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# Hooking Your Solver to AMPL

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20001005: omit Table 5 and renumber tables; Table 4 gives
the ordering of nonlinear variables used since 19930630.

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*ABSTRACT*

This report tells how to make solvers work with AMPL's `solve` command. It describes an interface library, `amplsolver.a`, whose source is available from *netlib*. Examples include programs for listing LPs, automatic conversion to the LP dual (shell-script as solver), solvers for various nonlinear problems (with first and sometimes second derivatives computed by automatic differentiation), and getting C or Fortran 77 for nonlinear constraints, objectives and their first derivatives. Drivers for various well known linear, mixed-integer, and nonlinear solvers provide more examples.

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## 1. Introduction

The AMPL modeling system [5] lets you express constrained optimization problems in an algebraic notation close to conventional mathematics. AMPL's `solve` command causes AMPL to instantiate the current problem, send it to a solver, and attempt to read a solution computed by the solver (for use in subsequent commands, e.g., to print values computed from the solution). This technical report tells how to arrange for your own solver to work with AMPL's `solve` command. See the AMPL Web site at

```
http://www.ampl.com/ampl/
```

for much more information about AMPL, and see Appendix A for a summary of changes from earlier versions of this report.

### *Stub*`.nl` files

AMPL runs solvers as separate programs and communicates with them by writing and reading files. The files have names of the form *stub*.*suffix*; AMPL usually chooses the *stub* automatically, but one can specify the *stub* explicitly with AMPL's `write` command. Before invoking a solver, AMPL normally writes a file named *stub*`.nl`. This file contains a description of the problem to be solved. AMPL invokes the solver with two arguments, the *stub* and a string whose first five characters are `-AMPL`, and expects the solver to write a file named *stub*`.sol` containing a termination message and the solution it has found.

Most linear programming solvers are prepared to read so-called MPS files, which are described, e.g., in chapter 9 of [14]; see also the linear programming FAQ at

```
http://www.mcs.anl.gov/home/otc/Guide/faq/
```

AMPL can be provoked to write an MPS file, *stub*`.mps`, rather than *stub*`.nl`, but MPS files are slower to read and write, entail loss of accuracy (because of rounding to fit numbers into 12-column fields), and can only describe linear and mixed-integer problems (with some differences in interpretations among solvers for the latter). AMPL's *stub*`.nl` files, on the other hand, contain a complete and unambiguous problem description of both linear and nonlinear problems, and they introduce no new rounding errors.

In the following, we assume you are familiar with C and that your solver is callable from C or C++. If your solver is written in some other language, it is probably callable from C, though the details are likely to be system-dependent. If your solver is written in Fortran 77, you can make the details system-independent by running your Fortran source through the Fortran-to-C converter *f2c* [4]. For more information about *f2c*, including how to get Postscript for [4], send the electronic-mail message

```
send readme from f2c
```

to `netlib@research.bell-labs.com`, or read

```
ftp://netlib.bell-labs.com/netlib/f2c/readme.gz
```

*Netlib*'s AMPL/solver interface directory,

```
http://netlib.bell-labs.com/netlib/ampl/solvers/
```

which here is simply called `solvers`, contains some useful header files and source for a library, `amplsolver.a`, of routines for reading *stub*`.nl` and writing *stub*`.sol` files. Much of the rest of this report is about using routines in `amplsolver.a`.

Material for many of the examples discussed here is in `solvers/examples`; you will find it helpful to look at these files while reading this report. You can get both them and source for the `solvers` directory from *netlib*. For more details, send the electronic-mail message

```
send readme from ampl/solvers
```

to `netlib@research.bell-labs.com`, or see

```
ftp://netlib.bell-labs.com/netlib/ampl/solvers/readme.gz
```

As the above URLs suggest, this material is available by anonymous *ftp* and Web browser, as well as by E-mail. For *ftp* access, log in as `anonymous`, give your E-mail address as password, and look in `/netlib/ampl/solvers` and its subdirectories. The *ftp* files are all compressed, as discussed in

```
http://netlib.bell-labs.com/netlib/bib/compression.html
```

Be sure to copy compressed files in binary mode. Appending ‘‘.tar’’ to a directory name gives the name of a *tar* file containing the directory and its subdirectories, so you can get `ampl/solvers` and its subdirectories by changing to directory

```
ftp://netlib.bell-labs.com/netlib/ampl
```

and saying

```
binary
get solvers.tar
```

From a World Wide Web browser, give URL

```
http://netlib.bell-labs.com/netlib/ampl/
```

and click on ‘‘tar’’ in the line

• *lib* solvers (tar)

to get the same `solvers.tar` file.

In this report, we use ANSI/ISO C syntax and header files, but the interface source and header files are designed to allow use with C++ and K&R C compilers as well. (To activate the older syntax, compile with `-DKR_headers`, i.e., with `KR_headers #defined`.)

## 2. Linear Problems

### Row-wise treatment

For simplicity, we first consider linear programming (LP) problems. Solvers can view an LP as the problem of finding $x \in \mathbb{R}^n$ to

$$\begin{array}{rl} \text{minimize or maximize} & c^T x \\ \text{subject to} & b \le Ax \le d \\ \text{and} & \ell \le x \le u \end{array} \qquad \text{(LP)}$$

where $A \in \mathbb{R}^{m \times n}$, $b, d \in \mathbb{R}^m$, and $c, \ell, u \in \mathbb{R}^n$. Again for simplicity, the initial examples of reading linear problems simply print out the data ($A$, $b$, $c$, $d$, $\ell$, $u$) and perhaps the primal and dual initial guesses.

The first example, `solvers/examples/lin1.c`, just prints the data. (On a Unix system, type

```
make lin1
```

to compile and load it; `solvers/examples/makefile` has rules for making all of the examples in the `solvers/examples` directory. This directory also has some `makefile` variants for several PC compilers; see the comments in the `README` file and the first few lines of the `makefile.*` files.) File `lin1.c` starts with

```
#include "asl.h"
```

(i.e., `solvers/asl.h`; the phrase ‘‘asl’’ or ‘‘ASL’’ that appears in many names stands for *A*MPL/*S*olver interface *L*ibrary). In turn, `asl.h` includes various standard header files: `math.h`, `stdio.h`, `string.h`, `stdlib.h`, `setjmp.h`, and `errno.h`. Among other things, `asl.h` defines type `ASL` for a structure that holds various problem-specific data, and `asl.h` provides a long list of `#define`s to facilitate accessing items in an `ASL` when a pointer `asl` declared

```
ASL *asl;
```

is in scope. Among the components of an `ASL` are various pointers and such integers as the numbers of variables (`n_var`), constraints (`n_con`), and objectives (`n_obj`). Most higher-level interface routines have their prototypes in `asl.h`, and a few more appear in `getstub.h`, which is discussed later. Also defined in `asl.h` are the types `Long` (usually the name of a 32-bit integer type, which is usually `long` or `int`), `fint` (''Fortran integer'', normally a synonym for `Long`), `real` (normally a synonym for `double`), and `ftnlen` (also normally a synonym for `Long`, and used to convey string lengths to Fortran 77 routines that follow the *f2c* calling conventions).

The `main` routine in `lin1.c` expects to see one command-line argument: the *stub* of file *stub*`.nl` written by AMPL, as explained above. After checking that it has a command-line argument, the `main` routine allocates an `ASL` via

```
asl = ASL_alloc(ASL_read_f);
```

the argument to `ASL_alloc` determines how nonlinearities are handled and is discussed further below in the section headed ''Reading nonlinear problems''. The `main` routine appears to pass the *stub* to interface routine `jac0dim`, with prototype

```
FILE *jac0dim(char *stub, fint stub_len);
```

in reality, a `#define` in `asl.h` turns the call

```
jac0dim(stub, stublen)
```

into

```
jac0dim_ASL(asl, stub, stublen) .
```

There are analogous `#define`s in `asl.h` for most other high-level routines in `amplsolver.a`, but for simplicity, we henceforth just show the apparent prototypes (without leading `asl` arguments). This scheme makes code easier to read and preserves the usefulness of solver drivers written before the `_ASL` suffix was introduced.

For use with Fortran programs, `jac0dim` assumes `stub` is `stublen` characters long and is not null-terminated. After trimming any trailing blanks from `stub` (by allocating space for `ASL` field `filename`, i.e., `asl->i.filename_`, and copying `stub` there as the *stub*), `jac0dim` reads the first part of *stub*`.nl` and records some numbers in `*asl`, as summarized in Table 1. If *stub*`.nl` does not exist, `jac0dim` by default prints an error message and stops execution (but setting `return_nofile` to a nonzero value changes this behavior: see Table 2 below).

To read the rest of *stub*`.nl`, `lin1.c` invokes `f_read`. As discussed more fully below and shown in Table 6, several routines are available for reading *stub*`.nl`, one for each possible argument to `ASL_alloc`; `f_read` just reads linear problems, complaining and aborting execution if it sees any nonlinearities. `F_read` allocates memory as necessary by calling `Malloc`, which appears in most of our examples; `Malloc` calls `malloc` and aborts execution if `malloc` returns 0. (The reason for breaking the reading of *stub*`.nl` into two steps will be seen in more detail below: sometimes it is convenient to modify the behavior of the *stub*`.nl` reader — here `f_read` — by allocating problem-dependent arrays before calling it.)

AMPL may transmit several objectives. The linear part of each is contained in a list of `ograd` structures (declared in `asl.h`; note that `asl.h` declares

```
typedef struct ograd ograd;
```

and has similar `typedef`s for all the other structures it declares). `ASL` field `Ograd[`*i*`]` points to the head of a linked-list of `ograd` structures for objective $i + 1$, so the sequence

| Component | Meaning |
|---|---|
| `n_var` | number of variables (total) |
| `nbv` | number of binary variables |
| `niv` | number of other integer variables |
| `n_con` | number of constraints (total) |
| `n_obj` | number of objectives (total) |
| `nlo` | number of nonlinear objectives: they come before linear objectives |
| `nranges` | number of ranged constraints: $\lvert\{i \colon -\infty < b_i < d_i < \infty\}\rvert$ |
| `nlc` | number of nonlinear general constraints, including nonlinear network constraints |
| `nlnc` | number of nonlinear network constraints: they come after general nonlinear constraints and before any linear constraints |
| `nlvb`* | number of variables appearing nonlinearly in both constraints and objectives |
| `nlvbi`* | number of integer variables appearing nonlinearly in both constraints and objectives |
| `nlvc` | number of variables appearing nonlinearly in constraints |
| `nlvci`* | number of integer variables appearing nonlinearly just in constraints |
| `nlvo` | number of variables appearing nonlinearly in objectives |
| `nlvoi`* | number of integer variables appearing nonlinearly just in objectives |
| `lnc` | number of linear network constraints |
| `nzc` | number of nonzeros in the Jacobian matrix |
| `nzo` | number of nonzeros in objective gradients |
| `maxrownamelen` | length of longest constraint or objective name (0 if no *stub*`.row` file) |
| `maxcolnamelen` | length of longest variable name (0 if no *stub*`.col` file) |
| `n_conjac[0]` `n_conjac[1]` | Conval and Jacval operate on constraints *i* for `n_conjac[0]` ≤ *i* < `n_conjac[1]`, initially `n_conjac[0]` = 0 and `n_conjac[1]` = `n_con` (all constraints) |

**Table 1:** `ASL` *components set by* `jac0dim`.
∗ AMPL versions ≥ 19930630; otherwise `nlvb` = –1.

```
        c = (real *)Malloc(n_var*sizeof(real));
        for(i = 0; i < n_var; i++)
                c[i] = 0;
        if (n_obj)
                for(og = Ograd[0]; og; og = og->next)
                        c[og->varno] = og->coef;
```

allocates a scratch vector `c`, initializes it to zero, and (if there is at least one objective) stores the coefficients of the first objective in `c`. (The `varno` values in the `ograd` structure specify 0 for the first variable, 1 for the second, etc.)

