.3). Any duplicated entries that appear in the sparse co-ordinate or row-wise schemes will be summed.
- `row` is a rank-one allocatable array of type `INTEGER(ip_)`, and dimension at least `ne`, that may hold the row indices of the entries. (see §2.1.2).

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`col` is a rank-one allocatable array of type `INTEGER(ip_)`, and dimension at least `ne`, that may the column indices of the entries (see §2.1.2–2.1.3).

`ptr` is a rank-one allocatable array of type `INTEGER(ip_)`, and dimension at least `m + 1`, that may hold the pointers to the first entry in each row (see §2.1.3).

2.3.2 The derived data type for holding the problem

The derived data type `QPT_problem_type` is used to hold the problem. The components of `QPT_problem_type` are:

`n` is a scalar variable of type `INTEGER(ip_)`, that holds the number of optimization variables, n .

`H` is scalar variable of type `SMT_TYPE` that holds the Hessian matrix \mathbf{H} . The following components are used:

`H%type` is an allocatable array of rank one and type default `CHARACTER`, that is used to indicate the storage scheme used. If the dense storage scheme (see Section 2.1.1) is used, the first five components of `H%type` must contain the string `DENSE`. For the sparse co-ordinate scheme (see Section 2.1.2), the first ten components of `H%type` must contain the string `COORDINATE`, for the sparse row-wise storage scheme (see Section 2.1.3), the first fourteen components of `H%type` must contain the string `SPARSE_BY_ROWS`, and for the diagonal storage scheme (see Section 2.1.4), the first eight components of `H%type` must contain the string `DIAGONAL`.

For convenience, the procedure `SMT_put` may be used to allocate sufficient space and insert the required keyword into `H%type`. For example, if `prob` is of derived type `BQP_problem_type` and involves a Hessian we wish to store using the co-ordinate scheme, we may simply

```
CALL SMT_put( prob%H%type, 'COORDINATE', istat )
```

See the documentation for the GALAHAD package `SMT` for further details on the use of `SMT_put`.

`H%ne` is a scalar variable of type `INTEGER(ip_)`, that holds the number of entries in the **lower triangular** part of \mathbf{H} in the sparse co-ordinate storage scheme (see Section 2.1.2). It need not be set for any of the other three schemes.

`H%val` is a rank-one allocatable array of type `REAL(rp_)`, that holds the values of the entries of the **lower triangular** part of the Hessian matrix \mathbf{H} in any of the storage schemes discussed in Section 2.1.

`H%row` is a rank-one allocatable array of type `INTEGER(ip_)`, that holds the row indices of the **lower triangular** part of \mathbf{H} in the sparse co-ordinate storage scheme (see Section 2.1.2). It need not be allocated for any of the other three schemes.

`H%col` is a rank-one allocatable array variable of type `INTEGER(ip_)`, that holds the column indices of the **lower triangular** part of \mathbf{H} in either the sparse co-ordinate (see Section 2.1.2), or the sparse row-wise (see Section 2.1.3) storage scheme. It need not be allocated when the dense or diagonal storage schemes are used.

`H%ptr` is a rank-one allocatable array of dimension `n+1` and type `INTEGER(ip_)`, that holds the starting position of each row of the **lower triangular** part of \mathbf{H} , as well as the total number of entries plus one, in the sparse row-wise storage scheme (see Section 2.1.3). It need not be allocated when the other schemes are used.

`G` is a rank-one allocatable array of dimension `n` and type `REAL(rp_)`, that holds the gradient \mathbf{g} of the linear term of the quadratic objective function. The j -th component of `G`, $j = 1, \dots, n$, contains \mathbf{g}_j .

`f` is a scalar variable of type `REAL(rp_)`, that holds the constant term, f , in the objective function.

`X_l` is a rank-one allocatable array of dimension `n` and type `REAL(rp_)`, that holds the vector of lower bounds \mathbf{x}^l on the variables. The j -th component of `X_l`, $j = 1, \dots, n$, contains \mathbf{x}_j^l . Infinite bounds are allowed by setting the corresponding components of `X_l` to any value smaller than `-infinity`, where `infinity` is a component of the control array `control` (see Section 2.3.3).

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- `X_u` is a rank-one allocatable array of dimension n and type `REAL(rp_)`, that holds the vector of upper bounds \mathbf{x}'' on the variables. The j -th component of `X_u`, $j = 1, \dots, n$, contains \mathbf{x}''_j . Infinite bounds are allowed by setting the corresponding components of `X_u` to any value larger than that `infinity`, where `infinity` is a component of the control array `control` (see Section 2.3.3).
- `X` is a rank-one allocatable array of dimension n and type `REAL(rp_)`, that holds the values \mathbf{x} of the optimization variables. The j -th component of `X`, $j = 1, \dots, n$, contains x_j .
- `Z` is a rank-one allocatable array of dimension n and type default `REAL(rp_)`, that holds the values \mathbf{z} of estimates of the dual variables corresponding to the simple bound constraints (see Section 4). The j -th component of `Z`, $j = 1, \dots, n$, contains z_j .

2.3.3 The derived data type for holding control parameters

The derived data type `BQP_control_type` is used to hold controlling data. Default values may be obtained by calling `BQP_initialize` (see Section 2.4.1), while components may also be changed by calling `BQP_read_specfile` (see Section 2.8.1). The components of `BQP_control_type` are:

- `error` is a scalar variable of type `INTEGER(ip_)`, that holds the stream number for error messages. Printing of error messages in `BQP_solve` and `BQP_terminate` is suppressed if `error` ≤ 0 . The default is `error` = 6.
- `out` is a scalar variable of type `INTEGER(ip_)`, that holds the stream number for informational messages. Printing of informational messages in `BQP_solve` is suppressed if `out` < 0 . The default is `out` = 6.
- `print_level` is a scalar variable of type `INTEGER(ip_)`, that is used to control the amount of informational output which is required. No informational output will occur if `print_level` ≤ 0 . If `print_level` = 1, a single line of output will be produced for each iteration of the process. If `print_level` ≥ 2 , this output will be increased to provide significant detail of each iteration. The default is `print_level` = 0.
- `start_print` is a scalar variable of type `INTEGER(ip_)`, that specifies the first iteration for which printing will be permitted in `GALAHAD_BQP_solve`. If `start_print` is negative, printing will be permitted from the outset. The default is `start_print` = -1.
- `stop_print` is a scalar variable of type `INTEGER(ip_)`, that specifies the last iteration for which printing will be permitted in `GALAHAD_BQP_solve`. If `stop_print` is negative, printing will be permitted once it has been started by `start_print`. The default is `stop_print` = -1.
- `print_gap` is a scalar variable of type `INTEGER(ip_)`. Once printing has been started, output will occur once every `print_gap` iterations. If `print_gap` is no larger than 1, printing will be permitted on every iteration. The default is `print_gap` = 1.
- `maxit` is a scalar variable of type `INTEGER(ip_)`, that holds the maximum number of iterations which will be allowed in `GALAHAD_BQP_solve`. The default is `maxit` = 1000.
- `cold_start` is a scalar variable of type `INTEGER(ip_)`, that should be set to 0 if a warm start is required (with variables assigned according to `B_stat`, see below), and to any other value if the values given in `prob%X` suffice. The default is `cold_start` = 1.
- `ratio_cg_vs_sd` is a scalar variable of type `INTEGER(ip_)`, that specifies the ratio of how many iterations use CG rather steepest descent will be attempted. The default is `ratio_cg_vs_sd` = 1.
- `change_max` is a scalar variable of type `INTEGER(ip_)`, that specifies the maximum number of per-iteration changes in the working set permitted when allowing subspace solution rather than steepest descent (see §4). The default is `change_max` = 2.

