C interfaces to GALAHAD ARC

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Chapter 1

GALAHAD C package arc

1.1 Introduction

1.1.1 Purpose

The arc package uses a **regularization method to find a (local) unconstrained minimizer of a differentiable objective function $\mathbf{f}(\mathbf{x})$ of many variables $\mathbf{x}$.** The method offers the choice of direct and iterative solution of the key regularization subproblems, and is most suitable for large problems. First derivatives are required, and if second derivatives can be calculated, they will be exploited—if the product of second derivatives with a vector may be found, but not the derivatives themselves, that may also be exploited.

1.1.2 Authors

N. I. M. Gould, STFC-Rutherford Appleton Laboratory, England, and M. Porcelli, University of Bologna, Italy.

C interface, additionally J. Fowkes, STFC-Rutherford Appleton Laboratory.

Julia interface, additionally A. Montoison and D. Orban, Polytechnique Montréal.

1.1.3 Originally released

May 2011, C interface August 2021.

1.1.4 Terminology

The *gradient* $\nabla_x f(x)$ of $f(x)$ is the vector whose i-th component is $\partial f(x)/\partial x_i$. The *Hessian* $\nabla_{xx} f(x)$ of $f(x)$ is the symmetric matrix whose i, j-th entry is $\partial^2 f(x)/\partial x_i \partial x_j$. The Hessian is *sparse* if a significant and useful proportion of the entries are universally zero.

1.1.5 Method

An adaptive cubic regularization method is used. In this, an improvement to a current estimate of the required minimizer, x_k is sought by computing a step s_k. The step is chosen to approximately minimize a model $m_k(s)$ of $f(x_k + s)$ that includes a weighted term $\sigma_k \|s_k\|^3$ for some specified positive weight σ_k. The quality of the resulting step s_k is assessed by computing the "ratio" $(f(x_k) - f(x_k + s_k))/(m_k(0) - m_k(s_k))$. The step is deemed to have succeeded if the ratio exceeds a given $\eta_s > 0$, and in this case $x_{k+1} = x_k + s_k$. Otherwise $x_{k+1} = x_k$, and the weight is increased by powers of a given increase factor up to a given limit. If the ratio is larger than $\eta_v \geq \eta_d$, the weight will be decreased by powers of a given decrease factor again up to a given limit. The method will terminate as soon as $\|\nabla_x f(x_k)\|$ is smaller than a specified value.

Either linear or quadratic models $m_k(s)$ may be used. The former will be taken as the first two terms $f(x_k) + s^T \nabla_x f(x_k)$ of a Taylor series about x_k, while the latter uses an approximation to the first three terms $f(x_k) + s^T \nabla_x f(x_k) + \frac{1}{2} s^T B_k s$, for which B_k is a symmetric approximation to the Hessian $\nabla_{xx} f(x_k)$; possible approximations include the true Hessian, limited-memory secant and sparsity approximations and a scaled identity matrix. Normally a two-norm regularization will be used, but this may change if preconditioning is employed.

An approximate minimizer of the cubic model is found using either a direct approach involving factorization or an iterative (conjugate-gradient/Lanczos) approach based on approximations to the required solution from a so-called Krlov subspace. The direct approach is based on the knowledge that the required solution satisfies the linear system of equations $(B_k + \lambda_k I) s_k = -\nabla_x f(x_k)$ involving a scalar Lagrange multiplier λ_k. This multiplier is found by uni-variate root finding, using a safeguarded Newton-like process, by the GALAHAD packages RQS or DPS (depending on the norm chosen). The iterative approach uses the GALAHAD packag GLRT, and is best accelerated by preconditioning with good approximations to B_k using GALAHAD's PSLS. The iterative approach has the advantage that only matrix-vector products $B_k v$ are required, and thus B_k is not required explicitly. However when factorizations of B_k are possible, the direct approach is often more efficient.

1.1.6 References

The generic adaptive cubic regularization method is described in detail in

C. Cartis, N. I. M. Gould and Ph. L. Toint, `‘Adaptive cubic regularisation methods for unconstrained optimization. Part I: motivation, convergence and numerical results'' Mathematical Programming 127(2) (2011) 245-295,

and uses `‘tricks'' as suggested in

N. I. M. Gould, M. Porcelli and Ph. L. Toint, `‘Updating the regularization parameter in the adaptive cubic regularization algorithm''. Computational Optimization and Applications 53(1) (2012) 1-22.

1.2 Call order

To solve a given problem, functions from the arc package must be called in the following order:

- arc_initialize - provide default control parameters and set up initial data structures
- arc_read_specfile (optional) - override control values by reading replacement values from a file
- arc_import - set up problem data structures and fixed values
- arc_reset_control (optional) - possibly change control parameters if a sequence of problems are being solved
- solve the problem by calling one of
  - arc_solve_with_mat - solve using function calls to evaluate function, gradient and Hessian values

- arc_solve_without_mat - solve using function calls to evaluate function and gradient values and Hessian-vector products
- arc_solve_reverse_with_mat - solve returning to the calling program to obtain function, gradient and Hessian values, or
- arc_solve_reverse_without_mat - solve returning to the calling prorgram to obtain function and gradient values and Hessian-vector products

- arc_information (optional) - recover information about the solution and solution process
- arc_terminate - deallocate data structures

See Section 4.1 for examples of use.

1.3 Symmetric matrix storage formats

The symmetric n by n matrix $H = \nabla_{xx} f$ may be presented and stored in a variety of formats. But crucially symmetry is exploited by only storing values from the lower triangular part (i.e, those entries that lie on or below the leading diagonal).

Both C-style (0 based) and fortran-style (1-based) indexing is allowed. Choose `control.f_indexing` as `false` for C style and `true` for fortran style; the discussion below presumes C style, but add 1 to indices for the corresponding fortran version.

Wrappers will automatically convert between 0-based (C) and 1-based (fortran) array indexing, so may be used transparently from C. This conversion involves both time and memory overheads that may be avoided by supplying data that is already stored using 1-based indexing.

1.3.1 Dense storage format

The matrix H is stored as a compact dense matrix by rows, that is, the values of the entries of each row in turn are stored in order within an appropriate real one-dimensional array. Since H is symmetric, only the lower triangular part (that is the part H_{ij} for $0 \leq j \leq i \leq n-1$) need be held. In this case the lower triangle should be stored by rows, that is component $i * i/2 + j$ of the storage array H_val will hold the value H_{ij} (and, by symmetry, H_{ji}) for $0 \leq j \leq i \leq n-1$.

1.3.2 Sparse co-ordinate storage format

Only the nonzero entries of the matrices are stored. For the l-th entry, $0 \leq l \leq ne-1$, of H, its row index i, column index j and value H_{ij}, $0 \leq j \leq i \leq n-1$, are stored as the l-th components of the integer arrays H_row and H_col and real array H_val, respectively, while the number of nonzeros is recorded as H_ne = ne. Note that only the entries in the lower triangle should be stored.

1.3.3 Sparse row-wise storage format

Again only the nonzero entries are stored, but this time they are ordered so that those in row i appear directly before those in row i+1. For the i-th row of H the i-th component of the integer array H_ptr holds the position of the first entry in this row, while H_ptr(n) holds the total number of entries. The column indices j, $0 \leq j \leq i$, and values H_{ij} of the entries in the i-th row are stored in components l = H_ptr(i), . . ., H_ptr(i+1)-1 of the integer array H_col, and real array H_val, respectively. Note that as before only the entries in the lower triangle should be stored. For sparse matrices, this scheme almost always requires less storage than its predecessor.