Among the arrays allocated in `lin1.c`'s call on `f_read` are an array of alternating lower and upper variable bounds called `LUv` and an array of alternating lower and upper constraint bounds called `LUrhs`. For the present exercise, these arrays could have been declared to be arrays of

```
struct LU_bounds { real lower, upper; };
```

however, for the convenience discussed below of being able to request separate lower and upper bound arrays, both `LUv` and `LUrhs` have type `real*`. Thus the code

```
printf("\nVariable\tlower bound\tupper bound\tcost\n");
for(i = 0; i < n_var; i++)
        printf("%8ld\t%-8g\t%-8g\t%g\n", i+1,
                LUv[2*i], LUv[2*i+1], c[i]);
```

prints the lower and upper bounds on each variable, along with its cost coefficient in the first objective.

For `lin1.c`, the linear part of each constraint is conveyed in the same way as the linear part of the objective, but by a list of `cgrad` structures. These structures have one more field,

```
int goff;
```

than `ograd` structures, to allow a ‘‘columnwise’’ representation of the Jacobian matrix in nonlinear problems; the computation of Jacobian elements proceeds ‘‘row-wise’’. The final `for` loops of `lin1.c` present the *A* of (LP) row by row. The outer loop compares the constraint lower and upper bounds against `negInfinity` and `Infinity` (declared in `asl.h` and available after `ASL_alloc` has been called) to see if they are $-\infty$ or $+\infty$.

**Columnwise treatment**

Most LP solvers expect a ‘‘columnwise’’ representation of the constraint matrix *A* of (LP). By allocating some arrays (and setting pointers to them in the `ASL` structure), you can make the *stub*`.nl` reader give you such a representation, with subscripts optionally adjusted for the convenience of Fortran. The next examples illustrate this. Their source files are `lin2.c` and `lin3.c` in `solvers/examples`, and you can say

```
make lin2 lin3
```

to compile and link them.

The beginning of `lin2.c` differs from that of `lin1.c` in that `lin2.c` executes

```
A_vals = (real *)Malloc(nzc*sizeof(real));
```

before invoking `f_read`. When a *stub*`.nl` reader finds `A_vals` non-null, it allocates integer arrays `A_colstarts` and `A_rownos` and stores the linear part of the constraints columnwise as follows: `A_colstarts` is an array of column offsets, and linear coefficient `A_vals[`*i*`]` appears in row `A_rownos[`*i*`]`; the *i* values for column *j* satisfy `A_colstarts[`*j*`]` $\le i <$ `A_colstarts[`*j*+1`]` (in C notation). The column offsets and the row numbers start with the value `Fortran` (i.e., `asl->i.Fortran_`), which is 0 by default — the convenient value for use with C. For Fortran solvers, it is often convenient to set `Fortran` to 1 before invoking a *stub*`.nl` reader. This is illustrated in `lin3.c`, which also illustrates getting separate arrays of lower and upper bounds on the variables and constraints: if `LUv` and `Uvx` are not null, the *stub*`.nl` readers store the lower bound on the variables in `LUv` and the upper bounds in `Uvx`; similarly, if `LUrhs` and `Urhsx` are not null, the *stub*`.nl` readers store the constraint lower bounds in `LUrhs` and the constraint upper bounds in `Urhsx`. Table 2 summarizes these and other `ASL` components that you can optionally set.

**Optional `ASL` components**

Table 2 lists some `ASL` (i.e., `asl->i.`...`_`) components that you can optionally set and summarizes their effects.

**Example: *linrc*, a ‘‘solver’’ for row-wise printing**

It is easy to extend the above examples to show the variable and constraint names used in an AMPL model. When writing *stub*`.nl`, AMPL optionally stores these names in files *stub*`.col` and *stub*`.row`, as described in §A13.6 (page 333) of the AMPL book [5]. As an illustration, example file `linrc.c` is a

| Component | Type | Meaning |
|---|---|---|
| `return_nofile` | `int` | If nonzero, `jac0dim` returns 0 rather than halting execution if *stub*`.nl` does not exist. |
| `want_derivs` | `int` | If you want to compute nonlinear functions but will never compute derivatives, reduce overhead by setting `want_derivs = 0` (before calling `fg_read`). |
| `Fortran` | `int` | Adjustment to `A_colstarts` and `A_rownos`. |
| `LUv` | `real*` | Array of lower (and, if `UVx` is null, upper) bounds on variables. |
| `Uvx` | `real*` | Array of upper bounds on variables. |
| `LUrhs` | `real*` | Array of lower (and, if `Urhsx` is null, upper) constraint bounds. |
| `Urhsx` | `real*` | Array of upper bounds on constraints. |
| `X0` | `real*` | Primal initial guess: only retained if `X0` is not null. |
| `havex0` | `char*` | If not null, `havex0[`*i*`]` != 0 means `X0[`*i*`]` was specified (even if it is zero). |
| `pi0` | `real*` | Dual initial guess: only retained if `pi0` is not null. |
| `havepi0` | `char*` | If not null, `havepi0[`*i*`]` != 0 means `pi0[`*i*`]` was specified (even if it is zero). |
| `want_xpi0` | `int` | `want_xpi0 & 1 == 1` tells *stub*`.nl` readers to allocate `X0` if a primal initial guess is available; `want_xpi0 & 2 == 2` tells *stub*`.nl` readers to allocate `pi0` if a dual initial guess is available. |
| `A_vals` | `real*` | If not null, store linear Jacobian coefficients in `A_vals`, `A_rownos`, and `A_colstarts` rather than in lists of `cgrad` structures. |
| `A_rownos` | `int*` | Row numbers when `A_vals` is not null; allocated by *stub*`.nl` readers if necessary. |
| `A_colstarts` | `int*` | Column starts when `A_vals` is not null; allocated by *stub*`.nl` readers if necessary. |
| `err_jmp` | `Jmp_buf*` | If not null and an error occurs during nonlinear expression evaluation, `longjmp` here (without printing an error message). |
| `err_jmp1` | `Jmp_buf*` | If not null and an error occurs during nonlinear expression evaluation, `longjmp` here after printing an error message. |
| `obj_no` | `fint` | Objective number for `writesol()` and `qpcheck()`: 0 = first objective, −1 = no objective, i.e., just find a feasible point. |

**Table 2:** *Optionally settable* `ASL` *components.*

variant of `lin1.c` that shows these names if they are available — and tells how to get them if they are not. Among other embellishments, `linrc.c` uses the value of environment variable `display_width` to decide when to break lines. (By the way, `$display_width` denotes this value, and other environment-variable values are denoted analogously.) Say

```
make linrc
```

to create a `linrc` program based on `linrc.c`, and say

```
linrc '-?'
```

to see a summary of its usage. It can be used stand-alone, or as the ‘‘solver’’ in an AMPL session:

```
ampl: option solver linrc, linrc_auxfiles rc; solve;
```

will send a listing of the linear part of the current problem to the screen, and

```
        ampl: solve >foo;
```

will send it to file `foo`. Thus `linrc` can act much like AMPL's `expand` and `solexpand` commands. See

```
        http://www.ampl.com/ampl/NEW/examine.html
```

for more details on these commands. They are among the commands introduced after publication of the AMPL book.

**Affine objectives: linear plus a constant**

Adding a constant to a linear objective makes the problem no harder to solve. (The constant may be stated explicitly in the original model formulation, or may arise when AMPL's *presolve* phase deduces the values of some variables and removes them from the problem that the solver sees.) For algorithmic purposes, the solver can ignore the constant, but it should take the constant into account when reporting objective values. Some solvers, such as MINOS, make explicit provision for adding a constant to an otherwise linear objective. For other solvers, such as CPLEX® and OSL, we must resort to introducing a new variable that is either fixed by its bounds (CPLEX) or by a new constraint (OSL). Function `objconst`, with apparent signature

```
        real objconst(int objno)
```

returns the constant term for objective `objno` (with $0 \le$ `objno < n_obj`). See the printing of the ''Objective adjustment'' in `solvers/examples/linrc.c` for an example of invoking `objconst`.

**Example: shell script as solver for the dual LP**

Sometimes it is convenient for the solver AMPL invokes to be a shell script that runs several programs, e.g., to transform *stub*`.nl` to the form the underlying solver expects and to create the *stub*`.sol` that AMPL expects. As an illustration, `solvers/examples` contains a shell script called `dminos` that arranges for `minos` to solve the dual of an LP. Why is this interesting? Well, sometimes the dual of an LP is much easier to solve than the original (''primal'') LP. Because of this, several of the LP solvers whose interface source appears in subdirectories of `ampl/solvers`, such as `cplex` and `osl`, have provision for solving the dual LP. (This is not to be confused with using the dual simplex algorithm, which might be applied to either the primal or the dual problem.) Because `minos` is meant primarily for solving nonlinear problems (whose duals are more elaborate than the dual of an LP), `minos` currently lacks provision for solving dual LPs directly. At the cost of some extra overhead (over converting an LP to its dual within `minos`) and loss of flexibility (of deciding whether to solve the primal or the dual LP after looking at the problem), the `dminos` shell script provides an easy way to see how `minos` would behave on the dual of an LP. And one can use `dminos` to feed dual LPs to other LP solvers that understand *stub*`.nl` files: it's just a matter of setting the shell variable `$dsolver` (which is discussed below).