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`cg_maxit` is a scalar variable of type `INTEGER(ip_)`, that holds the maximum number of conjugate-gradient iterations which will be allowed per main iteration in `GALAHAD_BQP_solve`. The default is `cg_maxit = 1000`.

`infinity` is a scalar variable of type `REAL(rp_)`, that is used to specify which constraint bounds are infinite. Any bound larger than `infinity` in modulus will be regarded as infinite. The default is `infinity = 1019`.

`stop_p` is a scalar variable of type `REAL(rp_)`, that holds the required accuracy for the primal infeasibility (see Section 4). The default is `stop_p = $u^{1/3}$` , where u is `EPSILON(1.0)` (`EPSILON(1.0D0)` in `GALAHAD_BQP_double`).

`stop_d` is a scalar variable of type default `REAL(rp_)`, that holds the required accuracy for the dual infeasibility (see Section 4). The default is `stop_d = $u^{1/3}$` , where u is `EPSILON(1.0)` (`EPSILON(1.0D0)` in `GALAHAD_BQP_double`).

`stop_c` is a scalar variable of type default `REAL(rp_)`, that holds the required accuracy for the violation of complementarity slackness (see Section 4). The default is `stop_c = $u^{1/3}$` , where u is `EPSILON(1.0)` (`EPSILON(1.0D0)` in `GALAHAD_BQP_double`).

`identical_bounds_tol` is a scalar variable of type `REAL(rp_)`. Each pair of variable bounds (x_j^l, x_j^u) that is closer than `identical_bounds_tol` will be reset to the average of their values, $\frac{1}{2}(x_j^l + x_j^u)$. The default is `identical_bounds_tol = u` , where u is `EPSILON(1.0)` (`EPSILON(1.0D0)` in `GALAHAD_BQP_double`).

`stop_cg_relative` and `stop_cg_absolute` are scalar variables of type `REAL(rp_)`, that hold the relative and absolute convergence tolerances for the conjugate-gradient iteration that occurs in the face of currently-active constraints when constructing the search direction. `stop_cg_relative = 0.01` and `stop_cg_absolute = \sqrt{u}` , where u is `EPSILON(1.0)` (`EPSILON(1.0D0)` in `GALAHAD_BQP_double`).

`zero_curvature` is a scalar variable of type `REAL(rp_)` that specifies the threshold below which any objective-function curvature encountered is regarded as zero. The default is `zero_curvature = $10u$` , where u is `EPSILON(1.0)` (`EPSILON(1.0D0)` in `GALAHAD_BQP_double`).

`cpu_time_limit` is a scalar variable of type `REAL(rp_)`, that is used to specify the maximum permitted CPU time. Any negative value indicates no limit will be imposed. The default is `cpu_time_limit = - 1.0`.

`exact_arcsearch` is a scalar variable of type default `LOGICAL`, that should be set `.TRUE.` if the exact generalized Cauchy point, the first estimate of the minimizer of the objective in the Cauchy direction within the feasible box, is required, and `.FALSE.` if an approximation suffices. The default is `exact_arcsearch = .TRUE..`

`space_critical` is a scalar variable of type default `LOGICAL`, that must be set `.TRUE.` if space is critical when allocating arrays and `.FALSE.` otherwise. The package may run faster if `space_critical` is `.FALSE.` but at the possible expense of a larger storage requirement. The default is `space_critical = .FALSE..`

`deallocate_error_fatal` is a scalar variable of type default `LOGICAL`, that must be set `.TRUE.` if the user wishes to terminate execution if a deallocation fails, and `.FALSE.` if an attempt to continue will be made. The default is `deallocate_error_fatal = .FALSE..`

`prefix` is a scalar variable of type default `CHARACTER` and length 30, that may be used to provide a user-selected character string to preface every line of printed output. Specifically, each line of output will be prefaced by the string `prefix(2:LEN(TRIM(prefix))-1)`, thus ignoring the first and last non-null components of the supplied string. If the user does not want to preface lines by such a string, they may use the default `prefix = ""`.

`SBLs_control` is a scalar variable of type `SBLs_control_type` whose components are used to control the factorization and/or preconditioner used, performed by the package `GALAHAD_SBLs`. See the documentation for `GALAHAD_SBLs` for further details.

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2.3.4 The derived data type for holding timing information

The derived data type `BQP_time_type` is used to hold elapsed CPU times for the various parts of the calculation. The components of `BQP_time_type` are:

`total` is a scalar variable of type default `REAL`, that gives the total time spent in the package.

`analyse` is a scalar variable of type default `REAL`, that gives the time spent analysing the required matrices prior to factorization.

`factorize` is a scalar variable of type default `REAL`, that gives the time spent factorizing the required matrices.

`solve` is a scalar variable of type default `REAL`, that gives the time spent computing the search direction.

2.3.5 The derived data type for holding informational parameters

The derived data type `BQP_inform_type` is used to hold parameters that give information about the progress and needs of the algorithm. The components of `BQP_inform_type` are:

`status` is a scalar variable of type `INTEGER(ip_)`, that gives the exit status of the algorithm. See Section 2.7 for details.

`alloc_status` is a scalar variable of type `INTEGER(ip_)`, that gives the status of the last attempted array allocation or deallocation. This will be 0 if `status = 0`.

`bad_alloc` is a scalar variable of type default `CHARACTER` and length 80, that gives the name of the last internal array for which there were allocation or deallocation errors. This will be the null string if `status = 0`.

`factorization_status` is a scalar variable of type `INTEGER(ip_)`, that gives the return status from the matrix factorization.

`iter` is a scalar variable of type `INTEGER(ip_)`, that gives the number of iterations performed.

`obj` is a scalar variable of type `REAL(rp_)`, that holds the value of the objective function at the best estimate of the solution found.

`time` is a scalar variable of type `BQP_time_type` whose components are used to hold elapsed CPU times for the various parts of the calculation (see Section 2.3.4).

`SBLS_inform` is a scalar variable of type `SBLS_inform_type` whose components provide information about the progress and needs of the factorization/preconditioner performed by the package `GALAHAD_SBLS`. See the documentation for `GALAHAD_SBLS` for further details.

2.3.6 The derived data type for holding problem data

The derived data type `BQP_data_type` is used to hold all the data for a particular problem, or sequences of problems with the same structure, between calls of BQP procedures. This data should be preserved, untouched, from the initial call to `BQP_initialize` to the final call to `BQP_terminate`.