Chapter 2

File Index

2.1 File List

Here is a list of all files with brief descriptions:

Chapter 3

File Documentation

3.1 galahad_arc.h File Reference

```
#include <stdbool.h>
#include <stdint.h>
#include "galahad_precision.h"
#include "galahad_cfunctions.h"
#include "galahad_rqs.h"
#include "galahad_glrt.h"
#include "galahad_dps.h"
#include "galahad_psls.h"
#include "galahad_lms.h"
#include "galahad_sha.h"
```

Data Structures

- struct arc_control_type
- struct arc_time_type
- struct arc_inform_type

Functions

- void arc_initialize (void ∗∗data, struct arc_control_type ∗control, int ∗status)
- void arc_read_specfile (struct arc_control_type ∗control, const char specfile[ ])
- void arc_import (struct arc_control_type ∗control, void ∗∗data, int ∗status, int n, const char H_type[ ], int ne, const int H_row[ ], const int H_col[ ], const int H_ptr[ ])
- void arc_reset_control (struct arc_control_type ∗control, void ∗∗data, int ∗status)
- void arc_solve_with_mat (void ∗∗data, void ∗userdata, int ∗status, int n, real_wp_ x[ ], real_wp_ g[ ], int ne, int(∗eval_f)(int, const real_wp_[ ], real_wp_ ∗, const void ∗), int(∗eval_g)(int, const real_wp_[ ], real_wp_↩ [ ], const void ∗), int(∗eval_h)(int, int, const real_wp_[ ], real_wp_[ ], const void ∗), int(∗eval_prec)(int, const real_wp_[ ], real_wp_[ ], const real_wp_[ ], const void ∗))
- void arc_solve_without_mat (void ∗∗data, void ∗userdata, int ∗status, int n, real_wp_ x[ ], real_wp_ g[ ], int(∗eval_f)(int, const real_wp_[ ], real_wp_ ∗, const void ∗), int(∗eval_g)(int, const real_wp_[ ], real_wp_↩ [ ], const void ∗), int(∗eval_hprod)(int, const real_wp_[ ], real_wp_[ ], const real_wp_[ ], bool, const void ∗), int(∗eval_prec)(int, const real_wp_[ ], real_wp_[ ], const real_wp_[ ], const void ∗))
- void arc_solve_reverse_with_mat (void ∗∗data, int ∗status, int ∗eval_status, int n, real_wp_ x[ ], real_wp_ f, real_wp_ g[ ], int ne, real_wp_ H_val[ ], const real_wp_ u[ ], real_wp_ v[ ])
- void arc_solve_reverse_without_mat (void ∗∗data, int ∗status, int ∗eval_status, int n, real_wp_ x[ ], real_wp↩ _ f, real_wp_ g[ ], real_wp_ u[ ], real_wp_ v[ ])
- void arc_information (void ∗∗data, struct arc_inform_type ∗inform, int ∗status)
- void arc_terminate (void ∗∗data, struct arc_control_type ∗control, struct arc_inform_type ∗inform)

3.1.1 Data Structure Documentation

3.1.1.1 struct arc_control_type

control derived type as a C struct

Examples

arct.c, and arctf.c.

Data Fields

bool	f_indexing	use C or Fortran sparse matrix indexing
int	error	error and warning diagnostics occur on stream error
int	out	general output occurs on stream out
int	print_level	the level of output required. • ≤ 0 gives no output, • = 1 gives a one-line summary for every iteration, • = 2 gives a summary of the inner iteration for each iteration, • ≥ 3 gives increasingly verbose (debugging) output
int	start_print	any printing will start on this iteration
int	stop_print	any printing will stop on this iteration
int	print_gap	the number of iterations between printing
int	maxit	the maximum number of iterations performed
int	alive_unit	removal of the file alive_file from unit alive_unit terminates execution
char	alive_file[31]	see alive_unit
int	non_monotone	the descent strategy used. Possible values are • $<= 0$ a monotone strategy is used. • anything else, a non-monotone strategy with history length .non_monotine is used.
int	model	the model used. Possible values are • 0 dynamic (*not yet implemented*) • 1 first-order (no Hessian) • 2 second-order (exact Hessian) • 3 barely second-order (identity Hessian) • 4 secant second-order (limited-memory BFGS, with .lbfgs_vectors history) (*not yet implemented*) • 5 secant second-order (limited-memory SR1, with .lbfgs_vectors history) (*not yet implemented*)

Data Fields

int	norm	the regularization norm used. The norm is defined via $\|v\|^2 = v^T P v$, and will define the preconditioner used for iterative methods. Possible values for P are • -3 users own preconditioner • -2 $P =$ limited-memory BFGS matrix (with .lbfgs_vectors history) • -1 identity (= Euclidan two-norm) • 0 automatic (*not yet implemented*) • 1 diagonal, $P =$ diag(max(Hessian, .min_diagonal)) • 2 banded, $P =$ band(Hessian) with semi-bandwidth .semi_bandwidth • 3 re-ordered band, P=band(order(A)) with semi-bandwidth .semi_bandwidth • 4 full factorization, $P =$ Hessian, Schnabel-Eskow modification • 5 full factorization, $P =$ Hessian, GMPS modification (*not yet implemented*) • 6 incomplete factorization of Hessian, Lin-More' • 7 incomplete factorization of Hessian, HSL_MI28 • 8 incomplete factorization of Hessian, Munskgaard (*not yet implemented*) • 9 expanding band of Hessian (*not yet implemented*) • 10 diagonalizing norm from GALAHAD_DPS (*subproblem_direct only*)
int	semi_bandwidth	specify the semi-bandwidth of the band matrix P if required
int	lbfgs_vectors	number of vectors used by the L-BFGS matrix P if required
int	max_dxg	number of vectors used by the sparsity-based secant Hessian if required
int	icfs_vectors	number of vectors used by the Lin-More' incomplete factorization matrix P if required
int	mi28_lsize	the maximum number of fill entries within each column of the incomplete factor L computed by HSL_MI28. In general, increasing .mi28_lsize improve the quality of the preconditioner but increases the time to compute and then apply the preconditioner. Values less than 0 are treated as 0

Data Fields

int	mi28_rsize	the maximum number of entries within each column of the strictly lower triangular matrix R used in the computation of the preconditioner by HSL_MI28. Rank-1 arrays of size .mi28_rsize $*$ n are allocated internally to hold R. Thus the amount of memory used, as well as the amount of work involved in computing the preconditioner, depends on .mi28_rsize. Setting .mi28_rsize $>$ 0 generally leads to a higher quality preconditioner than using .mi28_rsize = 0, and choosing .mi28_rsize $>=$ .mi28_lsize is generally recommended
int	advanced_start	try to pick a good initial regularization weight using .advanced_start iterates of a variant on the strategy of Sartenaer SISC 18(6) 1990:1788-1803
real_wp_	stop_g_absolute	overall convergence tolerances. The iteration will terminate when the norm of the gradient of the objective function is smaller than MAX(.stop_g_absolute, .stop_g_relative $*$ norm of the initial gradient) or if the step is less than .stop_s
real_wp_	stop_g_relative	see stop_g_absolute
real_wp_	stop_s	see stop_g_absolute
real_wp_	initial_weight	Initial value for the regularisation weight (-ve =$>$ 1/||g_0||)
real_wp_	minimum_weight	minimum permitted regularisation weight
real_wp_	reduce_gap	expert parameters as suggested in Gould, Porcelli & Toint, "Updating the regularization parameter in the adaptive cubic regularization algorithm" RAL-TR-2011-007, Rutherford Appleton Laboratory, England (2011), http://epubs.stfc.ac.uk/bitstream/6181/RAL-TR-2011-007.pdf (these are denoted beta, epsilon_chi and alpha_max in the paper)
real_wp_	tiny_gap	see reduce_gap
real_wp_	large_root	see reduce_gap
real_wp_	eta_successful	a potential iterate will only be accepted if the actual decrease f - f(x_new) is larger than .eta_successful times that predicted by a quadratic model of the decrease. The regularization weight will be decreased if this relative decrease is greater than .eta_very_successful but smaller than .eta_too_successful (the first is eta in Gould, Porcell and Toint, 2011)
real_wp_	eta_very_successful	see eta_successful
real_wp_	eta_too_successful	see eta_successful
real_wp_	weight_decrease_min	on very successful iterations, the regularization weight will be reduced by the factor .weight_decrease but no more than .weight_decrease_min while if the iteration is unsuccessful, the weight will be increased by a factor .weight_increase but no more than .weight_increase_max (these are delta_1, delta_2, delta3 and delta_max in Gould, Porcelli and Toint, 2011)
real_wp_	weight_decrease	see weight_decrease_min
real_wp_	weight_increase	see weight_decrease_min
real_wp_	weight_increase_max	see weight_decrease_min
real_wp_	obj_unbounded	the smallest value the onjective function may take before the problem is marked as unbounded

Data Fields

real_wp_	cpu_time_limit	the maximum CPU time allowed (-ve means infinite)
real_wp_	clock_time_limit	the maximum elapsed clock time allowed (-ve means infinite)
bool	hessian_available	is the Hessian matrix of second derivatives available or is access only via matrix-vector products?
bool	subproblem_direct	use a direct (factorization) or (preconditioned) iterative method to find the search direction
bool	renormalize_weight	should the weight be renormalized to account for a change in preconditioner?
bool	quadratic_ratio_test	should the test for acceptance involve the quadratic model or the cubic?
bool	space_critical	if .space_critical true, every effort will be made to use as little space as possible. This may result in longer computation time
bool	deallocate_error_fatal	if .deallocate_error_fatal is true, any array/pointer deallocation error will terminate execution. Otherwise, computation will continue
char	prefix[31]	all output lines will be prefixed by .prefix(2:LEN(TRIM(.prefix))-1) where .prefix contains the required string enclosed in quotes, e.g. "string" or 'string'
struct rqs_control_type	rqs_control	control parameters for RQS
struct glrt_control_type	glrt_control	control parameters for GLRT
struct dps_control_type	dps_control	control parameters for DPS
struct psls_control_type	psls_control	control parameters for PSLS
struct lms_control_type	lms_control	control parameters for LMS
struct lms_control_type	lms_control_prec	
struct sha_control_type	sha_control	control parameters for SHA