The `dminos` shell script relies on a program called `dualconv` whose source, `dualconv.c`, also appears in `solvers/examples`. `Dualconv` reads the *stub*`.nl` for an LP and writes a *stub*`.nl` (or *stub*`.mps`) for the dual of the LP. `Dualconv` also writes a *stub*`.duw` file that it can use in a subsequent invocation to translate the *stub*`.sol` file from solving the dual LP into the primal *stub*`.sol` that AMPL expects. Thus `dualconv` is really two programs packaged, for convenience, as one. (Type

```
        make dualconv
```

to create `dualconv` and then

```
        dualconv '-?'
```

for more detail on its invocation than we discuss below.)

Here is a simplified version of the `dminos` shell script (for Unix systems):

```
#!/bin/sh
dualconv $1
minos $1 -AMPL
dualconv -u $1
rm $1.duw
```

This simplified script and the fancier version shown below use Bourne shell syntax. In this syntax, `$1` is the script's first argument, which should be the *stub*. Thus

```
dualconv $1
```

passes the *stub* to `dualconv`, which overwrites *stub*`.nl` with a description of the dual LP (or complains, as discussed below). If all goes well,

```
minos $1 -AMPL
```

will cause `minos` to write *stub*`.sol`, and

```
dualconv -u $1
```

will overwrite *stub*`.sol` with the form that AMPL expects. Finally,

```
rm $1.duw
```

cleans up: in the usual case where AMPL chooses the *stub*, AMPL removes the intermediate files about which it knows (e.g., *stub*`.nl` and *stub*`.sol`), but AMPL does not know about *stub*`.duw`.

The simplified `dminos` script above does not clean up properly if it is interrupted, e.g., if you turn off your terminal while it is running. Here is the more robust `solvers/examples/dminos`:

```
#!/bin/sh
# Script that uses dualconv to feed a dual LP problem to $dsolver
dsolver=${dsolver-minos}
trap "rm -f $1.duw" 1 2 3 4 13
dualconv $1
case $? in 0)
        $dsolver $1 -AMPL
        case $? in 0) dualconv -u $1;; esac
        ;; esac
rc=$?
rm -f $1.duw
exit $rc
```

It starts by determining the name of the underlying solver to invoke:

```
dsolver=${dsolver-minos}
```

is an idiom of the Bourne shell that checks whether `$dsolver` is null; if so, it sets `$dsolver` to `minos`. The line

```
trap "rm -f $1.duw" 1 2 3 4 13
```

arranges for automatic cleanup in the event of various signals. The next line

```
dualconv $1
```

works as before. If all goes well, `dualconv` gives a zero exit code; but if `dualconv` cannot overwrite *stub*`.nl` with a description of the dual LP (e.g., because *stub*`.nl` does not represent an LP), `dualconv` complains and gives return code 1. The next line

```
case $? in 0)
```

checks the return code; only if it is 0 is `$dsolver` invoked. If the latter is happy (i.e., gives zero return code), the line

```
                case $? in 0) dualconv -u $1;; esac
```

adjusts *stub*`.sol` appropriately. In any event,

```
        rc=$?
```

saves the current return code (i.e., `$?` is the return code from the most recently executed program), since the following clean-up line

```
        rm -f $1.duw
```

will change `$?`. Finally,

```
        exit $rc
```

uses the saved return code as `dminos`'s return code. This is important, as AMPL only tries to read *stub*`.sol` if the solver gives a 0 return code.

To write *stub*`.sol` files, `dualconv` calls `write_sol`, which appears in most of the subsequent examples and is documented below in the section on ''Writing the *stub*`.sol` file''.

## 3. Integer and Nonlinear Problems

### Ordering of integer variables and constraints

When writing *stub*`.nl`, AMPL orders the variables as shown in Tables 3 and 4 and the constraints as shown in Table 5. These tables also give expressions for how many entities are in each category. Table 4 applies to AMPL versions ≥ 19930630; `nlvb` = −1 signifies earlier versions. For all versions, the first `nlvc` variables appear nonlinearly in at least one constraint. If `nlvo` > `nlvc`, the first `nlvc` variables may or may not appear nonlinearly in an objective, but the next `nlvo` − `nlvc` variables do appear nonlinearly in at least one objective. Otherwise all of the first `nlvo` variables appear nonlinearly in an objective. ''Linear arcs'' are linear variables declared with an `arc` declaration in the AMPL model, and ''nonlinear network'' constraints are nonlinear constraints introduced with a `node` declaration.

| Category | Count |
|---|---|
| nonlinear | max(`nlvc`, `nlvo`); see Table 4. |
| linear arcs | `nwv` |
| other linear | `n_var` − (max {`nlvc`, `nlvo`} + `niv` + `nbv` + `nwv`) |
| binary | `nbv` |
| other integer | `niv` |

**Table 3:** *Ordering of Variables.*

| Smoothness | Appearance | Count |
|---|---|---|
| continuous | in an objective and in a constraint | `nlvb − nlvbi` |
| integer | in an objective and in a constraint | `nlvbi` |
| continuous | just in constraints | `nlvc − (nlvb + nlvci)` |
| integer | just in constraints | `nlvci` |
| continuous | just in objectives | `nlvo − (nlvc + nlvoi)` |
| integer | just in objectives | `nlvoi` |

**Table 4:** *Ordering of Nonlinear Variables.*

| Category | Count |
|---|---|
| nonlinear general | `nlc` – `nlnc` |
| nonlinear network | `nlnc` |
| linear network | `lnc` |
| linear general | `n_con` – (`nlc` + `lnc`) |

**Table 5:** *Ordering of Constraints.*

**Priorities for integer variables**

Some integer programming solvers let you assign branch priorities to the variables. Interface routine `mip_pri` provides a simple way to get branch priorities from `$mip_priorities`. It complains if *stub*`.col` is not available. Otherwise, it looks in `$mip_priorities` for variable names followed by integer priorities (separated by white space). See the comments in `solvers/mip_pri.c` for more details. For examples, see `solvers/cplex/cplex.c` and `solvers/osl/osl.c`.

**Reading nonlinear problems**

It is convenient to build data structures for computing derivatives while reading a *stub*`.nl` file, and `amplsolver.a` provides several ways of doing this, to suit the needs of various solvers. Table 6 summarizes the available *stub*`.nl` readers and the kinds of nonlinear information they make available. They are to be used with `ASL_alloc` invocations of the form

```
asl = ASL_alloc(ASLtype);
```

Table 6's *ASLtype* column indicates the argument to supply for *ASLtype*. (This argument affects the size of the allocated `ASL` structure. Though we could easily arrange for a single routine to call the reader of the appropriate *ASLtype*, on some systems this would cause many otherwise unused routines from `amplsolver.a` to be linked with the solver. Explicitly calling the relevant reader avoids this problem.)

| reader | *ASLtype* | nonlinear information |
|---|---|---|
| `f_read` | `ASL_read_f` | no derivatives: linear objectives and constraints only |
| `fg_read` | `ASL_read_fg` | first derivatives |
| `fgh_read` | `ASL_read_fgh` | first derivatives and Hessian-vector products |
| `pfg_read` | `ASL_read_pfg` | first derivatives and partially separable structure |
| `pfgh_read` | `ASL_read_pfgh` | first and second derivatives and partially separable structure |

**Table 6:** *stub*`.nl` *readers.*

All these readers have apparent signature

```
int reader(FILE *nl, int flags);
```

they return 0 if all goes well. The bits in the `flags` argument are described by `enum ASL_reader_flag_bits` in `asl.h`; most of them pertain only to reading partially separable problems, which are discussed later, but one bit, `ASL_return_read_err`, is relevant to all the readers: it governs their behavior if they detect an error. If this bit is 0, the readers print an error message and abort execution; otherwise they return one of the nonzero values in `enum ASL_reader_error_codes`. See `asl.h` for details.

**Evaluating nonlinear functions**

Specific evaluation routines are associated with each *stub*`.nl` reader. For simplicity, the readers supply pointers to the specific routines in the `ASL` structure, and `asl.h` provides macros to simplify calling the specific routines. The macros provide the following apparent signatures and functionality; many of them appear in the examples that follow. Reader `pfg_read` is mainly for debugging and does not provide any evaluation routines; it is used in solver ‘‘`v8`’’, discussed below. Reader `fgh_read` is mainly for debugging of Hessian-vector products, but does provide all of the routines described below except for the full Hessian computations (which would have to be done with `n_var` Hessian-vector products). Reader `pfgh_read` generally provides more efficient Hessian computations and provides the full complement of evaluation routines. If you invoke an ‘‘unavailable’’ routine, an error message is printed and execution is aborted.

Many of the evaluation routines have final argument `nerror` of type `fint*`. This argument controls what happens if the routine detects an error. If `nerror` is null or points to a negative value, an error message is printed and, unless `err_jmp1` (i.e., `asl->i.err_jmp1_`) is nonzero, execution is aborted. (You can set `err_jmp1` much the same way that `obj1val_ASL` and `obj1grd_ASL` in file `objval.c` set `err_jmp` to gain control after the error message is printed.) If `nerror` points to a nonnegative value, `*nerror` is set to 0 if no error occurs and to a positive value otherwise.

```
    real objval(int nobj, real *X, fint *nerror)
```

returns the value of objective `nobj` (with $0 \le$ `nobj` $<$ `n_obj`) at the point `X`.

```
    void objgrd(int nobj, real *X, real *G, fint *nerror)
```

computes the gradient of objective `nobj` and stores it in `G[`$i$`]`, $0 \le i <$ `n_var`.

```
    void conval(real *X, real *R, fint *nerror)
```

evaluates the *bodies* of constraints at point `X` and stores them in `R`. Recall that AMPL puts constraints into the canonical form

$$\textit{left-hand side} \le \textit{body} \le \textit{right-hand side},$$

with left- and right-hand sides contained in the `LUrhs` and perhaps `Urhsx` arrays, as explained above in the section on ‘‘Row-wise treatment’’. `Conval` operates on constraints $i$ with

$$\texttt{n\_conjac[0]} \le i < \texttt{n\_conjac[1]}$$

(i.e., all constraints, unless you adjust the `n_conjac` values) and stores the body of constraint $i$ in `R[`$i$`–n_conjac[0]]`, i.e., it stores the first constraint body it evaluates in `R[0]`.

```
    void jacval(real *X, real *J, fint *nerror)
```

computes the Jacobian matrix of the constraints evaluated by `conval` and stores it in `J`, at the `goff` offsets in the `cgrad` structures discussed above. In other words, there is one `goff` value for each nonzero in the Jacobian matrix, and the `goff` values determine where in `J` the nonzeros get stored. The *stub*`.nl` readers compute `goff` values so a Fortran program will see Jacobian matrices stored columnwise, but you can adjust the `goff` fields to make other arrangements.

```
    real conival(int ncon, real *X, fint *nerror)
```