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2.3.7 The derived data type for holding user data

The derived data type `NLPT_userdata_type` is available to allow the user to pass data to and from user-supplied matrix-vector product and preconditioning subroutines (see Section 2.5). Components of variables of type `NLPT_userdata_type` may be allocated as necessary. The following components are available:

`integer` is a rank-one allocatable array of type `INTEGER(ip_)`.

`real` is a rank-one allocatable array of type default `REAL(rp_)`

`complex` is a rank-one allocatable array of type default `COMPLEX` (double precision complex in `GALAHAD_BQP_double`).

`character` is a rank-one allocatable array of type default `CHARACTER`.

`logical` is a rank-one allocatable array of type default `LOGICAL`.

`integer_pointer` is a rank-one pointer array of type `INTEGER(ip_)`.

`real_pointer` is a rank-one pointer array of type default `REAL(rp_)`

`complex_pointer` is a rank-one pointer array of type default `COMPLEX` (double precision complex in `GALAHAD_BQP_double`).

`character_pointer` is a rank-one pointer array of type default `CHARACTER`.

`logical_pointer` is a rank-one pointer array of type default `LOGICAL`.

2.3.8 The derived data type for holding reverse-communication data

The derived data type `BQP_reverse_type` is used to hold data needed for reverse communication when this is required. The components of `BQP_reverse_type` are:

`nz_v_start` is a scalar variable of type `INTEGER(ip_)`, that may be used to hold the starting position in `NZ_v` (see below) of the list of indices of nonzero components of \mathbf{v} .

`nz_v_end` is a scalar variable of type `INTEGER(ip_)`, that may be used to hold the finishing position in `NZ_v` (see below) of the list of indices of nonzero components of \mathbf{v} .

`NZ_v` is a rank-one allocatable array of dimension n and type `INTEGER(ip_)`, that may be used to hold the indices of the nonzero components of \mathbf{v} . If used, components `NZ_v(nz_v_start:nz_v_end)` of \mathbf{v} (see below) will be nonzero.

\mathbf{V} is a rank-one allocatable array of dimension n and type `REAL(rp_)`, that is used to hold the components of the output vector \mathbf{v} .

`PROD` is a rank-one allocatable array of dimension n and type `REAL(rp_)`, that is used to record the components of the resulting vector \mathbf{Hv} .

`nz_prod_end` is a scalar variable of type `INTEGER(ip_)`, that is used to record the finishing position in `NZ_prod` (see below) of the list of indices of nonzero components of \mathbf{Hv} if required.

`NZ_prod` is a rank-one allocatable array of dimension n and type `INTEGER(ip_)`, that is used to record the list of indices of nonzero components of \mathbf{Hv} if required. Components `NZ_prod(1:nz_prod_end)` of `PROD` should then be nonzero.

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2.4 Argument lists and calling sequences

There are three procedures for user calls (see Section 2.8 for further features):

1. The subroutine `BQP_initialize` is used to set default values, and initialize private data, before solving one or more problems with the same sparsity and bound structure.
2. The subroutine `BQP_solve` is called to solve the problem.
3. The subroutine `BQP_terminate` is provided to allow the user to automatically deallocate array components of the private data, allocated by `BQP_solve`, at the end of the solution process.

We use square brackets [] to indicate OPTIONAL arguments.

2.4.1 The initialization subroutine

Default values are provided as follows:

```
CALL BQP_initialize( data, control )
```

`data` is a scalar INTENT(INOUT) argument of type `BQP_data_type` (see Section 2.3.6). It is used to hold data about the problem being solved.

`control` is a scalar INTENT(OUT) argument of type `BQP_control_type` (see Section 2.3.3). On exit, `control` contains default values for the components as described in Section 2.3.3. These values should only be changed after calling `BQP_initialize`.

2.4.2 The quadratic programming subroutine

The quadratic programming solution algorithm is called as follows:

```
CALL BQP_solve( prob, B_stat, data, control, inform, userdata[, reverse, eval_HPROD] )
```

`prob` is a scalar INTENT(INOUT) argument of type `QPT_problem_type` (see Section 2.3.2). It is used to hold data about the problem being solved. The user must allocate all the array components, and set values for all components, except perhaps `prob%H`; if the effect of **H** is only available to form products via reverse communication (see `reverse` below) or with a user-supplied subroutine (see `eval_HPROD` below) `prob%H` and it is not needed, but otherwise `prob%H` should be set using whichever of the matrix formats described in Section 2.1 is appropriate for **H** for the user's application.

The components `prob%X` and `prob%Z` must be set to initial estimates of the primal variables, **x** and dual variables for the bound constraints, **z**, respectively. Inappropriate initial values will be altered, so the user should not be overly concerned if suitable values are not apparent, and may be content with merely setting `prob%X=0.0` and `prob%Z=0.0`.

On exit, the components `prob%X` and `prob%Z` will contain the best estimates of the primal variables **x**, and dual variables for the bound constraints **z**, respectively. **Restrictions:** `prob%n > 0` and (if **H** is provided) `prob%H%ne ≥ -2`. `prob%H-type ∈ { 'DENSE', 'COORDINATE', 'SPARSE-BY-ROWS', 'DIAGONAL' }`.

`B_stat` is a rank-one INTENT(INOUT) array argument of dimension `prob%n` and type `INTEGER(ip_)`, that indicates which of the simple bound constraints are in the current working set. Possible values for `B_stat(j)`, $j = 1, \dots, \text{prob}\%n$, and their meanings are

- <0 the j -th simple bound constraint is in the working set, on its lower bound,
- >0 the j -th simple bound constraint is in the working set, on its upper bound, and
- 0 the j -th simple bound constraint is not in the working set.

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Suitable values must be supplied if `control%bqp_control%cold_start = 0` on entry, but need not be provided for other input values of `control%cold_start`. Inappropriate values will be ignored. On exit, `B_stat` will contain values appropriate for the ultimate working set.

`data` is a scalar `INTENT(INOUT)` argument of type `BQP_data_type` (see Section 2.3.6). It is used to hold data about the problem being solved. It must not have been altered **by the user** since the last call to `BQP_initialize`.

`control` is a scalar `INTENT(IN)` argument of type `BQP_control_type` (see Section 2.3.3). Default values may be assigned by calling `BQP_initialize` prior to the first call to `BQP_solve`.

`inform` is a scalar `INTENT(INOUT)` argument of type `BQP_inform_type` (see Section 2.3.5). On initial entry, the component `status` must be set to 1, while other components need not be set. A successful call to `BQP_solve` is indicated when the component `status` has the value 0. For other return values of `status`, see Sections 2.6 and 2.7.

`userdata` is a scalar `INTENT(INOUT)` argument of type `NLPT_userdata_type` whose components may be used to communicate user-supplied data (see Section 2.3.7) to and from the `OPTIONAL` subroutine `eval_HPROD` (see below).

`reverse` is an `OPTIONAL` scalar `INTENT(INOUT)` argument of type `BQP_reverse_type` (see Section 2.3.8). It is used to communicate reverse-communication data between the subroutine and calling program. If `reverse` is `PRESENT` and `eval_HPROD` (see below) is absent, the user should monitor `inform%status` on exit (see Section 2.6).