3.1.1.2 struct arc_time_type

time derived type as a C struct

Data Fields

real_sp_	total	the total CPU time spent in the package
real_sp_	preprocess	the CPU time spent preprocessing the problem
real_sp_	analyse	the CPU time spent analysing the required matrices prior to factorizatio
real_sp_	factorize	the CPU time spent factorizing the required matrices
real_sp_	solve	the CPU time spent computing the search direction
real_wp_	clock_total	the total clock time spent in the package
real_wp_	clock_preprocess	the clock time spent preprocessing the problem
real_wp_	clock_analyse	the clock time spent analysing the required matrices prior to factorizat
real_wp_	clock_factorize	the clock time spent factorizing the required matrices
real_wp_	clock_solve	the clock time spent computing the search direction

3.1.1.3 struct arc_inform_type

inform derived type as a C struct

Examples

arct.c, and arctf.c.

Data Fields

int	status	return status. See ARC_solve for details
int	alloc_status	the status of the last attempted allocation/deallocation
char	bad_alloc[81]	the name of the array for which an allocation/deallocation error occurred
int	iter	the total number of iterations performed
int	cg_iter	the total number of CG iterations performed
int	f_eval	the total number of evaluations of the objective function
int	g_eval	the total number of evaluations of the gradient of the objective functio
int	h_eval	the total number of evaluations of the Hessian of the objective function
int	factorization_status	the return status from the factorization
int	factorization_max	the maximum number of factorizations in a sub-problem solve
int64_t	max_entries_factors	the maximum number of entries in the factors
int64_t	factorization_integer	the total integer workspace required for the factorization
int64_t	factorization_real	the total real workspace required for the factorization
real_wp_	factorization_average	the average number of factorizations per sub-problem solve
real_wp_	obj	the value of the objective function at the best estimate of the solution determined by the package.
real_wp_	norm_g	the norm of the gradient of the objective function at the best estimate of the solution determined by the package.
real_wp_	weight	the current value of the regularization weight
struct arc_time_type	time	timings (see above)
struct rqs_inform_type	rqs_inform	inform parameters for RQS
struct glrt_inform_type	glrt_inform	inform parameters for GLRT
struct dps_inform_type	dps_inform	inform parameters for DPS
struct psls_inform_type	psls_inform	inform parameters for PSLS
struct lms_inform_type	lms_inform	inform parameters for LMS
struct lms_inform_type	lms_inform_prec	
struct sha_inform_type	sha_inform	inform parameters for SHA

3.1.2 Function Documentation

3.1.2.1 arc_initialize()

```
void arc_initialize (
            void ** data,
```

```
            struct arc_control_type * control,
            int * status )
```

Set default control values and initialize private data

Parameters

in,out	*data*	holds private internal data
out	*control*	is a struct containing control information (see arc_control_type)
out	*status*	is a scalar variable of type int, that gives the exit status from the package. Possible values are (currently): • 0. The import was succesful.

Examples

arct.c, and arctf.c.

3.1.2.2 arc_read_specfile()

```
void arc_read_specfile (
            struct arc_control_type * control,
            const char specfile[] )
```

Read the content of a specification file, and assign values associated with given keywords to the corresponding control parameters. By default, the spcification file will be named RUNARC.SPC and lie in the current directory. Refer to Table 2.1 in the fortran documentation provided in $GALAHAD/doc/arc.pdf for a list of keywords that may be set.

Parameters

in,out	*control*	is a struct containing control information (see arc_control_type)
in	*specfile*	is a character string containing the name of the specification file

3.1.2.3 arc_import()

```
void arc_import (
            struct arc_control_type * control,
            void ** data,
            int * status,
            int n,
            const char H_type[],
            int ne,
            const int H_row[],
            const int H_col[],
            const int H_ptr[] )
```

Import problem data into internal storage prior to solution.

Parameters

in	*control*	is a struct whose members provide control paramters for the remaining prcedures (see arc_control_type)
in,out	*data*	holds private internal data
in,out	*status*	is a scalar variable of type int, that gives the exit status from the package. Possible values are: • 1. The import was succesful, and the package is ready for the solve phase • -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. The restriction n $>$ 0 or requirement that type contains its relevant string 'dense', 'coordinate', 'sparse_by_rows', 'diagonal' or 'absent' has been violated.
in	*n*	is a scalar variable of type int, that holds the number of variables
in	*H_type*	is a one-dimensional array of type char that specifies the symmetric storage scheme used for the Hessian. It should be one of 'coordinate', 'sparse_by_rows', 'dense', 'diagonal' or 'absent', the latter if access to the Hessian is via matrix-vector products; lower or upper case variants are allowed
in	*ne*	is a scalar variable of type int, that holds the number of entries in the lower triangular part of H in the sparse co-ordinate storage scheme. It need not be set for any of the other three schemes.
in	*H_row*	is a one-dimensional array of size ne and type int, that holds the row indices of the lower triangular part of H in the sparse co-ordinate storage scheme. It need not be set for any of the other three schemes, and in this case can be NULL
in	*H_col*	is a one-dimensional array of size ne and type int, that holds the column indices of the lower triangular part of H in either the sparse co-ordinate, or the sparse row-wise storage scheme. It need not be set when the dense or diagonal storage schemes are used, and in this case can be NULL
in	*H_ptr*	is a one-dimensional array of size n+1 and type int, that holds the starting position of each row of the lower triangular part of H, as well as the total number of entries, in the sparse row-wise storage scheme. It need not be set when the other schemes are used, and in this case can be NULL

Examples

arct.c, and arctf.c.

3.1.2.4 arc_reset_control()

```
void arc_reset_control (
            struct arc_control_type * control,
            void ** data,
            int * status )
```

Reset control parameters after import if required.

Parameters

in	*control*	is a struct whose members provide control paramters for the remaining prcedures (see arc_control_type)
in,out	*data*	holds private internal data
in,out	*status*	is a scalar variable of type int, that gives the exit status from the package. Possible values are: • 1. The import was succesful, and the package is ready for the solve phase

3.1.2.5 arc_solve_with_mat()

```
void arc_solve_with_mat (
            void ** data,
            void * userdata,
            int * status,
            int n,
            real_wp_ x[ ],
            real_wp_ g[ ],
            int ne,
            int(*)(int, const real_wp_[ ], real_wp_ *, const void *) eval_f,
            int(*)(int, const real_wp_[ ], real_wp_[ ], const void *) eval_g,
            int(*)(int, int, const real_wp_[ ], real_wp_[ ], const void *) eval_h,
            int(*)(int, const real_wp_[ ], real_wp_[ ], const real_wp_[ ], const void *) eval_↩
prec )
```

Find a local minimizer of a given function using a regularization method.

This call is for the case where $H = \nabla_{xx} f(x)$ is provided specifically, and all function/derivative information is available by function calls.

Parameters

in,out	*data*	holds private internal data
in	*userdata*	is a structure that allows data to be passed into the function and derivative evaluation programs.

Parameters

in,out	*status*	is a scalar variable of type int, that gives the entry and exit status from the package. On initial entry, status must be set to 1. Possible exit are: • 0. The run was succesful • -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. The restriction n $>$ 0 or requirement that type contains its relevant string 'dense', 'coordinate', 'sparse_by_rows', 'diagonal' or 'absent' has been violated. • -7. The objective function appears to be unbounded from below • -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. • -11. The solution of a set of linear equations using factors from the factorization package 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. • -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. • -82. The user has forced termination of solver by removing the file named control.alive_file from unit unit control.alive_unit.
in	*n*	is a scalar variable of type int, that holds the number of variables
in,out	*x*	is a one-dimensional array of size n and type double, that holds the values x of the optimization variables. The j-th component of x, j = 0, ... , n-1, contains x_j.
in,out	*g*	is a one-dimensional array of size n and type double, that holds the gradient $g = \nabla_x f(x)$ of the objective function. The j-th component of g, j = 0, ... , n-1, contains g_j.
in	*ne*	is a scalar variable of type int, that holds the number of entries in the lower triangular part of the Hessian matrix H.
	eval_f	is a user-supplied function that must have the following signature: `int eval_f( int n, const double x[], double *f, const void *userdata )` The value of the objective function $f(x)$ evaluated at x= x must be assigned to f, and the function return value set to 0. If the evaluation is impossible at x, return should be set to a nonzero value. Data may be passed into `eval_f` via the structure `userdata`.