evaluates and returns the body of constraint `ncon` (with $0 \le$ `ncon` $<$ `n_con`).

```
    void congrd(int ncon, real *X, real *G, fint *nerror)
```

computes the gradient of constraint `ncon` and stores it in `G`. By default, `congrd` sets `G[`$i$`]`, $0 \le i <$ `n_var`, but if you set `asl->i.congrd_mode` = 1, it will just store the partials that are not identically 0 consecutively in `G`, and if you set `asl->i.congrd_mode` = 2, it will store them at the `goff` offsets of the `cgrad` structures for this constraint.

```
    void hvcomp(real *HV, real *P, int nobj, real *OW, real *Y)
```

stores in `HV` (a full vector of length `n_var`) the Hessian of the Lagrangian times vector `P`. In other words, `hvcomp` computes

$$\texttt{HV} = W \cdot \texttt{P},$$

where $W$ is the Lagrangian Hessian,

$$W = \nabla^2 \left[ \sum_{i=0}^{\texttt{n\_obj}-1} \texttt{OW}[i] f_i + \sigma \sum_{i=0}^{\texttt{n\_con}-1} \texttt{Y}[i] c_i \right], \qquad (*)$$

in which $f_i$ and $c_i$ denote objective function $i$ and constraint $i$, respectively, and $\sigma$ is an extra scaling factor (most commonly $+1$ or $-1$) that is $+1$ unless specified otherwise by a previous call on `lagscale` (see below). If $0 \le$ `nobj` $<$ `n_obj`, `hvcomp` behaves as though `OW` were a vector of all zeros, except for `OW[nobj]` = 1; otherwise, if `OW` is null, `hvcomp` behaves as though it were a vector of all zeros; and if `Y` is null, `hvcomp` behaves as though `Y` were a vector of zeros. *W* is evaluated at the point where the objective(s) and constraints were most recently computed (by calls on `objval` or `objgrd`, and on `conval`, `conival`, `jacval`, or `congrd`, in any convenient order). Normally one computes gradients before dealing with *W*, and if necessary, the gradient computing routines first recompute the objective(s) and constraints at the point specified in their argument lists. The Hessian computations use partial derivatives stored during the objective and constraint evaluations.

```
    void duthes(real *H, int nobj, real *OW, real *Y)
```

evaluates and stores in `H` the *d*ense *u*pper *t*riangle of the *Hes*sian of the Lagrangian function *W*. Here and below, arguments `nobj`, `OW` and `Y` have the same meaning as in `hvcomp`, so `duthes` stores the upper triangle by columns in `H`, in the sequence

$$W_{0,0} \quad W_{0,1} \quad W_{1,1} \quad W_{0,2} \quad W_{1,2} \quad W_{2,2} \quad \cdots$$

of length `n_var*(n_var+1)/2` (with 0-based subscripts for *W*).

```
    void fullhes(real *H, fint LH, int nobj, real *OW, real *Y)
```

computes the *W* of (∗) and stores it in `H` as a Fortran 77 matrix declared

```
    integer LH
    double precision H(LH,*)
```

In C notation, `fullhes` sets

$$\mathtt{H}[i + j \cdot \mathtt{LH}] = W_{i,j}$$

for $0 \le i <$ `n_var` and $0 \le j <$ `n_var`. Both `duthes` and `fullhes` compute the same numbers; `fullhes` first computes the Hessian's upper triangle, then copies it to the lower triangle, so the result is symmetric.

```
    fint sphsetup(int nobj, int ow, int y, int uptri)
```

returns the number of nonzeros in the *sp*arse *H*essian *W* of the Lagrangian (∗) (if `uptri` = 0) or its upper triangle (if `uptri` = 1), and stores in fields `sputinfo->hrownos` and `sputinfo->hcolstarts` a description of the sparsity of *W*, as discussed below with `sphes`. For `sphes`'s computation, which determines the components of *W* that could be nonzero, arguments `ow` and `y` indicate whether `OW` and `Y`, respectively, will be zero or nonzero in subsequent calls on `sphes`. In analogy with `hvcomp`, `duthes`, `fullhes` and `sphes`, if $0 \le$ `nobj` $<$ `n_obj`, then `nobj` takes precedence over `ow`.

```
    void sphes(real *H, int nobj, real *OW, real *Y)
```

computes the *W* given by (∗) and stores it or its sparse upper triangle in `H`; `sphsetup` must have been called previously with arguments `nobj`, `ow` and `y` of the same sparsity (zero/nonzero structure), i.e., with the same `nobj,` with `ow` nonzero if ever `OW` will be nonzero, and with `y` nonzero if ever `Y` will be nonzero. Argument `uptri` to `sphsetup` determines whether `sphes` computes *W*'s upper triangle (`uptri` = 1) or all of *W* (`uptri` = 0); in the latter case, the computation proceeds by first computing the upper triangle, then copying it to the lower triangle, so the result is guaranteed to be symmetric. Fields `sputinfo->hrownos` and `sputinfo->hcolstarts` are pointers to arrays that describe the sparsity of *W* in the usual columnwise way:

$$\mathtt{H}[j] = W_{i,\mathtt{rownows}[j]}$$

for $0 \le i < n\_var$ and $\mathtt{hcolstarts}[i] \le j < \mathtt{hcolstarts}[i+1]$. Before returning, `sphsetup` adds the `ASL` value `Fortran` to the values in the `hrownos` and `hcolstarts` arrays. The row numbers in `hrownos` for each column are in ascending order.

```
    void xknown(real *X)
```

indicates that this X will be provided to the function and gradient computing routines in subsequent calls until either another xknown invocation makes a new X known, or xunknown() is executed. The latter, with apparent signature

```
void xunknown(void)
```

reinstates the default behavior of checking the X arguments against the previous value to see whether common expressions (or, for gradients, the corresponding functions) need to be recomputed. Appropriately calling xknown and xunknown can reduce the overhead in some computations.

```
void conscale(int i, real s, fint *nerror)
```

scales function body i by s, initial dual value pi0[i] by 1/s, and the lower and upper bounds on constraint i by s, interchanging these bounds if s < 0. This only affects the pi0, LUrhs and Urhsx arrays and the results computed by conval, jacval, conival, congrd, duthes, fullhes, sphes, and hvcomp. The write_sol routine described below takes calls on conscale into account.

```
void lagscale(real sigma, fint *nerror)
```

specifies the extra scaling factor $\sigma$ := sigma in the formula ($*$) for the Lagrangian Hessian.

```
void varscale(int i, real s, fint *nerror)
```

scales variable i, its initial value X0[i] and its lower and upper bounds by 1/s, and it interchanges these bounds if s < 0. Thus varscale effectively scales the partial derivative of variable i by s. This only affects the nonlinear evaluation routines and the arrays X0, LUv and Uvx. The write_sol routine described below accounts for calls on varscale.

**Example: nonlinear minimization subject to simple bounds**

Our first nonlinear example ignores any constraints other than bounds on the variables and assumes there is one objective to be minimized. This example involves the PORT solver dmngb, which amounts to subroutine SUMSL of [6] with added logic for bounds on the variables (as described in [7]). If need be, you can get (Fortran 77) source for dmngb by asking *netlib* to

```
send dmngb from port
```

(It is best to use an E-mail request, as this brings subroutine dmngb and all the routines that it calls, directly or indirectly.) Source for this example is solvers/examples/mng1.c.

Most of mng1.c is specific to dmngb. For example, dmngb expects subroutine parameters calcf and calcg for evaluating the objective function and its gradient. Interface routines objval and objgrd actually evaluate the objective and its gradient; the calcf and calcg defined in mng1.c simply adjust the calling sequences appropriately. The calling sequences for objval and objgrd were shown above.

Since dmngb is prepared to deal with evaluation errors (which it learns about when argument *NF to calcf and calcg is set to 0), calcf and calcg pass a pointer to 0 for nerror.

The main routine in mng1.c is called MAIN__ rather than main because it is meant to be used with an *f2c*-compatible Fortran library. (A C main appears in this Fortran library and arranges to catch certain signals and flush buffers. The main makes its arguments argc and argv available in the external cells xargc and xargv.)

Recall that when AMPL invokes a solver, it passes two arguments: the *stub* and an argument that starts with -AMPL. Thus mng1.c gets the *stub* from the first command-line argument. Before passing it to jac0dim, mng1.c calls ASL_alloc(ASL_read_fg) to make an ASL structure available. ASL_alloc stores its return value in the global cell cur_ASL. Since mng1.c starts with

```
#include "asl.h"
#define asl cur_ASL
```

the value returned by ASL_alloc is visible throughout mng1.c as ‘‘asl’’. This saves the hassle of making asl visible to calcf and calcg by some other means.

The invocation of dmngb directly accesses two ASL pointers: X0 and LUv (i.e., asl->i.X0_ and asl->i.LUv_). X0 contains the initial guess (if any) specified in the AMPL model, and LUv is an array of lower and upper bounds on the variables. Before calling fg_read to read the rest of *stub*.nl, mng1.c asks fg_read to save X0 (if an initial guess is provided in the AMPL model or data, and otherwise to initialize X0 to zeros) by executing

```
X0 = (real *)Malloc(n_var*sizeof(real));
```

After invoking dmngb, mng1.c writes a termination message into the scratch array buf and passes it, along with the computed solution, to interface routine write_sol, discussed later, which writes the termination message and solution to file *stub*.sol in the form that AMPL expects to read them.

The use of Cextern in the declaration

```
typedef void (*U_fp)(void);
Cextern int dmngb_(fint *n, real *d, real *x, real *b,
            U_fp calcf, U_fp calcg,
            fint *iv, fint *liv, fint *lv, real *v,
            fint *uiparm, real *urparm, U_fp ufparm);
```

at the start of mng1.c permits compiling this example with either a C or a C++ compiler; Cextern is #defined in asl.h.