`eval_HPROD` is an `OPTIONAL` user-supplied subroutine whose purpose is to evaluate the value of the product $\mathbf{H}\mathbf{v}$ of the Hessian of the objective function with a given vector \mathbf{v} . See Section 2.5.1 for details. If `eval_HPROD` is present, it must be declared `EXTERNAL` in the calling program. If `eval_HPROD` is absent, `GALAHAD_BQP_solve` will use reverse communication (see Section 2.6) to obtain Hessian-vector products if `reverse` is `PRESENT` or otherwise require that the user has provided all relevant components of `prob%H`.

2.4.3 The termination subroutine

All previously allocated arrays are deallocated as follows:

```
CALL BQP_terminate( data, control, inform )
```

`data` is a scalar `INTENT(INOUT)` argument of type `BQP_data_type` exactly as for `BQP_solve`, which must not have been altered **by the user** since the last call to `BQP_initialize`. On exit, array components will have been deallocated.

`control` is a scalar `INTENT(IN)` argument of type `BQP_control_type` exactly as for `BQP_solve`.

`inform` is a scalar `INTENT(OUT)` argument of type `BQP_inform_type` exactly as for `BQP_solve`. Only the component `status` will be set on exit, and a successful call to `BQP_terminate` is indicated when this component `status` has the value 0. For other return values of `status`, see Section 2.7.

2.5 Matrix-vector operations

2.5.1 Hessian-vector products via internal evaluation

If the argument `eval_HPROD` is present when calling `GALAHAD_BQP_solve`, the user is expected to provide a subroutine of that name to evaluate the product of the Hessian of the objective function \mathbf{H} with a given vector \mathbf{v} . The routine must be specified as

```
SUBROUTINE eval_HPROD( status, userdata, V, PROD[, NZ_v, nz_v_start, nz_v_end, &
                      NZ_prod, nz_prod_end] )
```

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whose arguments are as follows:

`status` is a scalar `INTENT (OUT)` argument of type `INTEGER(ip_)`, that should be set to 0 if the routine has been able to evaluate the product $\mathbf{H}\mathbf{v}$ and to a non-zero value if the evaluation has not been possible.

`userdata` is a scalar `INTENT (INOUT)` argument of type `NLPT_userdata_type` whose components may be used to communicate user-supplied data to and from the subroutine (see Section 2.3.7).

`V` is a rank-one `INTENT (IN)` array argument of type `REAL(rp_)` whose components contain the vector \mathbf{v} . If components `nz_v_start`, `nz_v_end` and `NZ_v` (see below) are `PRESENT`, only components `NZ_v(nz_v_start:nz_v_end)` of `V` will be nonzero and the remaining components of `V` should be ignored. Otherwise, all components of `V` should be presumed to be nonzero.

`PROD` is a rank-one `INTENT (OUT)` array argument of type `REAL(rp_)` whose components on output contain the required components of $\mathbf{H}\mathbf{v}$. If components `nz_prod_end` and `NZ_prod` (see below) are `PRESENT`, only the nonzero components `NZ_prod(1:nz_prod_end)` of `PROD` need be assigned. Otherwise, all components of `PROD` must be set.

`nz_v_start` is an `OPTIONAL` scalar variable of type `INTEGER(ip_)`, that, if `PRESENT`, holds the starting position in `NZ_v` of the list of indices of nonzero components of \mathbf{v} .

`nz_v_end` is an `OPTIONAL` scalar variable of type `INTEGER(ip_)`, that, if `PRESENT`, holds the finishing position in `NZ_v` of the list of indices of nonzero components of \mathbf{v} .

`NZ_v` is an `OPTIONAL` rank-one allocatable array of dimension n and type `INTEGER(ip_)` that, if `PRESENT`, holds the indices of the nonzero components of \mathbf{v} . If any of `nz_v_start`, `nz_v_end` and `NZ_v` are absent, all components of `V` are assumed to be nonzero.

`nz_prod_end` is an `OPTIONAL` scalar variable of type `INTEGER(ip_)`, that, if `PRESENT`, must be set to record the number of non-zeros in $\mathbf{H}\mathbf{v}$.

`NZ_prod` is an `OPTIONAL` rank-one allocatable array of dimension n and type `INTEGER(ip_)` that, if `PRESENT`, must be set to record the list of indices of nonzero components of $\mathbf{H}\mathbf{v}$. If either of `nz_prod_end` and `NZ_prod` are absent, all components of `PROD` should be set even if they are zero.

2.6 Reverse Communication Information

A positive value of `inform%status` on exit from `BQP_solve` indicates that `GALAHAD_BQP_solve` is seeking further information—this will happen if the user has chosen to evaluate matrix-vector products by reverse communication. The user should compute the required information and re-enter `GALAHAD_BQP_solve` with `inform%status` and all other arguments (except those specifically mentioned below) unchanged.

Possible values of `inform%status` and the information required are

2. The user should compute the matrix-vector product $\mathbf{H}\mathbf{v}$ using the vector \mathbf{v} whose components are stored in `reverse%V` and store the required product in `reverse%PROD`.
3. The user should compute the matrix-vector product $\mathbf{H}\mathbf{v}$ using the vector \mathbf{v} whose nonzero components are stored in positions `reverse%NZ_v(reverse%nz_v_start:reverse%nz_v_end)` of `reverse%V`. The remaining components of `reverse%V` should be ignored.
4. The user should compute the nonzero components of the matrix-vector product $\mathbf{H}\mathbf{v}$ using the vector \mathbf{v} whose nonzero components are stored in positions `reverse%NZ_v(reverse%nz_v_start:reverse%nz_v_end)` of `reverse%V`. The remaining components of `reverse%V` should be ignored. The nonzero components must occupy positions `reverse%NZ_prod(1:reverse%nz_prod_end)` of `reverse%PROD`, and the components `reverse%NZ_prod` and `reverse%nz_prod_end` must be set. This return can only happen if `control%exact_arcsearch` is `.TRUE..`

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2.7 Warning and error messages

A negative value of `inform%status` on exit from `BQP_solve` or `BQP_terminate` indicates that an error has occurred. No further calls should be made until the error has been corrected. Possible values are:

- 1. An allocation error occurred. A message indicating the offending array is written on unit `control%error`, and the returned allocation status and a string containing the name of the offending array are held in `inform%alloc_status` and `inform%bad_alloc` respectively.
- 2. A deallocation error occurred. A message indicating the offending array is written on unit `control%error` and the returned allocation status and a string containing the name of the offending array are held in `inform%alloc_status` and `inform%bad_alloc` respectively.
- 3. One of the restrictions `prob%n > 0` or the requirement that `prob%H_type` contain its relevant string 'DENSE', 'COORDINATE', 'SPARSE_BY_ROWS' or 'DIAGONAL' when **H** is available, has been violated.
- 4. The bound constraints are inconsistent.
- 9. The analysis phase of the factorization failed; the return status from the factorization package is given in the component `inform%factor_status`.
- 10. The factorization failed; the return status from the factorization package is given in the component `inform%factor_status`.
- 16. The problem is so ill-conditioned that further progress is impossible.
- 17. The step is too small to make further impact.
- 18. Too many iterations have been performed. This may happen if `control%maxit` is too small, but may also be symptomatic of a badly scaled problem.
- 19. The CPU time limit has been reached. This may happen if `control%cpu_time_limit` is too small, but may also be symptomatic of a badly scaled problem.
- 20. The Hessian matrix **H** of the objective function appears to be indefinite.
- 23. An entry from the strict upper triangle of **H** has been specified.