Parameters

	eval_g	is a user-supplied function that must have the following signature: `int eval_g( int n, const double x[], double g[], const void *userdata )` The components of the gradient $g = \nabla_x f(x)$ of the objective function evaluated at x= x must be assigned to g, and the function return value set to 0. If the evaluation is impossible at x, return should be set to a nonzero value. Data may be passed into `eval_g` via the structure `userdata`.
	eval_h	is a user-supplied function that must have the following signature: `int eval_h( int n, int ne, const double x[], double h[], const void *userdata )` The nonzeros of the Hessian $H = \nabla_{xx} f(x)$ of the objective function evaluated at x= x must be assigned to h in the same order as presented to arc_import, and the function return value set to 0. If the evaluation is impossible at x, return should be set to a nonzero value. Data may be passed into `eval_h` via the structure `userdata`.
	eval_prec	is an optional user-supplied function that may be NULL. If non-NULL, it must have the following signature: `int eval_prec( int n, const double x[], double u[], const double v[], const void *userdata )` The product $u = P(x)v$ of the user's preconditioner $P(x)$ evaluated at x with the vector v = v, the result u must be retured in u, and the function return value set to 0. If the evaluation is impossible at x, return should be set to a nonzero value. Data may be passed into `eval_prec` via the structure `userdata`.

Examples

arct.c, and arctf.c.

3.1.2.6 arc_solve_without_mat()

```
void arc_solve_without_mat (
            void ** data,
            void * userdata,
            int * status,
            int n,
            real_wp_ x[ ],
            real_wp_ g[ ],
            int(*)(int, const real_wp_[ ], real_wp_ *, const void *) eval_f,
            int(*)(int, const real_wp_[ ], real_wp_[ ], const void *) eval_g,
            int(*)(int, const real_wp_[ ], real_wp_[ ], const real_wp_[ ], bool, const void *)
eval_hprod,
            int(*)(int, const real_wp_[ ], real_wp_[ ], const real_wp_[ ], const void *) eval_←
prec )
```

Find a local minimizer of a given function using a regularization method.

This call is for the case where access to $H = \nabla_{xx} f(x)$ is provided by Hessian-vector products, and all function/derivative information is available by function calls.

Parameters

`in,out`	*data*	holds private internal data
`in`	*userdata*	is a structure that allows data to be passed into the function and derivative evaluation programs.

Parameters

in,out	*status*	is a scalar variable of type int, that gives the entry and exit status from the package. On initial entry, status must be set to 1. Possible exit are: • 0. The run was succesful • -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. The restriction n $>$ 0 or requirement that type contains its relevant string 'dense', 'coordinate', 'sparse_by_rows', 'diagonal' or 'absent' has been violated. • -7. The objective function appears to be unbounded from below • -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. • -11. The solution of a set of linear equations using factors from the factorization package 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. • -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. • -82. The user has forced termination of solver by removing the file named control.alive_file from unit unit control.alive_unit.
in	*n*	is a scalar variable of type int, that holds the number of variables
in,out	*x*	is a one-dimensional array of size n and type double, that holds the values x of the optimization variables. The j-th component of x, j = 0, ... , n-1, contains x_j.
in,out	*g*	is a one-dimensional array of size n and type double, that holds the gradient $g = \nabla_x f(x)$ of the objective function. The j-th component of g, j = 0, ... , n-1, contains g_j.
	eval_f	is a user-supplied function that must have the following signature: `int eval_f( int n, const double x[], double *f, const void *userdata )` The value of the objective function $f(x)$ evaluated at x= x must be assigned to f, and the function return value set to 0. If the evaluation is impossible at x, return should be set to a nonzero value. Data may be passed into `eval_f` via the structure `userdata`.

Parameters

	eval_g	is a user-supplied function that must have the following signature: `int eval_g( int n, const double x[], double g[], const void *userdata )` The components of the gradient $g = \nabla_x f(x)$ of the objective function evaluated at x= x must be assigned to g, and the function return value set to 0. If the evaluation is impossible at x, return should be set to a nonzero value. Data may be passed into `eval_g` via the structure `userdata`.
	eval_hprod	is a user-supplied function that must have the following signature: `int eval_hprod( int n, const double x[], double u[], const double v[], bool got_h, const void *userdata )` The sum $u + \nabla_{xx} f(x)v$ of the product of the Hessian $\nabla_{xx} f(x)$ of the objective function evaluated at x= x with the vector v= v and the vector $ u must be returned in u, and the function return value set to 0. If the evaluation is impossible at x, return should be set to a nonzero value. The Hessian has already been evaluated or used at x if got_h is true. Data may be passed into `eval_hprod` via the structure `userdata`.
	eval_prec	is an optional user-supplied function that may be NULL. If non-NULL, it must have the following signature: `int eval_prec( int n, const double x[], double u[], const double v[], const void *userdata )` The product $u = P(x)v$ of the user's preconditioner $P(x)$ evaluated at x with the vector v = v, the result u must be retured in u, and the function return value set to 0. If the evaluation is impossible at x, return should be set to a nonzero value. Data may be passed into `eval_prec` via the structure `userdata`.

Examples

arct.c, and arctf.c.

3.1.2.7 arc_solve_reverse_with_mat()

```
void arc_solve_reverse_with_mat (
            void ** data,
            int * status,
            int * eval_status,
            int n,
            real_wp_ x[ ],
            real_wp_ f,
            real_wp_ g[ ],
            int ne,
            real_wp_ H_val[ ],
            const real_wp_ u[ ],
            real_wp_ v[ ] )
```

Find a local minimizer of a given function using a regularization method.

This call is for the case where $H = \nabla_{xx} f(x)$ is provided specifically, but function/derivative information is only available by returning to the calling procedure

Parameters

in,out	*data*	holds private internal data

Parameters

`in,out`	*status*	is a scalar variable of type int, that gives the entry and exit status from the package. On initial entry, status must be set to 1. Possible exit are: • 0. The run was succesful • -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. The restriction n $>$ 0 or requirement that type contains its relevant string 'dense', 'coordinate', 'sparse_by_rows', 'diagonal' or 'absent' has been violated. • -7. The objective function appears to be unbounded from below • -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. • -11. The solution of a set of linear equations using factors from the factorization package 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. • -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. • -82. The user has forced termination of solver by removing the file named control.alive_file from unit unit control.alive_unit.

Parameters

	status	(continued) • 2. The user should compute the objective function value $f(x)$ at the point x indicated in x and then re-enter the function. The required value should be set in f, and eval_status should be set to 0. If the user is unable to evaluate $f(x)$— for instance, if the function is undefined at x— the user need not set f, but should then set eval_status to a non-zero value. • 3. The user should compute the gradient of the objective function $\nabla_x f(x)$ at the point x indicated in x and then re-enter the function. The value of the i-th component of the g radient should be set in g[i], for i = 0, ..., n-1 and eval_status should be set to 0. If the user is unable to evaluate a component of $\nabla_x f(x)$ — for instance if a component of the gradient is undefined at x -the user need not set g, but should then set eval_status to a non-zero value. • 4. The user should compute the Hessian of the objective function $\nabla_{xx} f(x)$ at the point x indicated in x and then re-enter the function. The value l-th component of the Hessian stored according to the scheme input in the remainder of H should be set in H_val[l], for l = 0, ..., ne-1 and eval_status should be set to 0. If the user is unable to evaluate a component of $\nabla_{xx} f(x)$ — for instance, if a component of the Hessian is undefined at x — the user need not set H_val, but should then set eval_status to a non-zero value. • 6. The user should compute the product $u = P(x)v$ of their preconditioner $P(x)$ at the point x indicated in x with the vector v and then re-enter the function. The vector v is given in v, the resulting vector $u = P(x)v$ should be set in u and eval_status should be set to 0. If the user is unable to evaluate the product— for instance, if a component of the preconditioner is undefined at x — the user need not set u, but should then set eval_status to a non-zero value.
`in,out`	*eval_status*	is a scalar variable of type int, that is used to indicate if objective function/gradient/Hessian values can be provided (see above)
`in`	*n*	is a scalar variable of type int, that holds the number of variables
`in,out`	*x*	is a one-dimensional array of size n and type double, that holds the values x of the optimization variables. The j-th component of x, j = 0, ... , n-1, contains x_j.
`in`	*f*	is a scalar variable pointer of type double, that holds the value of the objective function.
`in,out`	*g*	is a one-dimensional array of size n and type double, that holds the gradient $g = \nabla_x f(x)$ of the objective function. The j-th component of g, j = 0, ... , n-1, contains g_j.
`in`	*ne*	is a scalar variable of type int, that holds the number of entries in the lower triangular part of the Hessian matrix H.
`in`	*H_val*	is a one-dimensional array of size ne and type double, that holds the values of the entries of the lower triangular part of the Hessian matrix H in any of the available storage schemes.
`in`	*u*	is a one-dimensional array of size n and type double, that is used for reverse communication (see above for details)
`in,out`	*v*	is a one-dimensional array of size n and type double, that is used for reverse communication (see above for details)

Examples

arct.c, and arctf.c.