**Example: nonlinear least squares subject to simple bounds**

The previous example dealt only with a nonlinear objective and bounds on the variables. The next example deals only with nonlinear equality constraints and bounds on the variables. It minimizes an implicit objective: the sum of squares of the errors in the constraints. The underlying solver, dn2gb, again comes from the PORT subroutine library; it is a variant of the unconstrained nonlinear least-squares solver NL2SOL [2, 3] that enforces simple bound constraints on the variables. If need be, you can get (Fortran) source for dn2gb by asking *netlib* to

```
send dn2gb from port
```

Source for this example is solvers/examples/nl21.c. Much like mng1.c, it starts with

```
#include "asl.h"
#define asl cur_ASL
```

followed by declarations for the definitions of two interface routines: calcr computes the residual vector (vector of errors in the equations), and calcj computes the corresponding Jacobian matrix (of first partial derivatives). Again these are just wrappers that invoke amplsolver.a routines described above, conval and jacval. Parameter NF to calcr and calcj works the same way as in the calcf and calcg of mng1.c. Recall again that AMPL puts constraints into the canonical form

$$\textit{left-hand side} \le \textit{body} \le \textit{right-hand side}.$$

Subroutine calcr calls conval to have a vector of n_con *body* values stored in array R. The MAIN__ routine in nl21.c makes sure the left- and right-hand sides are equal, and passes the vector LUrhs of left- and right-hand side pairs as parameter UR to dn2gb, which passes them unchanged as parameter UR to calcr. (Of course, calcr could also access LUrhs directly.) Thus the loop

```
for(Re = R + *N; R < Re; UR += 2)
        *R++ -= *UR;
```

in calcr converts the constraint body values into the vector of residuals.

MAIN__ invokes the interface routine dense_j() to tell jacval that it wants a dense Jacobian matrix, i.e., a full matrix with explicit zeros for partial derivatives that are always zero. If necessary, dense_j adjusts the goff components of the cgrad structures and tells jacval to zero its J array before computing derivatives.

## Partially separable structure

Many optimization problems involve a *partially separable* objective function, one that has the form

$$f(x) \;=\; \sum_{i=1}^{q} f_i(U_i x),$$

in which $U_i$ is an $m_i \times n$ matrix with a small number $m_i$ of rows [11, 12]. Partially separable structure is of interest because it permits better Hessian approximations or more efficient Hessian computations. Many partially separable problems exhibit a more detailed structure, which the authors of LANCELOT [1] call ‘‘group partially separable structure’’:

$$f(x) \;=\; \sum_{i=1}^{q} \theta_i \Bigl( \sum_{j=1}^{r_i} f_{ij}(U_{ij} x) \Bigr),$$

where $\theta_i : \mathbb{R} \to \mathbb{R}$ is a unary operator. Using techniques described in [10], the *stub*`.nl` readers `pfg_read` and `pfgh_read` discern this latter structure automatically, and the Hessian computations that `pfgh_read` makes available exploit it. Some solvers, such as LANCELOT and VE08 [17], want to see partially separable structure. Driving such solvers involves a fair amount of solver-specific coding. Directory `solvers/examples` has drivers for two variants of VE08: `ve08` ignores whereas `v8` exploits partially separable structure, using reader `pfg_read`. Directory `solvers/lancelot` contains source for `lancelot`, a solver based on LANCELOT that uses reader `pfgh_read`.

## Fortran variants

Fortran variants `fmng1.f` and `fnl21.f` of `mng1.c` and `nl21.c` appear in `solvers/examples`; the `makefile` has rules to make programs `fmng1` and `fnl21` from them. Both invoke interface routines `jacdim_` and `jacinc_`. The former allocates an `ASL` structure (with `ASL_alloc(ASL_read_fg)`) and reads a *stub*`.nl` file with `fg_read`, and the latter provides arrays of lower and upper constraint bounds, the initial guess, the Jacobian incidence matrix (which neither example uses), and (in the last variable passed to `jacinc_`) the value `Infinity` that represents $\infty$. These routines have Fortran signatures

```
subroutine jacdim(stub, M, N,  NO, NZ, MXROW, MXCOL)
character*(*) stub
integer M, N, NO, NZ, MXROW, MXCOL

subroutine jacinc(M, N, NZ, JP, JI, X, L, U, Lrhs, Urhs, Inf)
integer M, N, NZ, JP
integer*2 JI
double precision X(N), L(N), U(N), Lrhs(M), Urhs(M), Inf
```

`Jacdim_` sets its arguments as shown in Table 7. The values `MXROW` and `MXCOL` are unlikely to be of much interest; `MXROW` is 0 unless AMPL wrote *stub*`.row` (a file of constraint and objective names), in which case `MXROW` is the length of the longest name in *stub*`.row`. Similarly, `MXCOL` is 0 unless AMPL wrote *stub*`.col`, in which case `MXROW` is the length of the longest variable name in *stub*`.col`.

| | | | | |
|---|---|---|---|---|
| `*M` | = | `n_con` | = | number of constraints |
| `*N` | = | `n_var` | = | number of variables |
| `*NO` | = | `n_obj` | = | number of objectives |
| `*NZ` | = | `ncz` | = | number of Jacobian nonzeros |
| `*MXROW` | = | `maxrownamelen` | = | length of longest constraint name |
| `*MXCOL` | = | `maxcolnamelen` | = | length of longest variable name |

**Table 7:** *Assignments made by* `jacdim_`.

The Fortran examples call Fortran variants of some of the nonlinear evaluation routines. Table 8 summarizes the currently available Fortran variants; others (e.g., for evaluating Hessian information) could be made available easily if demand were to warrant them. In Table 8, Fortran notation appears under

‘‘Fortran variant’’; the corresponding C routines have an underscore appended to their names and are declared in `asl.h`. The Fortran routines shown in Table 8 operate on the `ASL` structure at which `cur_ASL` points. Thus, without help from a C routine to adjust `cur_ASL`, they only deal with one problem at a time. After solving a problem and executing

```
call delprb
```

a Fortran code could call `jacdim` and `jacinc` again to start processing another problem.

| Routine | Fortran variant |
|---|---|
| `congrd` | `congrd(N, I, X, G, NERROR)` |
| `conival` | `cnival(N, I, X, NERROR)` |
| `conval` | `conval(M, N, X, R, NERROR)` |
| `dense_j` | `densej()` |
| `hvcomp` | `hvcomp(HV, P, NOBJ, OW, Y)` |
| `jacval` | `jacval(M, N, NZ, X, J, NERROR)` |
| `objgrd` | `objgrd(N, X, NOBJ, G, NERROR)` |
| `objval` | `objval(N, X, NOBJ, NERROR)` |
| `writesol` | `wrtsol(MSG, NLINES, X, Y)` |
| `xknown` | `xknown(X)` |
| `xunkno` | `xunkno()` |
| `delprb_` | `delprb()` |

| Argument | Type | Description |
|---|---|---|
| `N` | `integer` | number of variables (`n_var`) |
| `M` | `integer` | number of constraints (`n_con`) |
| `NZ` | `integer` | number of Jacobian nonzeros (`nzc`) |
| `NERROR` | `integer` | if ≥ 0, set NERROR to 0 if all goes well and to a positive value if the evaluation fails |
| `I` | `integer` | which constraint |
| `NOBJ` | `integer` | which objective |
| `NLINES` | `integer` | lines in `MSG` |
| `MSG` | `character*(*)` | solution message, dimension(`NLINES`) |
| `X` | `double precision` | incoming vector of variables |
| `G` | `double precision` | result gradient vector |
| `J` | `double precisoin` | result Jacobian matrix |
| `OW` | `double precision` | objective weights |
| `Y` | `double precision` | dual variables |
| `P` | `double precision` | vector to be multiplied by Hessian |
| `HV` | `double precision` | result of Hessian times P |

**Table 8:** *Fortran variants.*

## Nonlinear test problems

Some nonlinear AMPL models appear in directory

```
http://netlib.bell-labs.com/netlib/ampl/models/nlmodels/
```

The *tar* version of this directory is

```
ftp://netlib.bell-labs.com/netlib/ampl/models/nlmodels.tar
```

## 4. Advanced Interface Topics

### Writing the *stub*.sol file

Interface routine write_sol returns the computed solution and a termination message to AMPL. This routine has apparent prototype

```
void write_sol(char *msg, real *x, real *y, Option_Info *oi);
```

The first argument is for the (null-terminated) termination message. It should not contain any empty embedded lines (though, e.g., " \n", i.e., a line consisting of a single blank, is fine) and may end with an arbitrary number of newline characters (including none, as in mng1.c). The second and third arguments, x and y, are pointers to arrays of primal and dual variable values to be passed back to AMPL. Either or both may be null (as is y in mng1.c), which causes no corresponding values to be passed. Normally it is helpful to return the best approximate solution found, but for some errors (such as trouble detected before the solution algorithm can be started) it may be appropriate for both x and y to be null. The fourth argument points to an optional Option_Info structure, which is discussed below in the section on ‘‘Conveying solver options’’.

### Locating evaluation errors

If the routines in amplsolver.a detect an error during evaluation of a nonlinear expression, they look to see if *stub*.row (or, if evaluation of a ‘‘defined variable’’ was in progress, *stub*.fix) is available. If so, they use it to report the name of the constraint, objective, or defined variable that they were trying to evaluate. Otherwise they simply report the number of the constraint, objective, or variable in question (first one = 1). This is why the Student Edition of AMPL provides the default value RF for $minos_auxfiles. See the discussion of auxiliary files in §A13.6 of the AMPL book [5]; as documented in *netlib*’s ‘‘changes from ampl’’, i.e.,

```
ftp://netlib.bell-labs.com/netlib/ampl/changes.gz
```

capital letters in $solver_auxfiles have the same effect as their lower-case equivalents on nonlinear problems, including problems with integer variables, and have no effect on purely linear problems. (We hope soon to permit two-way conversations with solvers, which will simplify this detail.)

### User-defined functions

An AMPL model may involve user-defined functions. If invocations of such functions involve variables, the solver must be able to evaluate the functions. You can tell your solver about the relevant functions by supplying a suitable funcadd function, rather than loading a dummy funcadd compiled from solvers/funcadd0.c. (To facilitate dynamic linking, which will be documented separately, this dummy funcadd no longer appears in amplsolver.a.) Include file funcadd.h gives funcadd’s prototype:

```
void funcadd(AmplExports *ae);
```

Among the fields in the AmplExports structure are some function pointers, such as

```
void (*Addfunc)(char *name, real (*f)(Arglist*), int type,
                int nargs, void *funcinfo, AmplExports *ae);
```

also in funcadd.h are #defines that simplify using the function pointers, assuming

```
AmplExports *ae
```

is visible. In particular, funcadd.h gives addfunc the apparent prototype

```
void addfunc(char *name, real (*f)(Arglist*), int type,
             int nargs, void *funcinfo);
```

To make user-defined functions known, funcadd should call addfunc once for each one. The first argument, name, is the function’s name in the AMPL model. The second argument points to the function itself. The type argument tells whether the function is prepared to accept symbolic arguments (character strings): 0 means ‘‘no’’, 1 means ‘‘yes’’. Argument `nargs` tells how many arguments the function expects; if `nargs` $\geq 0$, the function expects exactly that many arguments; otherwise it expects at least $-($`nargs` $+ 1)$. (Thus `nargs` $= -1$ means 0 or more arguments, `nargs` $= -2$ means 1 or more, etc. The argument count and type checking occurs when the *stub*`.nl` file is subsequently read.) Finally, argument `funcinfo` is for the function to use as it sees fit; it will subsequently be passed to the function in field `funcinfo` of struct `arglist`.