2.8 Further features

In this section, we describe an alternative means of setting control parameters, that is components of the variable `control` of type `BQP_control_type` (see Section 2.3.3), by reading an appropriate data specification file using the subroutine `BQP_read_specfile`. This facility is useful as it allows a user to change BQP control parameters without editing and recompiling programs that call BQP.

A specification file, or `specfile`, is a data file containing a number of "specification commands". Each command occurs on a separate line, and comprises a "keyword", which is a string (in a close-to-natural language) used to identify a control parameter, and an (optional) "value", which defines the value to be assigned to the given control parameter. All keywords and values are case insensitive, keywords may be preceded by one or more blanks but values must not contain blanks, and each value must be separated from its keyword by at least one blank. Values must not contain more than 30 characters, and each line of the `specfile` is limited to 80 characters, including the blanks separating keyword and value.

The portion of the specification file used by `BQP_read_specfile` must start with a "BEGIN BQP" command and end with an "END" command. The syntax of the `specfile` is thus defined as follows:

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```
( .. lines ignored by BQP_read_specfile .. )
BEGIN BQP
  keyword      value
  .....      .....
  keyword      value
END
( .. lines ignored by BQP_read_specfile .. )
```

where keyword and value are two strings separated by (at least) one blank. The “BEGIN BQP” and “END” delimiter command lines may contain additional (trailing) strings so long as such strings are separated by one or more blanks, so that lines such as

```
BEGIN BQP SPECIFICATION
```

and

```
END BQP SPECIFICATION
```

are acceptable. Furthermore, between the “BEGIN BQP” and “END” delimiters, specification commands may occur in any order. Blank lines and lines whose first non-blank character is ! or * are ignored. The content of a line after a ! or * character is also ignored (as is the ! or * character itself). This provides an easy manner to “comment out” some specification commands, or to comment specific values of certain control parameters.

The value of a control parameters may be of three different types, namely integer, logical or real. Integer and real values may be expressed in any relevant Fortran integer and floating-point formats (respectively). Permitted values for logical parameters are “ON”, “TRUE”, “.TRUE.”, “T”, “YES”, “Y”, or “OFF”, “NO”, “N”, “FALSE”, “.FALSE.” and “F”. Empty values are also allowed for logical control parameters, and are interpreted as “TRUE”.

The specification file must be open for input when `BQP_read_specfile` is called, and the associated device number passed to the routine in `device` (see below). Note that the corresponding file is `REWINDed`, which makes it possible to combine the specifications for more than one program/routine. For the same reason, the file is not closed by `BQP_read_specfile`.

2.8.1 To read control parameters from a specification file

Control parameters may be read from a file as follows:

```
CALL BQP_read_specfile( control, device )
```

`control` is a scalar `INTENT(INOUT)` argument of type `BQP_control_type` (see Section 2.3.3). Default values should have already been set, perhaps by calling `BQP_initialize`. On exit, individual components of `control` may have been changed according to the commands found in the specfile. Specfile commands and the component (see Section 2.3.3) of `control` that each affects are given in Table 2.1.

`device` is a scalar `INTENT(IN)` argument of type `INTEGER(ip_)`, that must be set to the unit number on which the specfile has been opened. If `device` is not open, `control` will not be altered and execution will continue, but an error message will be printed on unit `control%error`.

2.9 Information printed

If `control%print_level` is positive, information about the progress of the algorithm will be printed on unit `control%out`. If `control%print_level = 1`, a single line of output will be produced for each iteration of the process. For the initial-feasible-point phase, this will include values of the current primal and dual infeasibility, and violation of complementary slackness, the feasibility-phase objective value, the current steplength, the value of the barrier

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command	component of control	value type
error-printout-device	%error	integer
printout-device	%out	integer
print-level	%print_level	integer
start-print	%start_print	integer
stop-print	%stop_print	integer
iterations-between-printing	%print_gap	integer
maximum-number-of-iterations	%maxit	integer
cold-start	%cold_start	integer
ratio-of-cg-iterations-to-steepest-descent	%ratio_cg_vs_sd	integer
max-change-to-working-set-for-subspace-solution	%change_max	integer
maximum-number-of-cg-iterations-per-iteration	%cg_maxit	integer
infinity-value	%infinity	real
primal-accuracy-required	%stop_p	real
dual-accuracy-required	%stop_d	real
complementary-slackness-accuracy-required	%stop_c	real
identical-bounds-tolerance	%identical_bounds_tol	real
cg-relative-accuracy-required	%stop_cg_relative	real
cg-absolute-accuracy-required	%stop_cg_absolute	real
zero-curvature-threshold	%zero_curvature	real
maximum-cpu-time-limit	%cpu_time_limit	real
exact-arcsearch-used	%exact_arcsearch	logical
space-critical	%space_critical	logical
deallocate-error-fatal	%deallocate_error_fatal	logical
output-line-prefix	%prefix	character

Table 2.1: Specfile commands and associated components of control.

parameter, the number of backtracks in the linesearch and the elapsed CPU time in seconds. Once a suitable feasible point has been found, the iteration is divided into major iterations, at which the barrier parameter is reduced, and minor iterations, and which the barrier function is approximately minimized for the current value of the barrier parameter. For the major iterations, the value of the barrier parameter, the required values of dual feasibility and violation of complementary slackness, and the current constraint infeasibility are reported. Each minor iteration of the optimality phase results in a line giving the current dual feasibility and violation of complementary slackness, the objective function value, the ratio of predicted to achieved reduction of the objective function, the trust-region radius, the number of backtracks in the linesearch, the number of conjugate-gradient iterations taken, and the elapsed CPU time in seconds.

If `control%print_level ≥ 2` this output will be increased to provide significant detail of each iteration. This extra output includes residuals of the linear systems solved, and, for larger values of `control%print_level`, values of the primal and dual variables and Lagrange multipliers.

3 GENERAL INFORMATION

Use of common: None.

Workspace: Provided automatically by the module.

Other routines called directly: None.

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Other modules used directly: BQP_solve calls the GALAHAD packages GALAHAD_CPU_time, GALAHAD_SYMBOLS, GALAHAD_SPACE, GALAHAD_SBLS, GALAHAD_QPT and GALAHAD_SPECFILE.

Input/output: Output is under control of the arguments control%error, control%out and control%print_level.

Restrictions: prob%n > 0, prob%H_type ∈ { 'DENSE', 'COORDINATE', 'SPARSE_BY_ROWS', 'DIAGONAL' } (if **H** is explicit).

Portability: ISO Fortran 95 + TR 15581 or Fortran 2003. The package is thread-safe.

4 METHOD

The required solution **x** necessarily satisfies the primal optimality conditions

$$\mathbf{x}^l \leq \mathbf{x} \leq \mathbf{x}^u, \quad (4.1)$$

the dual optimality conditions

$$\mathbf{H}\mathbf{x} + \mathbf{g} = \mathbf{z} \text{ and } \mathbf{z} = \mathbf{z}^l + \mathbf{z}^u, \quad (4.2)$$

and

$$\mathbf{z}^l \geq 0 \text{ and } \mathbf{z}^u \leq 0, \quad (4.3)$$

and the complementary slackness conditions

$$(\mathbf{x} - \mathbf{x}^l)^T \mathbf{z}^l = 0 \text{ and } (\mathbf{x} - \mathbf{x}^u)^T \mathbf{z}^u = 0, \quad (4.4)$$

where the components of the vector **z** are known as the dual variables for the bounds, and where the vector inequalities hold componentwise. Projected-gradient methods iterate towards a point that satisfies these conditions by ultimately aiming to satisfy (4.2), while ensuring that (4.1), and (4.3) and (4.4) are satisfied at each stage. Appropriate norms of the amounts by which (4.1), (4.2) and (4.4) fail to be satisfied are known as the primal and dual infeasibility, and the violation of complementary slackness, respectively.

The method is iterative. Each iteration proceeds in two stages. Firstly, the so-called generalized Cauchy point for the quadratic objective is found. (The purpose of this point is to ensure that the algorithm converges and that the set of bounds which are satisfied as equations at the solution is rapidly identified.) Thereafter an improvement to the objective is sought using either a direct-matrix or truncated conjugate-gradient algorithm.

References:

This is a specialised version of the method presented in

A. R. Conn, N. I. M. Gould and Ph. L. Toint (1988). Global convergence of a class of trust region algorithms for optimization with simple bounds. SIAM Journal on Numerical Analysis **25** 433-460,

5 EXAMPLE OF USE

Suppose we wish to minimize $\frac{1}{2}x_1^2 + x_2^2 + x_1x_2 + \frac{3}{2}x_3^2 + 2x_2 + 1$ subject to the simple bounds $-1 \leq x_1 \leq 1$ and $x_3 \leq 2$. Then, on writing the data for this problem as

$$\mathbf{H} = \begin{pmatrix} 1 & 1 & \\ 1 & 2 & \\ & & 3 \end{pmatrix}, \quad \mathbf{g} = \begin{pmatrix} 0 \\ 2 \\ 0 \end{pmatrix}, \quad \mathbf{x}^l = \begin{pmatrix} -1 \\ -\infty \\ -\infty \end{pmatrix} \text{ and } \mathbf{x}^u = \begin{pmatrix} 1 \\ \infty \\ 2 \end{pmatrix}$$

in sparse co-ordinate format, we may use the following code:

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```
! THIS VERSION: GALAHAD 4.2 - 2023-12-22 AT 14:45 GMT.
PROGRAM GALAHAD_BQP_EXAMPLE
USE GALAHAD_BQP_double      ! double precision version
IMPLICIT NONE
INTEGER, PARAMETER :: wp = KIND( 1.0D+0 ) ! set precision
REAL ( KIND = wp ), PARAMETER :: infinity = 10.0_wp ** 20
TYPE ( QPT_problem_type ) :: p
TYPE ( BQP_data_type ) :: data
TYPE ( BQP_control_type ) :: control
TYPE ( BQP_inform_type ) :: inform
TYPE ( GALAHAD_userdata_type ) :: userdata
INTEGER :: s
INTEGER, PARAMETER :: n = 3, h_ne = 4
INTEGER, ALLOCATABLE, DIMENSION( : ) :: B_stat
! start problem data
ALLOCATE( p%G( n ), p%X_l( n ), p%X_u( n ) )
ALLOCATE( p%X( n ), p%Z( n ) )
ALLOCATE( B_stat( n ) )
p%new_problem_structure = .TRUE.      ! new structure
p%n = n ; p%f = 1.0_wp                ! dimensions & objective constant
p%G = (/ 0.0_wp, 2.0_wp, 1.0_wp /)    ! objective gradient
p%X_l = (/ -1.0_wp, -infinity, 0.0_wp /) ! variable lower bound
p%X_u = (/ infinity, 1.0_wp, 2.0_wp /) ! variable upper bound
p%X = 0.0_wp ; p%Z = 0.0_wp ! start from zero
! sparse co-ordinate storage format
CALL SMT_put( p%H%type, 'COORDINATE', s ) ! Co-ordinate storage for H
ALLOCATE( p%H%val( h_ne ), p%H%row( h_ne ), p%H%col( h_ne ) )
p%H%val = (/ 1.0_wp, 2.0_wp, 1.0_wp, 3.0_wp /) ! Hessian H
p%H%row = (/ 1, 2, 2, 3 /) ! NB lower triangle
p%H%col = (/ 1, 2, 1, 3 /) ; p%H%ne = h_ne
! problem data complete
CALL BQP_initialize( data, control, inform ) ! Initialize control parameters
control%infinity = infinity ! Set infinity
! control%print_level = 1 ! print one line/iteration
inform%status = 1
CALL BQP_solve( p, B_stat, data, control, inform, userdata )
IF ( inform%status == 0 ) THEN ! Successful return
  WRITE( 6, "( ' BQP: ', I0, ' iterations ', /, &
    & ' Optimal objective value = ', &
    & ES12.4, /, ' Optimal solution = ', ( 5ES12.4 ) )" ) &
  inform%iter, inform%obj, p%X
ELSE ! Error returns
  WRITE( 6, "( ' BQP_solve exit status = ', I0 ) " ) inform%status
  WRITE( 6, * ) inform%alloc_status, inform%bad_alloc
END IF
CALL BQP_terminate( data, control, inform ) ! delete workspace
DEALLOCATE( p%G, p%X, p%X_l, p%X_u, p%Z, B_stat )
DEALLOCATE( p%H%val, p%H%row, p%H%col, p%H%type )
END PROGRAM GALAHAD_BQP_EXAMPLE
```

This produces the following output:

```
BQP: 2 iterations
Optimal objective value = -1.0000E+00
Optimal solution = 2.0000E+00 -2.0000E+00 0.0000E+00
```

The same problem may be solved holding the data in a sparse row-wise storage format by replacing the lines

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```
! sparse co-ordinate storage format
...
! problem data complete
```

by

```
! sparse row-wise storage format
CALL SMT_put( p%H%type, 'SPARSE_BY_ROWS', s ) ! Specify sparse-by-row
ALLOCATE( p%H%val( h_ne ), p%H%col( h_ne ), p%H%ptr( n + 1 ) )
ALLOCATE( p%A%val( a_ne ), p%A%col( a_ne ), p%A%ptr( m + 1 ) )
p%H%val = (/ 1.0_wp, 2.0_wp, 1.0_wp, 3.0_wp /) ! Hessian H
p%H%col = (/ 1, 2, 3, 3 /) ! NB lower triangular
p%H%ptr = (/ 1, 2, 3, 5 /) ! Set row pointers
! problem data complete
```

or using a dense storage format with the replacement lines