3.1.2.8 arc_solve_reverse_without_mat()

```
void arc_solve_reverse_without_mat (
            void ** data,
            int * status,
            int * eval_status,
            int n,
            real_wp_ x[],
            real_wp_ f,
            real_wp_ g[],
            real_wp_ u[],
            real_wp_ v[] )
```

Find a local minimizer of a given function using a regularization method.

This call is for the case where access to $H = \nabla_{xx} f(x)$ is provided by Hessian-vector products, but function/derivative information is only available by returning to the calling procedure.

Parameters

in,out	*data*	holds private internal data

Parameters

in,out	*status*	is a scalar variable of type int, that gives the entry and exit status from the package. On initial entry, status must be set to 1. Possible exit are: • 0. The run was succesful • -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. The restriction n $>$ 0 or requirement that type contains its relevant string 'dense', 'coordinate', 'sparse_by_rows', 'diagonal' or 'absent' has been violated. • -7. The objective function appears to be unbounded from below • -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. • -11. The solution of a set of linear equations using factors from the factorization package 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. • -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. • -82. The user has forced termination of solver by removing the file named control.alive_file from unit unit control.alive_unit.

Parameters

	status	(continued) • 2. The user should compute the objective function value $f(x)$ at the point x indicated in x and then re-enter the function. The required value should be set in f, and eval_status should be set to 0. If the user is unable to evaluate $f(x)$ — for instance, if the function is undefined at x — the user need not set f, but should then set eval_status to a non-zero value. • 3. The user should compute the gradient of the objective function $\nabla_x f(x)$ at the point x indicated in x and then re-enter the function. The value of the i-th component of the g radient should be set in g[i], for i = 0, ..., n-1 and eval_status should be set to 0. If the user is unable to evaluate a component of $\nabla_x f(x)$ — for instance if a component of the gradient is undefined at x -the user need not set g, but should then set eval_status to a non-zero value. • 5. The user should compute the product $\nabla_{xx} f(x)v$ of the Hessian of the objective function $\nabla_{xx} f(x)$ at the point x indicated in x with the vector v, add the result to the vector u and then re-enter the function. The vectors u and v are given in u and v respectively, the resulting vector $u + \nabla_{xx} f(x)v$ should be set in u and eval_status should be set to 0. If the user is unable to evaluate the product— for instance, if a component of the Hessian is undefined at x — the user need not alter u, but should then set eval_status to a non-zero value. • 6. The user should compute the product $u = P(x)v$ of their preconditioner $P(x)$ at the point x indicated in x with the vector v and then re-enter the function. The vector v is given in v, the resulting vector $u = P(x)v$ should be set in u and eval_status should be set to 0. If the user is unable to evaluate the product— for instance, if a component of the preconditioner is undefined at x — the user need not set u, but should then set eval_status to a non-zero value.
`in,out`	*eval_status*	is a scalar variable of type int, that is used to indicate if objective function/gradient/Hessian values can be provided (see above)
`in`	*n*	is a scalar variable of type int, that holds the number of variables
`in,out`	*x*	is a one-dimensional array of size n and type double, that holds the values x of the optimization variables. The j-th component of x, j = 0, ... , n-1, contains x_j.
`in`	*f*	is a scalar variable pointer of type double, that holds the value of the objective function.
`in,out`	*g*	is a one-dimensional array of size n and type double, that holds the gradient $g = \nabla_x f(x)$ of the objective function. The j-th component of g, j = 0, ... , n-1, contains g_j.
`in,out`	*u*	is a one-dimensional array of size n and type double, that is used for reverse communication (see above for details)
`in,out`	*v*	is a one-dimensional array of size n and type double, that is used for reverse communication (see above for details)

Examples

arct.c, and arctf.c.

3.1.2.9 arc_information()

```
void arc_information (
            void ** data,
            struct arc_inform_type * inform,
            int * status )
```

Provides output information

Parameters

in,out	*data*	holds private internal data
out	*inform*	is a struct containing output information (see arc_inform_type)
out	*status*	is a scalar variable of type int, that gives the exit status from the package. Possible values are (currently): • 0. The values were recorded succesfully

Examples

arct.c, and arctf.c.

3.1.2.10 arc_terminate()

```
void arc_terminate (
            void ** data,
            struct arc_control_type * control,
            struct arc_inform_type * inform )
```

Deallocate all internal private storage

Parameters

in,out	*data*	holds private internal data
out	*control*	is a struct containing control information (see arc_control_type)
out	*inform*	is a struct containing output information (see arc_inform_type)

Examples

arct.c, and arctf.c.

Chapter 4

Example Documentation

4.1 arct.c

This is an example of how to use the package both when the Hessian is directly available and when its product with vectors may be found. Both function call evaluations and returns to the calling program to find the required values are illustrated. A variety of supported Hessian storage formats are shown.