When a user-defined function is invoked, it always has a single argument, `al`, which points to an `arglist` structure. This structure is designed so the same user-defined function can be linked with AMPL (in case AMPL needs to evaluate the function); the final `arglist` components are relevant only to AMPL. The function receives `al->n` arguments, `al->nr` of which are numeric; for $0 \leq i <$ `al->n`,

if `al->at[`$i$`]` $\geq 0$, argument $i$ is `al->ra[al->at[`$i$`]]`
if `al->at[`$i$`]` $< 0$, argument $i$ is `al->sa[`$-($`al->at[`$i$`]` $+ 1)$`]`.

If `al->derivs` is nonzero, the function must store its first partial derivative with respect to `al->ra[`$i$`]` in `al->derivs[`$i$`]`, and if `al->hes` is nonzero (which is possible only with `fgh_read` or `pfgh_read`), it must also store the upper triangle of its Hessian matrix in `al->hes`, i.e., for
$0 \leq i \leq j <$ `al->nr`
it must store its second partial with respect to `al->ra[`$i$`]` and `al->ra[`$j$`]` in
`al->hes[`$i + \frac{1}{2} j(j+1)$`]`.

If the function does any printing, it should initially say

```
AmplExports *ae = al->AE;
```

to make special variants of `printf` available.

See `solvers/funcadd.c` for an example `funcadd`. The `mng`, `mnh` and `nl2` examples mentioned below illustrate linking with this `funcadd`.

**Checking for quadratic programs: example of a *DAG* walk**

Some solvers make special provision for handling quadratic programming problems, which have the form

$$\begin{array}{rl} \text{minimize or maximize} & \frac{1}{2} x^T Q x + c^T x \\ \text{subject to} & b \leq Ax \leq d \\ \text{and} & \ell \leq x \leq u \end{array} \qquad \text{(QP)}$$

in which $Q \in \mathbb{R}^{n \times n}$. For example, CPLEX, LOQO, and OSL handle general positive-definite $Q$ matrices, and the old KORBX solver handled positive-definite diagonal $Q$ matrices (‘‘convex separable quadratic programs’’). These solvers assume the explicit ½ shown above in the (QP) objective.

AMPL considers quadratic forms, such as the objective in (QP), to be nonlinear expressions. To determine whether a given objective function is a quadratic form, it is necessary to walk the directed acyclic graph (*DAG*) that represents the (possibly) nonlinear part of the objective. Function `nqpcheck` (in `solvers/nqpcheck.c`) illustrates such a walk. It is meant to be used with a variant of `fg_read` called `qp_read`, which has the same prototype as the other *stub*`.nl` readers, and which changes some function pointers to integers for the convenience of `nqpcheck`. After `qp_read` returns, you can invoke `nqpcheck` one or more times, but you may not call `objval`, `conval`, etc., until you have called `qp_opify`, with apparent prototype

```
void qp_opify(void)
```

to restore the function pointers. `Nqpcheck` itself has apparent prototype

```
fint nqpcheck(int co, fint **rowqp, fint **colqp, real **delsqp);
```

its first argument indicates the constraint or objective to which it applies: `co` $\geq 0$ means objective `co`, and `co` $< 0$ means constraint $-($`co` $+ 1)$. If the relevant objective or constraint is a quadratic form with Hessian $Q$, `nqpcheck` returns the number of nonzeros in $Q$ (which is 0 if the function is linear), and sets its pointer arguments to pointers to arrays that describe $Q$. Specifically, `*delsqp` points to an array of the nonzeros in *Q*, `*rowqp` to their row numbers (first row = 1), and `*colqp` to an array of subscripts, incremented by `Fortran`, of the first entry in `*rowqp` and `*delsqp` for each column, with `(*colqp)[n_var]` giving the subscript just after the last column. `Nqpcheck` sorts the nonzeros in each column of *Q* by their row indices and returns a symmetric *Q*. For non-quadratic functions, `npqcheck` returns – 1; it returns – 2 in the unlikely case that it sees a division by 0, and – 3 if `co` is out of range.

Usually it is most convenient to call `qpcheck` rather than `nqpcheck; qpcheck` has apparent prototype

```
fint qpcheck(fint **rowqp, fint **colqp, real **delsqp);
```

It looks at objective `obj_no` (i.e., `asl->i.obj_no_`, with default value 0) and complains and aborts execution if it sees something other than a linear or quadratic form. When it sees one of the latter, it gives the same return value as `nqpcheck` and sets its arguments the same way.

Drivers `solvers/cplex/cplex.c` and `solvers/osl/osl.c` call `qp_read` and `qpcheck`, and file `solvers/examples/qtest.c` illustrates invocations of `nqpcheck` and `qp_opify`.

More elaborate *DAG* walks are useful in other situations. For example, the `nlc` program discussed next does a more detailed *DAG* walk.

## C or Fortran 77 for a problem instance: *nlc*

Occasionally it may be convenient to turn a *stub*`.nl` file into C or Fortran. This can lead to faster function and gradient computations — but, because of the added compile and link times, many evaluations are usually necessary before any net time is saved. Program `nlc` converts *stub*`.nl` into C or Fortran code for evaluating objectives, constraints, and their derivatives. You can get source for `nlc` by asking *netlib* to

```
send all from ampl/solvers/nlc
```

or getting

```
ftp://netlib.bell-labs.com/netlib/ampl/solvers/nlc.tar
```

By default, `nlc` emits C source for functions `feval_` and `ceval_`; the former evaluates objectives and their gradients, the latter constraints and their Jacobian matrices (first derivatives). These functions have signatures

```
real feval_(fint *nobj, fint *needfg, real *x, real *g);
void ceval_(fint *needfg, real *x, real *c, real *J);
```

For both, `x` is the point at which evaluations take place, and `*needfg` tells whether the routines compute function values (if `*needfg` = 1), gradients (if `*needfg` = 2), or both (if `*needfg` = 3). For `feval_`, `*nobj` is the objective number (0 for the first objective), and `g` points to storage for the gradient (when `*needfg` = 2 or 3). For `ceval_`, `c` points to storage for the values of the constraint bodies, and `J` points to columnwise storage for the nonzeros in the Jacobian matrix. Auxiliary arrays

```
extern fint funcom_[];
extern real boundc_[], x0comn_[];
```

describe the problem dimensions, nonzeros in the Jacobian matrix, left- and right-hand sides of the constraints, bounds on the variables, and the starting guess. Specifically,

`funcom_[0] = n_var` = number of variables;
`funcom_[1] = n_obj` = number of objectives;
`funcom_[2] = n_con` = number of constraints;
`funcom_[3] = nzc` = number of Jacobian nonzeros;
`funcom_[4] = densej` is zero in the default case that the Jacobian matrix is stored sparsely, and is 1 if the full Jacobian matrix is stored (if requested by the `-d` command-line option to `nlc`).

`funcom_[`*i*`]`, 5 ≤ *i* ≤ 4 + `n_obj`, is 1 if the objective is to be maximized and 0 if it is to be minimized. If `densej = funcom_[4]` is 0, then `colstarts = funcom_ + n_obj + 5` and `rownos = funcom_ + n_obj + n_var + 6` are arrays describing the nonzeros in the columns of the Jacobian matrix: the nonzeros for column *i* (with *i* = 1 for the first column) are in `J[`*j*`]` for colstarts[$i-1$] $-$ 1 $\le j \le$ colstarts[$i$] $-$ 2, which looks more natural in Fortran notation: the calling sequences are compatible with the *f2c* calling conventions for Fortran.

Bounds are conveyed in boundc_ as follows:

boundc_[0] is the value passed for $\infty$;

boundc_ + 1 is an array of lower and upper bounds on the variables, and

boundc_ + 2*n_var + 1 is an array of lower and upper bounds on the constraint bodies. The initial guess appears in x0comn_.

The -f command-line option causes nlc to emit Fortran 77 equivalents of feval_ and ceval_; they correspond to the Fortran signatures

```
double precision function feval(nobj, needfg, x, g)
integer nobj,needfg
double precision x(*), g(*)
```

and

```
subroutine ceval(needfg, x, c, J)
integer needfg
double precision x(*), c(*), J(*)
```

and the auxiliary arrays are rendered as the COMMON blocks

```
common /funcom/ nvar, nobj, ncon, nzc, densej, colrow
integer nvar, nobj, ncon, nzc, densej, colrow(*)
common /boundc/ bounds
double precision bounds(*)
common /x0comn/ x0
double precision x0(*)
```

where colrow is only present if densej is 0 and the *'s have the values described above. (Strictly speaking, it would be necessary to make problem-specific adjustments to the dimensions in other Fortran source that referenced these common blocks, but most systems follow the rule that the array size seen first wins, in which case it suffices to load the object for feval and ceval first.)

Command-line option −1 causes nlc to emit variants feval0_ and ceval0_ of feval_ and ceval_ that omit gradient computations. They have signatures

```
real feval0_(fint *nobj, real *x);
void ceval0_(real *x, real *c);
```

With command-line option -3, nlc produces all four routines (or, if -f is also present, equivalent Fortran).

## Writing *stub*.nl files for debugging

You can use AMPL's write command or its -o command-line flag to get a *stub*.nl (and any other needed auxiliary files) for use in debugging. Normally AMPL writes a binary-format *stub*.nl, which corresponds to a command-line -ob*stub* argument. Such files are faster to read and write, but slightly less convenient for debugging, in that write_sol notes the format of *stub*.nl (binary or ASCII — by looking at binary_nl) and writes *stub*.sol in the same format. To get ASCII format files, either issue an AMPL write command of the form

```
write gstub;
```

or use the -og*stub* command-line option. Your solver should see exactly the same problem, and AMPL should get back exactly the same solution, whether you use binary or ASCII format *stub*.nl and *stub*.sol files (if your computer has reasonable floating-point arithmetic).

With AMPL versions ≥ 19970214, binary *stub*.nl files written on one machine with binary IEEE-arithmetic can be read on any other.