```
! dense storage format
CALL SMT_put( p%H%type, 'DENSE', s ) ! Specify dense
ALLOCATE( p%H%val( n * ( n + 1 ) / 2 ) )
p%H%val = (/ 1.0_wp, 0.0_wp, 2.0_wp, 0.0_wp, 1.0_wp, 3.0_wp /) ! Hessian
! problem data complete
```

respectively.

If instead **H** had been the diagonal matrix

$$\mathbf{H} = \begin{pmatrix} 1 & & \\ & 2 & \\ & & 3 \end{pmatrix}$$

but the other data is as before, the diagonal storage scheme might be used for **H**, and in this case we would instead

```
CALL SMT_put( prob%H%type, 'DIAGONAL', s ) ! Specify dense storage for H
ALLOCATE( p%H%val( n ) )
p%H%val = (/ 1.0_wp, 2.0_wp, 3.0_wp /) ! Hessian values
```

The same problem may be solved using reverse communication with the following code:

```
! THIS VERSION: GALAHAD 3.3 - 03/06/2021 AT 08:15 GMT.
PROGRAM GALAHAD_BQP_SECOND_EXAMPLE
USE GALAHAD_BQP_double ! double precision version
IMPLICIT NONE
INTEGER, PARAMETER :: wp = KIND( 1.0D+0 ) ! set precision
REAL ( KIND = wp ), PARAMETER :: infinity = 10.0_wp ** 20
TYPE ( QPT_problem_type ) :: p
TYPE ( BQP_reverse_type ) :: reverse
TYPE ( BQP_data_type ) :: data
TYPE ( BQP_control_type ) :: control
TYPE ( BQP_inform_type ) :: inform
TYPE ( GALAHAD_userdata_type ) :: userdata
INTEGER :: nflag, i, j, k, l
REAL ( KIND = wp ) :: v_j
INTEGER, PARAMETER :: n = 3, h_ne = 4, h_all = 5
! INTEGER, PARAMETER :: n = 3, h_ne = 3, h_all = 3
INTEGER, ALLOCATABLE, DIMENSION( : ) :: B_stat, FLAG, ROW, PTR
REAL ( KIND = wp ), ALLOCATABLE, DIMENSION( : ) :: VAL
```

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```

! start problem data
  ALLOCATE( p%G( n ), p%X_l( n ), p%X_u( n ) )
  ALLOCATE( p%X( n ), p%Z( n ) )
  ALLOCATE( B_stat( n ), FLAG( n ) )
  ALLOCATE( VAL( h_all ), ROW( h_all ), PTR( n + 1 ) )
  p%new_problem_structure = .TRUE.           ! new structure
  p%n = n ; p%f = 1.0_wp                    ! dimensions & objective constant
  p%G = (/ 0.0_wp, 2.0_wp, 1.0_wp /)        ! objective gradient
  p%X_l = (/ -1.0_wp, -infinity, 0.0_wp /) ! variable lower bound
  p%X_u = (/ infinity, 1.0_wp, 2.0_wp /)    ! variable upper bound
  p%X = 0.0_wp ; p%Z = 0.0_wp ! start from zero
  PTR = (/ 1, 3, 5, 6 /)                    ! whole Hessian by rows
  ROW = (/ 1, 2, 1, 2, 3 /)                ! for matrix-vector products
  VAL = (/ 1.0_wp, 1.0_wp, 1.0_wp, 2.0_wp, 3.0_wp /)
! problem data complete
  CALL BQP_initialize( data, control, inform ) ! Initialize control parameters
  control%infinity = infinity                ! Set infinity
! control%print_level = 1                   ! print one line/iteration
  control%maxit = 40                        ! limit the # iterations
! control%print_gap = 100                   ! print every 100 iterations
! control%exact_gcp = .FALSE.
  nflag = 0 ; FLAG = 0
  inform%status = 1
10 CONTINUE                                ! Solve problem - reverse communication loop
  CALL BQP_solve( p, B_stat, data, control, inform, userdata, reverse )
  SELECT CASE ( inform%status )
  CASE ( 0 )                               ! Successful return
    WRITE( 6, "( ' BQP: ', I0, ' iterations ', /,
    &      ' Optimal objective value = ',
    &      ES12.4, /, ' Optimal solution = ', ( 5ES12.4 ) )" )
    inform%iter, inform%obj, p%X
  CASE ( 2 )                               ! compute H * v
    reverse%PROD = 0.0_wp
    DO j = 1, p%n
      v_j = reverse%V( j )
      DO k = PTR( j ), PTR( j + 1 ) - 1
        i = ROW( k )
        reverse%PROD( i ) = reverse%PROD( i ) + VAL( k ) * v_j
      END DO
    END DO
    GO TO 10
  CASE ( 3 )                               ! compute H * v for sparse v
    reverse%PROD = 0.0_wp
    DO l = reverse%nz_v_start, reverse%nz_v_end
      j = reverse%NZ_v( l ) ; v_j = reverse%V( j )
      DO k = PTR( j ), PTR( j + 1 ) - 1
        i = ROW( k )
        reverse%PROD( i ) = reverse%PROD( i ) + VAL( k ) * v_j
      END DO
    END DO
    GO TO 10
  CASE ( 4 )                               ! compute H * v for very sparse v and record nonzeros
    nflag = nflag + 1
    reverse%nz_prod = 0
    DO l = reverse%nz_v_start, reverse%nz_v_end

```

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```

j = reverse%NZ_v( 1 ) ; v_j = reverse%V( j )
DO k = PTR( j ), PTR( j + 1 ) - 1
  i = ROW( k )
  IF ( FLAG( i ) < nflag ) THEN
    FLAG( i ) = nflag
    reverse%PROD( i ) = VAL( k ) * v_j
    reverse%nz_prod_end = reverse%nz_prod_end + 1
    reverse%NZ_prod( reverse%nz_prod_end ) = i
  ELSE
    reverse%PROD( i ) = reverse%PROD( i ) + VAL( k ) * v_j
  END IF
END DO
END DO
GO TO 10
CASE DEFAULT          ! Error returns
  WRITE( 6, "( ' BQP_solve exit status = ', I6 ) " ) inform%status
END SELECT
CALL BQP_terminate( data, control, inform, reverse ) ! delete workspace
DEALLOCATE( p%G, p%X, p%X_l, p%X_u, p%Z, B_stat, FLAG, PTR, ROW, VAL )
END PROGRAM GALAHAD_BQP_SECOND_EXAMPLE

```

Notice that storage for the Hessian is now not needed. This produces the same output.

The same problem may also be solved by user-provided matrix-vector products as follows:

```

! THIS VERSION: GALAHAD 3.3 - 03/06/2021 AT 08:15 GMT.
PROGRAM GALAHAD_BQP_THIRD_EXAMPLE
USE GALAHAD_BQP_double          ! double precision version
IMPLICIT NONE
INTEGER, PARAMETER :: wp = KIND( 1.0D+0 ) ! set precision
REAL ( KIND = wp ), PARAMETER :: infinity = 10.0_wp ** 20
TYPE ( QPT_problem_type ) :: p
TYPE ( BQP_reverse_type ) :: reverse
TYPE ( BQP_data_type ) :: data
TYPE ( BQP_control_type ) :: control
TYPE ( BQP_inform_type ) :: inform
TYPE ( GALAHAD_userdata_type ) :: userdata
INTEGER, PARAMETER :: n = 3, h_ne = 4, h_all = 5
INTEGER, PARAMETER :: len_integer = 2 * n + 3 + h_all, len_real = h_all
INTEGER, PARAMETER :: nflag = 2, st_flag = 2, st_ptr = st_flag + n
INTEGER, PARAMETER :: st_row = st_ptr + n + 1, st_val = 0
INTEGER, ALLOCATABLE, DIMENSION( : ) :: B_stat
EXTERNAL :: HPROD
! start problem data
ALLOCATE( p%G( n ), p%X_l( n ), p%X_u( n ) )
ALLOCATE( p%X( n ), p%Z( n ) )
ALLOCATE( userdata%integer( len_integer ), userdata%real( len_real ) )
ALLOCATE( B_stat( n ) )
p%new_problem_structure = .TRUE.          ! new structure
p%n = n ; p%f = 1.0_wp                   ! dimensions & objective constant
p%G = (/ 0.0_wp, 2.0_wp, 1.0_wp /)       ! objective gradient
p%X_l = (/ -1.0_wp, -infinity, 0.0_wp /) ! variable lower bound
p%X_u = (/ infinity, 1.0_wp, 2.0_wp /)    ! variable upper bound
p%X = 0.0_wp ; p%Z = 0.0_wp ! start from zero
! whole Hessian by rows for efficient matrix-vector products
userdata%integer( st_ptr + 1 : st_ptr + n + 1 ) = (/ 1, 3, 5, 6 /)
userdata%integer( st_row + 1 : st_row + h_all ) = (/ 1, 2, 1, 2, 3 /)

```

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```

        userdata%real( st_val + 1 : st_val + h_all )           &
        = (/ 1.0_wp, 1.0_wp, 1.0_wp, 2.0_wp, 3.0_wp /)
! problem data complete
    CALL BQP_initialize( data, control, inform ) ! Initialize control parameters
    control%infinity = infinity                ! Set infinity
! control%print_level = 1                      ! print one line/iteration
    control%maxit = 40                        ! limit the # iterations
! control%print_gap = 100                     ! print every 100 iterations
! control%exact_gcp = .FALSE.
    userdata%integer( 1 ) = n
    userdata%integer( nflag ) = 0
    userdata%integer( st_flag + 1 : st_flag + n ) = 0
    inform%status = 1
    CALL BQP_solve( p, B_stat, data, control, inform, userdata, &
        eval_HPROD = HPROD )
    IF ( inform%status == 0 ) THEN              ! Successful return
        WRITE( 6, "( ' BQP: ', I0, ' iterations ', /, &
        & ' Optimal objective value =', &
        & ES12.4, /, ' Optimal solution = ', ( 5ES12.4 ) )" ) &
        inform%iter, inform%obj, p%X
    ELSE
        WRITE( 6, "( ' BQP_solve exit status = ', I6 ) " ) inform%status
    END IF
    CALL BQP_terminate( data, control, inform ) ! delete workspace
    DEALLOCATE( p%G, p%X, p%X_l, p%X_u, p%X, B_stat )
    DEALLOCATE( userdata%integer, userdata%real )
    END PROGRAM GALAHAD_BQP_THIRD_EXAMPLE

    SUBROUTINE HPROD( status, userdata, V, PROD, NZ_v, nz_v_start, nz_v_end, &
        NZ_prod, nz_prod_end )
! compute the matrix-vector product H * v
    USE GALAHAD_USERDATA_double
    INTEGER, PARAMETER :: wp = KIND( 1.0D+0 )
    INTEGER, INTENT( OUT ) :: status
    TYPE ( GALAHAD_userdata_type ), INTENT( INOUT ) :: userdata
    REAL ( KIND = wp ), DIMENSION( : ), INTENT( IN ) :: V
    REAL ( KIND = wp ), DIMENSION( : ), INTENT( OUT ) :: PROD
    INTEGER, OPTIONAL, INTENT( IN ) :: nz_v_start, nz_v_end
    INTEGER, OPTIONAL, INTENT( INOUT ) :: nz_prod_end
    INTEGER, DIMENSION( : ), OPTIONAL, INTENT( INOUT ) :: NZ_v
    INTEGER, DIMENSION( : ), OPTIONAL, INTENT( INOUT ) :: NZ_prod
    INTEGER :: i, j, k, l, n, nflag, st_flag, st_ptr, st_row, st_val
    REAL ( KIND = wp ) :: v_j
    n = userdata%integer( 1 )
    nflag = 2
    st_flag = 2
    st_ptr = st_flag + n
    st_row = st_ptr + n + 1
    st_val = 0
! compute H * v for very sparse v and record nonzeros
    IF ( PRESENT( NZ_prod ) .AND. PRESENT( nz_prod_end ) ) THEN
        userdata%integer( nflag ) = userdata%integer( nflag ) + 1
        nz_prod = 0
        DO l = nz_v_start, nz_v_end
            j = NZ_v( l ) ; v_j = V( j )

```

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```

DO k = userdata%integer( st_ptr + j ), &
    userdata%integer( st_ptr + j + 1 ) - 1
    i = userdata%integer( st_row + k )
    IF ( userdata%integer( st_flag + i ) < &
        userdata%integer( nflag ) ) THEN
        userdata%integer( st_flag + i ) = userdata%integer( nflag )
        PROD( i ) = userdata%real( st_val + k ) * v_j
        nz_prod_end = nz_prod_end + 1
        NZ_prod( nz_prod_end ) = i
    ELSE
        PROD( i ) = PROD( i ) + userdata%real( st_val + k ) * v_j
    END IF
END DO
END DO
! compute H * v for sparse v
ELSE IF ( PRESENT( NZ_v ) .AND. PRESENT( nz_v_start ) .AND. &
    PRESENT( nz_v_end ) ) THEN
    PROD = 0.0_wp
    DO l = nz_v_start, nz_v_end
        j = NZ_v( l ) ; v_j = V( j )
        DO k = userdata%integer( st_ptr + j ), &
            userdata%integer( st_ptr + j + 1 ) - 1
            i = userdata%integer( st_row + k )
            PROD( i ) = PROD( i ) + userdata%real( st_val + k ) * v_j
        END DO
    END DO
! compute H * v
ELSE
    PROD = 0.0_wp
    DO j = 1, n
        v_j = V( j )
        DO k = userdata%integer( st_ptr + j ), &
            userdata%integer( st_ptr + j + 1 ) - 1
            i = userdata%integer( st_row + k )
            PROD( i ) = PROD( i ) + userdata%real( st_val + k ) * v_j
        END DO
    END DO
END IF
status = 0
END SUBROUTINE HPROD

```

Now notice how the matrix **H** is passed to the matrix-vector product evaluation routine via the integer and real components of the derived type `userdata`.

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