Notice that C-style indexing is used, and that this is flaggeed by setting `control.f_indexing` to `false`. In addition, see how parameters may be passed into the evaluation functions via `userdata`.

```
/* arct.c */
/* Full test for the ARC C interface using C sparse matrix indexing */
#include <stdio.h>
#include <math.h>
#include "galahad_precision.h"
#include "galahad_cfunctions.h"
#include "galahad_arc.h"
// Custom userdata struct
struct userdata_type {
   real_wp_ p;
};
// Function prototypes
int fun( int n, const real_wp_ x[], real_wp_ *f, const void * );
int grad( int n, const real_wp_ x[], real_wp_ g[], const void * );
int hess( int n, int ne, const real_wp_ x[], real_wp_ hval[], const void * );
int hess_dense( int n, int ne, const real_wp_ x[], real_wp_ hval[], const void * );
int hessprod( int n, const real_wp_ x[], real_wp_ u[], const real_wp_ v[], bool got_h,
              const void * );
int prec( int n, const real_wp_ x[], real_wp_ u[], const real_wp_ v[], const void * );
int fun_diag( int n, const real_wp_ x[], real_wp_ *f, const void * );
int grad_diag( int n, const real_wp_ x[], real_wp_ g[], const void * );
int hess_diag( int n, int ne, const real_wp_ x[], real_wp_ hval[], const void * );
int hessprod_diag( int n, const real_wp_ x[], real_wp_ u[], const real_wp_ v[],
                   bool got_h, const void * );
int main(void) {
    // Derived types
    void *data;
    struct arc_control_type control;
    struct arc_inform_type inform;
    // Set user data
    struct userdata_type userdata;
    userdata.p = 4.0;
    // Set problem data
    int n = 3; // dimension
    int ne = 5; // Hesssian elements
    int H_row[] = {0, 1, 2, 2, 2}; // Hessian H
    int H_col[] = {0, 1, 0, 1, 2}; // NB lower triangle
    int H_ptr[] = {0, 1, 2, 5};    // row pointers
    // Set storage
    real_wp_ g[n]; // gradient
    char st;
    int status;
    printf(" C sparse matrix indexing\n\n");
```

```
    printf(" tests options for all-in-one storage format\n\n");
    for( int d=1; d <= 5; d++){
        // Initialize ARC
        arc_initialize( &data, &control, &status );
        // Set user-defined control options
        control.f_indexing = false; // C sparse matrix indexing
        //control.print_level = 1;
        // Start from 1.5
        real_wp_ x[] = {1.5,1.5,1.5};
        switch(d){
            case 1: // sparse co-ordinate storage
                st = 'C';
                arc_import( &control, &data, &status, n, "coordinate",
                            ne, H_row, H_col, NULL );
                arc_solve_with_mat( &data, &userdata, &status,
                                    n, x, g, ne, fun, grad, hess, prec );
                break;
            case 2: // sparse by rows
                st = 'R';
                arc_import( &control, &data, &status, n, "sparse_by_rows",
                           ne, NULL, H_col, H_ptr);
                arc_solve_with_mat( &data, &userdata, &status,
                                    n, x, g, ne, fun, grad, hess, prec );
                break;
            case 3: // dense
                st = 'D';
                arc_import( &control, &data, &status, n, "dense",
                           ne, NULL, NULL, NULL );
                arc_solve_with_mat( &data, &userdata, &status,
                                    n, x, g, ne, fun, grad, hess_dense, prec );
                break;
            case 4: // diagonal
                st = 'I';
                arc_import( &control, &data, &status, n, "diagonal",
                           ne, NULL, NULL, NULL );
                arc_solve_with_mat( &data, &userdata, &status, n, x, g,
                                    ne, fun_diag, grad_diag, hess_diag, prec) ;
                break;
            case 5: // access by products
                st = 'P';
                arc_import( &control, &data, &status, n, "absent",
                           ne, NULL, NULL, NULL );
                arc_solve_without_mat( &data, &userdata, &status,
                                       n, x, g, fun, grad, hessprod, prec );
                break;
        }
        arc_information( &data, &inform, &status);
        if(inform.status == 0){
            printf("%c:%6i iterations. Optimal objective value = %5.2f status = %1i\n",
                   st, inform.iter, inform.obj, inform.status);
        }else{
            printf("%c: ARC_solve exit status = %1i\n", st, inform.status);
        }
        //printf("x: ");
        //for( int i = 0; i < n; i++) printf("%f ", x[i]);
        //printf("\n");
        //printf("gradient: ");
        //for( int i = 0; i < n; i++) printf("%f ", g[i]);
        //printf("\n");
        // Delete internal workspace
        arc_terminate( &data, &control, &inform );
    }
    printf("\n tests reverse-communication options\n\n");
    // reverse-communication input/output
    int eval_status;
    real_wp_ f = 0.0;
    real_wp_ u[n], v[n];
    int index_nz_u[n], index_nz_v[n];
    real_wp_ H_val[ne], H_dense[n*(n+1)/2], H_diag[n];

    for( int d=1; d <= 5; d++){
        // Initialize ARC
        arc_initialize( &data, &control, &status );
        // Set user-defined control options
        control.f_indexing = false; // C sparse matrix indexing
        //control.print_level = 1;
        // Start from 1.5
        real_wp_ x[] = {1.5,1.5,1.5};
        switch(d){
            case 1: // sparse co-ordinate storage
                st = 'C';
                arc_import( &control, &data, &status, n, "coordinate",
                           ne, H_row, H_col, NULL );
                while(true){ // reverse-communication loop
                    arc_solve_reverse_with_mat( &data, &status, &eval_status,
                                                n, x, f, g, ne, H_val, u, v );
                    if(status == 0){ // successful termination
```

```
                break;
            }else if(status < 0){ // error exit
                break;
            }else if(status == 2){ // evaluate f
                eval_status = fun( n, x, &f, &userdata );
            }else if(status == 3){ // evaluate g
                eval_status = grad( n, x, g, &userdata );
            }else if(status == 4){ // evaluate H
                eval_status = hess( n, ne, x, H_val, &userdata );
            }else if(status == 6){ // evaluate the product with P
                eval_status = prec( n, x, u, v, &userdata );
            }else{
                printf(" the value %1i of status should not occur\n",
                  status);
                break;
            }
        }
        break;
    case 2: // sparse by rows
        st = 'R';
        arc_import( &control, &data, &status, n, "sparse_by_rows", ne,
                   NULL, H_col, H_ptr);
        while(true){ // reverse-communication loop
            arc_solve_reverse_with_mat( &data, &status, &eval_status,
                                        n, x, f, g, ne, H_val, u, v );
            if(status == 0){ // successful termination
                break;
            }else if(status < 0){ // error exit
                break;
            }else if(status == 2){ // evaluate f
                eval_status = fun( n, x, &f, &userdata );
            }else if(status == 3){ // evaluate g
                eval_status = grad( n, x, g, &userdata );
            }else if(status == 4){ // evaluate H
                eval_status = hess( n, ne, x, H_val, &userdata );
            }else if(status == 6){ // evaluate the product with P
                eval_status = prec( n, x, u, v, &userdata );
            }else{
                printf(" the value %1i of status should not occur\n",
                  status);
                break;
            }
        }
        break;
    case 3: // dense
        st = 'D';
        arc_import( &control, &data, &status, n, "dense",
                   ne, NULL, NULL, NULL );
        while(true){ // reverse-communication loop
            arc_solve_reverse_with_mat( &data, &status, &eval_status,
                                 n, x, f, g, n*(n+1)/2, H_dense, u, v );
            if(status == 0){ // successful termination
                break;
            }else if(status < 0){ // error exit
                break;
            }else if(status == 2){ // evaluate f
                eval_status = fun( n, x, &f, &userdata );
            }else if(status == 3){ // evaluate g
                eval_status = grad( n, x, g, &userdata );
            }else if(status == 4){ // evaluate H
                eval_status = hess_dense( n, n*(n+1)/2, x, H_dense,
                                          &userdata );
            }else if(status == 6){ // evaluate the product with P
                eval_status = prec( n, x, u, v, &userdata );
            }else{
                printf(" the value %1i of status should not occur\n",
                  status);
                break;
            }
        }
        break;
    case 4: // diagonal
        st = 'I';
        arc_import( &control, &data, &status, n, "diagonal",
                   ne, NULL, NULL, NULL );
        while(true){ // reverse-communication loop
            arc_solve_reverse_with_mat( &data, &status, &eval_status,
                                        n, x, f, g, n, H_diag, u, v );
            if(status == 0){ // successful termination
                break;
            }else if(status < 0){ // error exit
                break;
            }else if(status == 2){ // evaluate f
                eval_status = fun_diag( n, x, &f, &userdata );
            }else if(status == 3){ // evaluate g
                eval_status = grad_diag( n, x, g, &userdata );
            }else if(status == 4){ // evaluate H
```

```
                        eval_status = hess_diag( n, n, x, H_diag, &userdata );
                    }else if(status == 6){ // evaluate the product with P
                        eval_status = prec( n, x, u, v, &userdata );
                    }else{
                        printf(" the value %1i of status should not occur\n",
                          status);
                        break;
                    }
                }
                break;
            case 5: // access by products
                st = 'P';
                arc_import( &control, &data, &status, n, "absent",
                           ne, NULL, NULL, NULL );
                while(true){ // reverse-communication loop
                    arc_solve_reverse_without_mat( &data, &status, &eval_status,
                                                   n, x, f, g, u, v );
                    if(status == 0){ // successful termination
                        break;
                    }else if(status < 0){ // error exit
                        break;
                    }else if(status == 2){ // evaluate f
                        eval_status = fun( n, x, &f, &userdata );
                    }else if(status == 3){ // evaluate g
                        eval_status = grad( n, x, g, &userdata );
                    }else if(status == 5){ // evaluate H
                        eval_status = hessprod( n, x, u, v, false, &userdata );
                    }else if(status == 6){ // evaluate the product with P
                        eval_status = prec( n, x, u, v, &userdata );
                    }else{
                        printf(" the value %1i of status should not occur\n",
                          status);
                        break;
                    }
                }
                break;
        }
        arc_information( &data, &inform, &status );
        if(inform.status == 0){
            printf("%c:%6i iterations. Optimal objective value = %5.2f status = %1i\n",
                   st, inform.iter, inform.obj, inform.status);
        }else{
            printf("%c: ARC_solve exit status = %1i\n", st, inform.status);
        }
        //printf("x: ");
        //for( int i = 0; i < n; i++) printf("%f ", x[i]);
        //printf("\n");
        //printf("gradient: ");
        //for( int i = 0; i < n; i++) printf("%f ", g[i]);
        //printf("\n");
        // Delete internal workspace
        arc_terminate( &data, &control, &inform );
    }
}
// Objective function
int fun( int n, const real_wp_ x[], real_wp_ *f, const void *userdata ){
    struct userdata_type *myuserdata = (struct userdata_type *) userdata;
    real_wp_ p = myuserdata->p;
    *f = pow(x[0] + x[2] + p, 2) + pow(x[1] + x[2], 2) + cos(x[0]);
    return 0;
}
// Gradient of the objective
int grad( int n, const real_wp_ x[], real_wp_ g[], const void *userdata ){
    struct userdata_type *myuserdata = (struct userdata_type *) userdata;
    real_wp_ p = myuserdata->p;
    g[0] = 2.0 * ( x[0] + x[2] + p ) - sin(x[0]);
    g[1] = 2.0 * ( x[1] + x[2] );
    g[2] = 2.0 * ( x[0] + x[2] + p ) + 2.0 * ( x[1] + x[2] );
    return 0;
}
// Hessian of the objective
int hess( int n, int ne, const real_wp_ x[], real_wp_ hval[],
         const void *userdata ){
    hval[0] = 2.0 - cos(x[0]);
    hval[1] = 2.0;
    hval[2] = 2.0;
    hval[3] = 2.0;
    hval[4] = 4.0;
    return 0;
}
// Dense Hessian
int hess_dense( int n, int ne, const real_wp_ x[], real_wp_ hval[],
               const void *userdata ){
    hval[0] = 2.0 - cos(x[0]);
    hval[1] = 0.0;
    hval[2] = 2.0;
    hval[3] = 2.0;
```

```
    hval[4] = 2.0;
    hval[5] = 4.0;
    return 0;
}
// Hessian-vector product
int hessprod( int n, const real_wp_ x[], real_wp_ u[], const real_wp_ v[],
              bool got_h, const void *userdata ){
    u[0] = u[0] + 2.0 * ( v[0] + v[2] ) - cos(x[0]) * v[0];
    u[1] = u[1] + 2.0 * ( v[1] + v[2] );
    u[2] = u[2] + 2.0 * ( v[0] + v[1] + 2.0 * v[2] );
    return 0;
}
// Apply preconditioner
int prec( int n, const real_wp_ x[], real_wp_ u[], const real_wp_ v[],
          const void *userdata ){
   u[0] = 0.5 * v[0];
   u[1] = 0.5 * v[1];
   u[2] = 0.25 * v[2];
   return 0;
}
 // Objective function
int fun_diag( int n, const real_wp_ x[], real_wp_ *f, const void *userdata ){
    struct userdata_type *myuserdata = (struct userdata_type *) userdata;
    real_wp_ p = myuserdata->p;
    *f = pow(x[2] + p, 2) + pow(x[1], 2) + cos(x[0]);
    return 0;
}
// Gradient of the objective
int grad_diag( int n, const real_wp_ x[], real_wp_ g[], const void *userdata ){
    struct userdata_type *myuserdata = (struct userdata_type *) userdata;
    real_wp_ p = myuserdata->p;
    g[0] = -sin(x[0]);
    g[1] = 2.0 * x[1];
    g[2] = 2.0 * ( x[2] + p );
    return 0;
}
// Hessian of the objective
int hess_diag( int n, int ne, const real_wp_ x[], real_wp_ hval[],
               const void *userdata ){
    hval[0] = -cos(x[0]);
    hval[1] = 2.0;
    hval[2] = 2.0;
    return 0;
}
// Hessian-vector product
int hessprod_diag( int n, const real_wp_ x[], real_wp_ u[], const real_wp_ v[],
                   bool got_h, const void *userdata ){
    u[0] = u[0] + - cos(x[0]) * v[0];
    u[1] = u[1] + 2.0 * v[1];
    u[2] = u[2] + 2.0 * v[2];
    return 0;
}
```