## Use with MATLAB®

It is easy to use AMPL with MATLAB — with the help of a *mex* file that reads *stub*`.nl` files, writes *stub*`.sol` files, and provides function, gradient, and Hessian values. Example file `amplfunc.c` is source for an `amplfunc.mex` that looks at its left- and right-hand sides to determine what it should do and works as follows:

```
[x,bl,bu,v,cl,cu] = amplfunc('stub')
```

reads `stub.nl` and sets

| | |
|---|---|
| `x` | = primal initial guess, |
| `bl` | = lower bounds on the primal variables, |
| `bu` | = upper bounds on the primal variables, |
| `v` | = dual initial guess (often a vector of zeros), |
| `cl` | = lower bounds on constraint bodies, and |
| `cu` | = upper bounds on constraint bodies. |

```
[f,c] = amplfunc(x,0)
```

sets

| | |
|---|---|
| `f` | = value of first objective at $x$ and |
| `c` | = values of constraint bodies at $x$. |

```
[g,Jac] = amplfunc(x,1)
```

sets

| | |
|---|---|
| `g` | = gradient of first objective at $x$ and |
| `Jac` | = Jacobian matrix of constraints at $x$. |

```
W = amplfunc(Y)
```

sets `W` to the Hessian of the Lagrangian (equation (*) in the section ‘‘Evaluating Nonlinear Functions’’ above) for the first objective at the point $x$ at which the objective and constraint bodies were most recently evaluated. Finally,

```
[] = amplfunc(msg,x,v)
```

calls `write_sol(msg,x,v,0)` to write the *stub*`.sol` file, with

| | |
|---|---|
| `msg` | = termination message (a string), |
| `x` | = optimal primal variables, and |
| `v` | = optimal dual variables. |

It is often convenient to use `.m` files to massage problems to a desired form. To illustrate this, the `examples` directory offers the following files (which are simplified forms of files used in joint work with Michael Overton and Margaret Wright):

• `init.m`, which expects variable `pname` to have been assigned a *stub* (a string value), reads *stub*`.nl`, and puts the problem into the form

$$\begin{aligned} &\text{minimize } f(x) \\ &\quad \text{s.t. } c(x) = 0 \\ &\quad \text{and } d(x) \ge 0. \end{aligned}$$

For simplicity, the example `init.m` assumes that the initial `x` yields `d(x)` > 0. A more elaborate version of `init.m` is required in general.

• `evalf.m`, which provides `[f,c,d] = evalf(x)`.

• `evalg.m`, which provides `[g,A,B] = evalg(x)`, where `A = c′(x)` and `B = d′(x)` are the Jacobian matrices of `c` and `d`.

• `evalw.m`, which computes the Lagrangian Hessian, `W = evalw(y,z)`, in which `y` and `z` are vectors of Lagrange multipliers for the constraints

$$c(x) = 0$$

and

$$d(x) \geq 0,$$

respectively.

• `enewt.m`, which uses `evalf.m`, `evalg.m` and `evalw.m` in a simple, non-robust nonlinear interior-point iteration that is meant mainly to illustrate setting up and solving an extended system involving the constraint Jacobian and Lagrangian Hessian matrices.

• `savesol.m`, which writes file *stub*`.sol` to permit reading a computed solution into an AMPL session.

• `hs100.amp`, an AMPL model for test problem 100 of Hock and Schittkowski [13].

• `hs100.nl`, derived from `hs100.amp`. To solve this problem, start MATLAB and type

```
pname = 'hs100';
init
enewt
savesol
```

`Amplfunc.c` provides dense Jacobian matrices and Lagrangian Hessians; `spamfunc.c` is a variant that provides sparse Jacobian matrices and Lagrangian Hessians. To see an example of using `spamfunc`, change all occurrences of ‘‘`amplfunc`’’ to ‘‘`spamfunc`’’ in the `.m` files.

## 5. Utility Routines and Interface Conventions

### –AMPL Flag

Sometimes it is convenient for a solver to behave differently when invoked by AMPL than when invoked ‘‘stand-alone’’. This is why AMPL passes a string that starts with `-AMPL` as the second command-line argument when it invokes a solver. As a simple example, `nl21.c` turns `dn2gb`’s default printing off when it sees `-AMPL`, and it only invokes `write_sol` when this flag is present.

### Conveying solver options

Most solvers have knobs (tolerances, switches, algorithmic options, etc.) that one might want to turn. An AMPL convention is that appending `_options` to the name of a solver gives the name of an environment variable (AMPL option) in which the solver looks for knob settings. Thus a solver named `wondersol` would take knob settings from `$wondersol_options` (the value of environment variable `wondersol_options`). For interactive use, it’s usually a good idea for a solver to print its name and perhaps version number when it starts, and to echo nondefault knob settings to confirm that they’ve been seen and accepted. It’s also conventional for the `msg` argument to `write_sol` to start with the solver’s name and perhaps version number. Since AMPL echoes the `write_sol`’s `msg` argument when it reads the solution, a minor problem arises: if there are no nondefault knob settings, an interactive user would see the solver’s name printed twice in a row. To keep this from happening, you can set `need_nl` (i.e., `asl->i.need_nl_`) to a positive value; this causes `write_sol` to insert that many backspace characters at the beginning of *stub*`.sol`. Usually this is done as follows: initially you execute, e.g.,

```
need_nl = printf("wondersol 3.2: ");
```

(Note that `printf` returns the number of characters it transmits — exactly what we need.) Subsequently, if you echo any options or otherwise print anything, also set `need_nl` to 0.

Conventionally, `$`*solver*`_options` may contain keywords and name-value pairs, separated by white space (spaces, tabs, newlines), with case ignored in names and keywords. For name-value pairs, the usual practice is to allow white space or an = (equality) sign, optionally surrounded by white space, between the name and the value. For debugging, it is sometimes convenient to pass keywords and name-value pairs on the solver's command line, rather than setting `$`*solver*`_options` appropriately. The usual practice is to look first in `$`*solver*`_options`, then at the command-line arguments, so the latter take precedence.

Interface routines `getstub`, `getopts`, and `getstops` facilitate the above conventions. They have apparent prototypes

```
char *getstub (char ***pargv, Option_Info *oi);
int   getopts (char **argv,   Option_Info *oi);
char *getstops(char ***pargv, Option_Info *oi);
```

which you can import by saying

```
include "getstub.h"
```

rather than (or in addition to)

```
include "asl.h"
```

Type `Option_Info` is also declared in `getstub.h`; it is a structure whose initial components are

```
char *sname;          /* invocation name of solver */
char *bsname;         /* solver name in startup "banner" */
char *opname;         /* name of solver_options environment var */
keyword *keywds;      /* key words */
int n_keywds;         /* number of key words */
int want_funcadd;     /* whether funcadd will be called */
char *version;        /* for -v and Ver_key_ASL() */
char **usage;         /* solver-specific usage message */
Solver_KW_func *kwf;  /* solver-specific keyword function */
Fileeq_func *feq;     /* for n=filename */
keyword *options;     /* command-line options (with -) before stub */
int n_options;        /* number of options */
```

Ordinarily a solver declares

```
static Option_Info Oinfo = { ... };
```

and supplies only the first few fields (in place of ‘‘`...`’’), relying on the convenience of static initialization setting the remaining fields to zero.

Function `getstub` looks in `*pargv` for the *stub*, possibly preceded by command-line options that start with ‘‘`-`’’; `getstub` provides a small default set of command-line options, which may be augmented or overridden by names in `oi->options`. Among the default command-line options are `'-?'`, which requests a usage summary that reports `oi->sname` as the invocation name of the solver; `'-='`, which summarizes possible keyword values; `-v`, which reports the versions of the solver (supplied by `oi->version`) and of `amplsolver.a` (which is available in cell `ASLdate_ASL`, declared in `asl.h`); and, if `oi->want_funcadd` is nonzero, `-u`, which lists the available user-defined functions; user-defined functions are discussed in their own section above. If it finds a *stub*, `getstub` checks whether the next argument begins with `-AMPL` and sets `amplflag` accordingly; if so, it executes

```
if (oi->bsname)
      need_nl = printf("%s: ", oi->bsname);
```

At any rate, it sets `*pargv` to the command-line argument following the *stub* and optional `-AMPL` and returns the *stub*. It returns 0 (NULL) if it does not find a *stub*.

Function `getopts` looks first in `$`*solver*`_options`, then at the command line for keywords and optional values; `oi->opname` provides the name of the *solver*`_options` environment variable. `Getopts` is separate from `getstub` because sometimes it is convenient to call `jac0dim`, do some storage allocation, or make other arrangements before processing the keywords. For cases where no such separation is useful, function `getstops` calls `getstub` and `getopts` and returns the *stub*, complaining and exiting if none is found.

Keywords are conveyed in `keyword` structures declared in `getstub.h`:

```
typedef struct keyword keyword;

typedef char *Kwfunc(Option_Info *oi, keyword *kw, char *value);

struct keyword {
    char *name;
    Kwfunc *kf;
    void *info;
    char *desc;
    };
```

Array `oi->keywds` describes `oi->n_keywds` keywords that may appear in `$`*solver*`_options`; these `keyword` structures must be sorted (with comparisons as though by `strcmp`) on their `name` fields, which must be in lower case. Similarly, `oi->options` is an array of `oi->n_options` `keyword`s for initial command-line options, which must also be sorted; often `oi->n_options` = 0. The `desc` field of a `keyword` may be null; it provides a short description of the keyword for use with the `-=` command-line option. If `desc` starts with an = sign, the text in `desc` up to the first space is appended to the keyword in the output of the `-=` command-line option. The `kf` field provides a function that processes the value (if any) of the keyword. Its arguments are `oi` (the `Option_Info` pointer passed to `getstub`), a pointer `kw` to the `keyword` structure itself, and a pointer `value` to the possible value for the keyword (stripped of preceding white space). The `kf` function may use `kw->info` as it sees fit and should return a pointer to the first character in `value` that it has not consumed. Ordinarily `getopts` echoes any keyword assignments it processes (and sets `need_nl` = 0), but the `kf` function can suppress this echoing for a particular assignment by executing

```
oi->option_echo &= ˜ASL_OI_echothis;
```

or for all subsequent assignments by executing

```
oi->option_echo &= ˜ASL_OI_echo;
```

| name | description of value |
|---|---|
| `CK_val` | known character value in known place |
| `C_val` | character value in known place |
| `DA_val` | real (double) value in asl |
| `DK_val` | known real (double) value in known place |
| `DU_val` | real (double) value: offset from uinfo |
| `D_val` | real (double) value in known place |
| `IA_val` | int value in asl |
| `IK0_val` | int value 0 in known place |
| `IK1_val` | int value 1 in known place |
| `IK_val` | known int value in known place |
| `IU_val` | int value: offset from uinfo |
| `I_val` | int value in known place |
| `LK_val` | known Long value in known place |
| `LU_val` | Long value: offset from uinfo |
| `L_val` | Long value in known place |
| `SU_val` | short value: offset from uinfo |
| `Ver_val` | report version |
| `WS_val` | set wantsol in Option_Info |

**Table 9:** *keyword functions in* `getstub.h`.

For convenience, `amplsolver.a` provides a variety of keyword-processing functions. Table 9 summarizes these functions; their prototypes appear in getstub.h, which also provides a macro, nkeywds, for computing the n_keywds field of an Option_Info structure from a keyword declaration of the form

```
static keyword keywds[] = { ... };
```

To allow compilation by a K&R C compiler, it is best to cast the info fields to (Char*) (which is (char*) with K&R C and (void*) with ANSI/ISO C and C++). Often it is convenient to use macro KW, defined in getstub.h, for this. An example appears in file tnmain.c, in which the keywds declaration is followed by

```
static Option_Info Oinfo =
    { "tn", "TN", "tn_options", keywds, nkeywds, 1 };
```

Many other examples appear in various subdirectories of *netlib*'s ampl/solvers directory. Occasionally it is necessary to make custom keyword-processing functions, as in the example files keywds.c, rvmsg.c and rvmsg.h, which are discussed further below.