4.2 arctf.c

This is the same example, but now fortran-style indexing is used.

```
/* arctf.c */
/* Full test for the ARC C interface using Fortran sparse matrix indexing */
#include <stdio.h>
#include <math.h>
#include "galahad_precision.h"
#include "galahad_cfunctions.h"
#include "galahad_arc.h"
// Custom userdata struct
struct userdata_type {
   real_wp_ p;
};
// Function prototypes
int fun( int n, const real_wp_ x[], real_wp_ *f, const void * );
int grad( int n, const real_wp_ x[], real_wp_ g[], const void * );
int hess( int n, int ne, const real_wp_ x[], real_wp_ hval[], const void * );
int hess_dense( int n, int ne, const real_wp_ x[], real_wp_ hval[],
                const void * );
int hessprod( int n, const real_wp_ x[], real_wp_ u[], const real_wp_ v[],
              bool got_h, const void * );
int prec( int n, const real_wp_ x[], real_wp_ u[], const real_wp_ v[],
          const void * );
int fun_diag( int n, const real_wp_ x[], real_wp_ *f, const void * );
int grad_diag( int n, const real_wp_ x[], real_wp_ g[], const void * );
int hess_diag( int n, int ne, const real_wp_ x[], real_wp_ hval[],
```

```
                const void * );
int hessprod_diag( int n, const real_wp_ x[], real_wp_ u[], const real_wp_ v[],
                   bool got_h, const void * );
int main(void) {
    // Derived types
    void *data;
    struct arc_control_type control;
    struct arc_inform_type inform;
    // Set user data
    struct userdata_type userdata;
    userdata.p = 4.0;
    // Set problem data
    int n = 3; // dimension
    int ne = 5; // Hesssian elements
    int H_row[] = {1, 2, 3, 3, 3}; // Hessian H
    int H_col[] = {1, 2, 1, 2, 3}; // NB lower triangle
    int H_ptr[] = {1, 2, 3, 6};    // row pointers
    // Set storage
    real_wp_ g[n]; // gradient
    char st;
    int status;
    printf(" Fortran sparse matrix indexing\n\n");
    printf(" tests options for all-in-one storage format\n\n");
    for( int d=1; d <= 5; d++){
        // Initialize ARC
        arc_initialize( &data, &control, &status );
        // Set user-defined control options
        control.f_indexing = true; // Fortran sparse matrix indexing
        //control.print_level = 1;
        // Start from 1.5
        real_wp_ x[] = {1.5,1.5,1.5};
        switch(d){
            case 1: // sparse co-ordinate storage
                st = 'C';
                arc_import( &control, &data, &status, n, "coordinate",
                            ne, H_row, H_col, NULL );
                arc_solve_with_mat( &data, &userdata, &status,
                                    n, x, g, ne, fun, grad, hess, prec );
                break;
            case 2: // sparse by rows
                st = 'R';
                arc_import( &control, &data, &status, n, "sparse_by_rows",
                           ne, NULL, H_col, H_ptr);
                arc_solve_with_mat( &data, &userdata, &status,
                                    n, x, g, ne, fun, grad, hess, prec );
                break;
            case 3: // dense
                st = 'D';
                arc_import( &control, &data, &status, n, "dense",
                           ne, NULL, NULL, NULL );
                arc_solve_with_mat( &data, &userdata, &status,
                                    n, x, g, ne, fun, grad, hess_dense, prec );
                break;
            case 4: // diagonal
                st = 'I';
                arc_import( &control, &data, &status, n, "diagonal",
                           ne, NULL, NULL, NULL );
                arc_solve_with_mat( &data, &userdata, &status, n, x, g,
                                    ne, fun_diag, grad_diag, hess_diag, prec) ;
                break;
            case 5: // access by products
                st = 'P';
                arc_import( &control, &data, &status, n, "absent",
                           ne, NULL, NULL, NULL );
                arc_solve_without_mat( &data, &userdata, &status,
                                       n, x, g, fun, grad, hessprod, prec );
                break;
        }
        arc_information( &data, &inform, &status);
        if(inform.status == 0){
            printf("%c:%6i iterations. Optimal objective value = %5.2f status = %1i\n",
                   st, inform.iter, inform.obj, inform.status);
        }else{
            printf("%c: ARC_solve exit status = %1i\n", st, inform.status);
        }
        //printf("x: ");
        //for( int i = 0; i < n; i++) printf("%f ", x[i]);
        //printf("\n");
        //printf("gradient: ");
        //for( int i = 0; i < n; i++) printf("%f ", g[i]);
        //printf("\n");
        // Delete internal workspace
        arc_terminate( &data, &control, &inform );
    }
    printf("\n tests reverse-communication options\n\n");
    // reverse-communication input/output
    int eval_status;
```

```
    real_wp_ f = 0.0;
    real_wp_ u[n], v[n];
    int index_nz_u[n], index_nz_v[n];
    real_wp_ H_val[ne], H_dense[n*(n+1)/2], H_diag[n];

    for( int d=1; d <= 5; d++){
        // Initialize ARC
        arc_initialize( &data, &control, &status );
        // Set user-defined control options
        control.f_indexing = true; // Fortran sparse matrix indexing
        //control.print_level = 1;
        // Start from 1.5
        real_wp_ x[] = {1.5,1.5,1.5};
        switch(d){
            case 1: // sparse co-ordinate storage
                st = 'C';
                arc_import( &control, &data, &status, n, "coordinate",
                           ne, H_row, H_col, NULL );
                while(true){ // reverse-communication loop
                    arc_solve_reverse_with_mat( &data, &status, &eval_status,
                                                n, x, f, g, ne, H_val, u, v );
                    if(status == 0){ // successful termination
                        break;
                    }else if(status < 0){ // error exit
                        break;
                    }else if(status == 2){ // evaluate f
                        eval_status = fun( n, x, &f, &userdata );
                    }else if(status == 3){ // evaluate g
                        eval_status = grad( n, x, g, &userdata );
                    }else if(status == 4){ // evaluate H
                        eval_status = hess( n, ne, x, H_val, &userdata );
                    }else if(status == 6){ // evaluate the product with P
                        eval_status = prec( n, x, u, v, &userdata );
                    }else{
                        printf(" the value %1i of status should not occur\n",
                          status);
                        break;
                    }
                }
                break;
            case 2: // sparse by rows
                st = 'R';
                arc_import( &control, &data, &status, n, "sparse_by_rows", ne,
                           NULL, H_col, H_ptr);
                while(true){ // reverse-communication loop
                    arc_solve_reverse_with_mat( &data, &status, &eval_status,
                                                n, x, f, g, ne, H_val, u, v );
                    if(status == 0){ // successful termination
                        break;
                    }else if(status < 0){ // error exit
                        break;
                    }else if(status == 2){ // evaluate f
                        eval_status = fun( n, x, &f, &userdata );
                    }else if(status == 3){ // evaluate g
                        eval_status = grad( n, x, g, &userdata );
                    }else if(status == 4){ // evaluate H
                        eval_status = hess( n, ne, x, H_val, &userdata );
                    }else if(status == 6){ // evaluate the product with P
                        eval_status = prec( n, x, u, v, &userdata );
                    }else{
                        printf(" the value %1i of status should not occur\n",
                          status);
                        break;
                    }
                }
                break;
            case 3: // dense
                st = 'D';
                arc_import( &control, &data, &status, n, "dense",
                           ne, NULL, NULL, NULL );
                while(true){ // reverse-communication loop
                    arc_solve_reverse_with_mat( &data, &status, &eval_status,
                                         n, x, f, g, n*(n+1)/2, H_dense, u, v );
                    if(status == 0){ // successful termination
                        break;
                    }else if(status < 0){ // error exit
                        break;
                    }else if(status == 2){ // evaluate f
                        eval_status = fun( n, x, &f, &userdata );
                    }else if(status == 3){ // evaluate g
                        eval_status = grad( n, x, g, &userdata );
                    }else if(status == 4){ // evaluate H
                        eval_status = hess_dense( n, n*(n+1)/2, x, H_dense,
                                                  &userdata );
                    }else if(status == 6){ // evaluate the product with P
                        eval_status = prec( n, x, u, v, &userdata );
                    }else{
```

```
                        printf(" the value %1i of status should not occur\n",
                          status);
                        break;
                    }
                }
                break;
            case 4: // diagonal
                st = 'I';
                arc_import( &control, &data, &status, n, "diagonal",
                           ne, NULL, NULL, NULL );
                while(true){ // reverse-communication loop
                    arc_solve_reverse_with_mat( &data, &status, &eval_status,
                                               n, x, f, g, n, H_diag, u, v );
                    if(status == 0){ // successful termination
                        break;
                    }else if(status < 0){ // error exit
                        break;
                    }else if(status == 2){ // evaluate f
                        eval_status = fun_diag( n, x, &f, &userdata );
                    }else if(status == 3){ // evaluate g
                        eval_status = grad_diag( n, x, g, &userdata );
                    }else if(status == 4){ // evaluate H
                        eval_status = hess_diag( n, n, x, H_diag, &userdata );
                    }else if(status == 6){ // evaluate the product with P
                        eval_status = prec( n, x, u, v, &userdata );
                    }else{
                        printf(" the value %1i of status should not occur\n",
                          status);
                        break;
                    }
                }
                break;
            case 5: // access by products
                st = 'P';
                arc_import( &control, &data, &status, n, "absent",
                           ne, NULL, NULL, NULL );
                while(true){ // reverse-communication loop
                    arc_solve_reverse_without_mat( &data, &status, &eval_status,
                                                  n, x, f, g, u, v );
                    if(status == 0){ // successful termination
                        break;
                    }else if(status < 0){ // error exit
                        break;
                    }else if(status == 2){ // evaluate f
                        eval_status = fun( n, x, &f, &userdata );
                    }else if(status == 3){ // evaluate g
                        eval_status = grad( n, x, g, &userdata );
                    }else if(status == 5){ // evaluate H
                        eval_status = hessprod( n, x, u, v, false, &userdata );
                    }else if(status == 6){ // evaluate the product with P
                        eval_status = prec( n, x, u, v, &userdata );
                    }else{
                        printf(" the value %1i of status should not occur\n",
                          status);
                        break;
                    }
                }
                break;
        }
        arc_information( &data, &inform, &status );
        if(inform.status == 0){
            printf("%c:%6i iterations. Optimal objective value = %5.2f status = %1i\n",
                   st, inform.iter, inform.obj, inform.status);
        }else{
            printf("%c: ARC_solve exit status = %1i\n", st, inform.status);
        }
        //printf("x: ");
        //for( int i = 0; i < n; i++) printf("%f ", x[i]);
        //printf("\n");
        //printf("gradient: ");
        //for( int i = 0; i < n; i++) printf("%f ", g[i]);
        //printf("\n");
        // Delete internal workspace
        arc_terminate( &data, &control, &inform );
    }
}
// Objective function
int fun( int n, const real_wp_ x[], real_wp_ *f, const void *userdata ){
    struct userdata_type *myuserdata = (struct userdata_type *) userdata;
    real_wp_ p = myuserdata->p;
    *f = pow(x[0] + x[2] + p, 2) + pow(x[1] + x[2], 2) + cos(x[0]);
    return 0;
}
// Gradient of the objective
int grad( int n, const real_wp_ x[], real_wp_ g[], const void *userdata ){
    struct userdata_type *myuserdata = (struct userdata_type *) userdata;
    real_wp_ p = myuserdata->p;
```

```
    g[0] = 2.0 * ( x[0] + x[2] + p ) - sin(x[0]);
    g[1] = 2.0 * ( x[1] + x[2] );
    g[2] = 2.0 * ( x[0] + x[2] + p ) + 2.0 * ( x[1] + x[2] );
    return 0;
}
// Hessian of the objective
int hess( int n, int ne, const real_wp_ x[], real_wp_ hval[],
         const void *userdata ){
    hval[0] = 2.0 - cos(x[0]);
    hval[1] = 2.0;
    hval[2] = 2.0;
    hval[3] = 2.0;
    hval[4] = 4.0;
    return 0;
}
// Dense Hessian
int hess_dense( int n, int ne, const real_wp_ x[], real_wp_ hval[],
                const void *userdata ){
    hval[0] = 2.0 - cos(x[0]);
    hval[1] = 0.0;
    hval[2] = 2.0;
    hval[3] = 2.0;
    hval[4] = 2.0;
    hval[5] = 4.0;
    return 0;
}
// Hessian-vector product
int hessprod( int n, const real_wp_ x[], real_wp_ u[], const real_wp_ v[],
              bool got_h, const void *userdata ){
    u[0] = u[0] + 2.0 * ( v[0] + v[2] ) - cos(x[0]) * v[0];
    u[1] = u[1] + 2.0 * ( v[1] + v[2] );
    u[2] = u[2] + 2.0 * ( v[0] + v[1] + 2.0 * v[2] );
    return 0;
}
// Apply preconditioner
int prec( int n, const real_wp_ x[], real_wp_ u[], const real_wp_ v[],
          const void *userdata ){
   u[0] = 0.5 * v[0];
   u[1] = 0.5 * v[1];
   u[2] = 0.25 * v[2];
   return 0;
}
 // Objective function
int fun_diag( int n, const real_wp_ x[], real_wp_ *f, const void *userdata ){
    struct userdata_type *myuserdata = (struct userdata_type *) userdata;
    real_wp_ p = myuserdata->p;
    *f = pow(x[2] + p, 2) + pow(x[1], 2) + cos(x[0]);
    return 0;
}
// Gradient of the objective
int grad_diag( int n, const real_wp_ x[], real_wp_ g[], const void *userdata ){
    struct userdata_type *myuserdata = (struct userdata_type *) userdata;
    real_wp_ p = myuserdata->p;
    g[0] = -sin(x[0]);
    g[1] = 2.0 * x[1];
    g[2] = 2.0 * ( x[2] + p );
    return 0;
}
// Hessian of the objective
int hess_diag( int n, int ne, const real_wp_ x[], real_wp_ hval[],
               const void *userdata ){
    hval[0] = -cos(x[0]);
    hval[1] = 2.0;
    hval[2] = 2.0;
    return 0;
}
// Hessian-vector product
int hessprod_diag( int n, const real_wp_ x[], real_wp_ u[], const real_wp_ v[],
                   bool got_h, const void *userdata ){
    u[0] = u[0] + - cos(x[0]) * v[0];
    u[1] = u[1] + 2.0 * v[1];
    u[2] = u[2] + 2.0 * v[2];
    return 0;
}
```