Some solvers, such as minos and npsol, have their own routines for parsing keyword phrases. For such a solver you can initialize oi->kwf with a pointer to a function that invokes it; if getopts sees a keyword that does not appear in oi->keywds, it changes any underscore characters to blanks and passes the resulting phrase to oi->kwf. Some solvers, such as minos, also need a way to associate Fortran unit numbers with file names; oi->feq (if not null) points to a function for doing this. See ampl/solvers/minos/m55.c for an example that uses all 12 of the Option_Info fields shown above, including oi->kwf and oi->feq.

Many solvers allow outlev to appear in $*solver*_options. Generally, outlev = 0 means ‘‘no printed output’’, and larger integers cause the solver to print more information while they work. Another common keyword is maxit, whose value bounds the number of iterations allowed. For stand-alone invocations (those without -AMPL), solvers commonly recognize wantsol=*n*, where *n* is the sum of

| | |
|---|---|
| 1 | to write a .sol file, |
| 2 | to print the primal variable values, |
| 4 | to print the dual variable values, and |
| 8 | to suppress printing the solution message. |

A special keyword function, WS_val, processes wantsol assignments, which are interpreted by write_sol. Strings WS_desc_ASL and WSu_desc_ASL provide descriptions of wantsol for constrained and unconstrained solvers, respectively, and appear in many of the sample drivers available from *netlib*.

## Printing and Stderr

To facilitate using AMPL and solvers in some contexts, such as Microsoft Windows (in various versions), it is best to route all printing through printf and fprintf; a separate report will provide more details. Because of this, and because some systems furnish a sprintf that does not give the return value specified by ANSI/ISO C, amplsolver.a provides suitable versions of printf, fprintf, sprintf, vfprintf and vsprintf that function as specified by ANSI/ISO C, except that they do not recognize the L qualifier (for long double), and, as in AMPL, they provide some extensions: they turn %.0g and %.0G into the shortest decimal string that rounds to the number being converted, and they allow negative precisions for %f. These provisions apply to systems with IEEE, VAX, or IBM mainframe arithmetic, and solvers/makefile explains how to use the system's printf routines on other systems.

On systems where it is convenient to redirect stderr, it is best to write error messages to stderr. Unfortunately, redirecting stderr is inconvenient on some systems (e.g., Microsoft systems with the usual Microsoft shells). To promote portability among systems, amplsolver.a provides access to

```
extern FILE *Stderr,
```

which can be set, as appropriate, to stderr or stdout. Thus we recommend writing error messages to Stderr rather than stderr, as is illustrated in various examples discussed above.

**Formatting the optimal value and other numbers**

An AMPL convention is that solvers should report (in the `msg` argument to `write_sol`) the final objective value to `$objective_precision` significant figures. Interface routines `g_fmtop` and `obj_prec` facilitate this. They have apparent prototypes

```
int g_fmtop(char *buf, double v);
int obj_prec(void);
```

For use as the ‘‘*’’ argument in the format `%.*g`, `obj_prec` returns `$objective_precision`. Occasionally it may be convenient to use `g_fmtop` instead. It stores the appropriate decimal approximation in `buf` (using the same conversion routine as AMPL’s printing commands), and returns the number of characters (excluding the terminating null) it has stored in `buf`. The end of `nl21.c` illustrates both the use of `g_fmtop` and of the `Sprintf` in `amplsolver.a`. The latter is there because, contrary to standard (ANSI/ISO) C, the `sprintf` on some systems does not return the count of characters written to its first argument. Ordinarily, `Sprintf` is the `sprintf` described above in the section ‘‘Printing and `stderr`’’, but if you are using the system’s `sprintf`, then `Sprintf` is similar to `sprintf`, but only understands `%c`, `%d`, `%ld`, and `%s` (and complains if it sees something else).

Two relatives of `g_fmtop` that are also in `amplsolver.a` are

```
int g_fmt( char *buf, double v);
int g_fmtp(char *buf, double v, int prec);
```

`g_fmtp` rounds its argument to `prec` significant figures unless `prec` is 0, in which case it stores in `buf` the shortest decimal string that rounds to `v` (provided the machine uses IEEE, VAX, or IBM mainframe arithmetic: see [8]); `g_fmt(buf,v)` = `g_fmtp(buf,v,0)`.

If they find an exponent field necessary, both `g_fmtop` and its relatives delimit it with the current value of

```
extern char g_fmt_E;
```

(whose declaration appears in `asl.h`). The default value of `g_fmt_E` is `’e’`.

By default, `g_fmtop` and its relatives only supply a decimal point if it is followed by a digit, but if you set

```
extern int g_fmt_decpt;
```

(declared in `asl.h`) to a nonzero value, they always supply a decimal point when `v` is finite. If you set `g_fmt_decpt` to 2, these routines supply an exponent field for finite `v`. The `nlc` program discussed above uses these features when it writes Fortran.

**More examples**

Some examples illustrating the above points appear in `solvers/examples`. One such example is `tnmain.c`, a wrapper for Stephen Nash’s `LMQN` and `LMQNBC` [16, 15], which solve unconstrained and simply bounded minimization problems by a truncated Newton algorithm. Since `tnmain.c` calls `getstub`, the resulting solver, `tn`, explains its usage when invoked

```
tn ’-?’
```

and summarizes the keywords it recognizes when invoked

```
tn ’-=’
```

For another example, files `mng.c` and `nl2.c` are for solvers called `mng` and `nl2`, which are more elaborate variants of the `mng1` and `nl21` considered above (source files `mng1.c` and `nl21.c`). Both use auxiliary files `keywds.c`, `rvmsg.c` and `rvmsg.h` to turn the knobs summarized in [9] and pass a more elaborate `msg` to `write_sol`. Their linkage, in `solvers/examples/makefile`, also illustrates adding user-defined functions, which we will discuss shortly. Unlike `mng1`, `mng` checks to see if the objective is to be maximized and internally negates it if so.

File `mnh.c` is a variant of `mng.c` that supplies the analytic Hessian matrix computed by `duthes` to solver `mnh`, based on PORT routine `dmnhb`. For maximum likelihood problems, it is sometimes appropriate to use the Hessian at the solution as an estimate of the variance-covariance matrix; `mnh` offers the option of computing standard-deviation estimates for the optimal solution from this variance-covariance matrix estimate. Specify `stddev=1` in `$mnh_options` or on the command line to exercise this option, or specify `stddev_file=`*filename* to have this information written to a file.

Various subdirectories of

```
http://netlib.bell-labs.com/netlib/ampl/solvers/
```

provide other examples of drivers for linear and nonlinear solvers. See

```
ftp://netlib.bell-labs.com/netlib/ampl/solvers/README.gz
```

for more details.

## Multiple problems and multiple threads

It is possible to have several problems in memory at once, each with its own `ASL` pointer. To free the memory associated with a particular `ASL` pointer `asl`, execute

```
ASL_free(&asl);
```

this call sets `asl` = 0. To allocate problem-specific memory that will be freed by `ASL_free`, call `M1alloc` rather than `Malloc`. Do not pass such memory to `realloc` or `free`.

Independent threads may operate on independent `ASL` structures when `amplsolver.a` is compiled with `MULTIPLE_THREADS #defined`. In this case, it is necessary to suitably `#define ACQUIRE_DTOA_LOCK(`*n*`)` and `FREE_DTOA_LOCK(`*n*`)` to provide exclusive access to a few short critical regions (with distinct values of *n*); the recommended procedure is first to create `arith.h` by saying ‘‘`make arith.h`’’, then to add

```
#define MULTIPLE_THREADS
```

and suitable definitions of `ACQUIRE_DTOA_LOCK(`*n*`)` and `FREE_DTOA_LOCK(`*n*`)` to the end of `arith.h`, and finally to create `amplsolver.a` by saying ‘‘`make`’’. It is possible for two or more threads to compute function values simultaneously from the same `ASL` structure (e.g., for different objectives or constraint bodies), but because of the way derivative values are stored, they should do so for the *same* `X` vector. Only one thread at a time should compute derivative values for a particular `ASL` structure because of the way the scratch vector for adjoint values is used. Lifting this restriction would likely slow the computations.

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## Appendix A: Changes from Earlier Versions

Some changes are cosmetic, such as updates to *netlib* addresses to reflect the breakup of AT&T. Others are intended to make the AMPL/solver interface library more flexible and useful. Changes introduced in 1997 include:

• New facilities for computing second derivatives in nonlinear problems.

• Facilities for addressing several problems independently.

• Adjustments to the external name space: most names contributed by the AMPL/solver interface library now end with `_ASL` (for *A*MPL/*S*olver *L*ibrary).

• New facilities for processing command-line arguments and *solver*`_options` environment variables, meant to unify behavior among solvers and simplify writing solver interfaces.

• Changes to the `#include` files: `jacdim.h` is gone, replaced for most purposes by `asl.h` or `getstub.h` (which includes `asl.h`).

• In the *stub*`.nl` readers, logic to recognize some of the ‘‘suffix’’ arrays that AMPL will soon be able to write. Use of these arrays will be documented in a revised version of this report.

• Function `funcadd`, which one provides to make user-defined functions available, now takes an argument, and the `addfunc` routine it calls has an additional argument; for more details, see the section on ‘‘User-defined functions’’ above.

• To allow for dynamic linking of user-defined functions, the dummy `funcadd` routine in source file `funcadd0.c` no longer appears in `amplsolver.a`; if desired, it must be linked explicitly.

Header file `asl.h` provides `#define`s that permit older solver interface routines to be used with only a few changes. Often it suffices to change ‘‘`jacdim.h`’’ to ‘‘`asl.h`’’ and to add

```
    #define asl cur_ASL
```

after the `#include` line.