(Downloaded from https://cs.stanford.edu/~knuth/programs.html and typeset on September 17, 2017)

1. Intro. This program is part of a series of "exact cover solvers" that I'm putting together for my own education as I prepare to write Section 7.2.2.1 of *The Art of Computer Programming*. My intent is to have a variety of compatible programs on which I can run experiments, in order to learn how different approaches work in practice.

The basic input format for all of these solvers is described at the beginning of program DLX1, and you should read that description now if you are unfamiliar with it. Please read also the opening paragraphs of DLX2, which adds "color controls" to nonprimary columns.

DLX3 extends DLX2 by allowing the column totals to be more flexible: Instead of insisting that each primary column occurs exactly once in the chosen rows, we prescribe an *interval* of permissible values $[a_j \mathinner{..} b_j]$ for each primary column j, and we find all solutions in which the sum $s_1 s_2 \ldots s_n$ of chosen rows satisfies $a_j \le s_j \le b_j$ for such j. (In a sense this represents a generalization from sets to *multisets*, although the rows themselves are still sets.)

These bounds appear in the first "column-naming" line of input: You can write '$a_j\,{:}\,b_j\,|$' just before the column name. But a_j and the colon can be omitted if $a_j = b_j$; both can be omitted if $a_j = b_j = 1$.

Here, for example, is a simple test case:

```
| A simple example of color controls
A B 2:3|C | X Y
A B X:0 Y:0
A C X:1 Y:1
C X:0
B X:1
C Y:1
```

The unique solution consists of rows `A C X:1 Y:1`, `B X:1`, `C Y:1`.

There's a subtle distinction between a primary column with bounds $[0 \mathinner{..} 1]$ and a secondary column with no bounds, because every row is required to include at least one primary column.

If the input contains no column-bound specifications, the behavior of DLX3 will almost exactly match that of DLX2, except for having a slightly longer program and taking a bit longer to input the rows.

[*Historical note:* My first program for multiset exact covering was MDANCE, written in August 2004 when I was thinking about packing various sizes of bricks into boxes. That program allowed users to specify arbitrary column sums, and it had the same structure as this one, but it was less general than DLX3 because it didn't allow lower bounds to be less than upper bounds. Later I came gradually to realize that the ideas have many, many other applications.]

2. The introduction of lower bounds adds a new twist. Suppose, for example, all lower bounds a_j are zero, while all upper bounds b_j exceed or equal the number of rows using that column. Then the column doesn't impose any constraint whatsoever, and all 2^m subsets of the m rows are solutions to the problem.

We can't expect a user to be so foolish as to present us with such a case. But we might well end up with a subproblem of that form; and then there seems to be no point in listing all of the solutions.

Thus we distinguish "core solutions" from "total solutions," where the number of total solutions is the sum of 2^k over all core solutions that have k free rows.

3. After this program finds all solutions, it normally prints their total number on *stderr*, together with statistics about how many nodes were in the search tree, and how many "updates" and "cleansings" were made. The running time in "mems" is also reported, together with the approximate number of bytes needed for data storage. (An "update" is the removal of a row from its column. A "cleansing" is the removal of a satisfied color constraint from its row. One "mem" essentially means a memory access to a 64-bit word. The reported totals don't include the time or space needed to parse the input or to format the output.)

Here is the overall structure:

```
#define o mems++   /* count one mem */
#define oo mems += 2   /* count two mems */
#define ooo mems += 3   /* count three mems */
#define O "%"   /* used for percent signs in format strings */
#define mod %   /* used for percent signs denoting remainder in C */
#define max_level 500   /* at most this many rows in a solution */
#define max_cols 1000   /* at most this many columns */
#define max_nodes 100000000   /* at most this many nonzero elements in the matrix */
#define bufsize (9 * max_cols + 3)   /* a buffer big enough to hold all column names */
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <ctype.h>
#include "gb_flip.h"
  typedef unsigned int uint;   /* a convenient abbreviation */
  typedef unsigned long long ullng;   /* ditto */
  ⟨Type definitions 7⟩;
  ⟨Global variables 4⟩;
  ⟨Subroutines 11⟩;
  main(int argc, char *argv[])
  {
    register int cc, i, j, k, p, pp, q, r, s, t, cur_node, best_col, stage, score, best_s, best_l;
    ⟨Process the command line 5⟩;
    ⟨Input the column names 15⟩;
    ⟨Input the rows 20⟩;
    if (vbose & show_basics) ⟨Report the successful completion of the input phase 24⟩;
    if (vbose & show_tots) ⟨Report the column totals 25⟩;
    imems = mems, mems = 0;
    ⟨Solve the problem 26⟩;
  done: if (vbose & show_tots) ⟨Report the column totals 25⟩;
    if (vbose & show_profile) ⟨Print the profile 48⟩;
    if (vbose & show_basics) ⟨Give statistics about the run 6⟩;
  }
```

4. You can control the amount of output, as well as certain properties of the algorithm, by specifying options on the command line:

- '`v`⟨integer⟩' enables or disables various kinds of verbose output on *stderr*, given by binary codes such as *show_choices*;
- '`m`⟨integer⟩' causes every mth solution to be output (the default is `m0`, which merely counts them);
- '`s`⟨integer⟩' causes the algorithm to make random choices in key places (thus providing some variety, although the solutions are by no means uniformly random), and it also defines the seed for any random numbers that are used;
- '`d`⟨integer⟩' to sets *delta*, which causes periodic state reports on *stderr* after the algorithm has performed approximately *delta* mems since the previous report;
- '`c`⟨positive integer⟩' limits the levels on which choices are shown during verbose tracing;
- '`C`⟨positive integer⟩' limits the levels on which choices are shown in the periodic state reports;
- '`l`⟨nonnegative integer⟩' gives a *lower* limit, relative to the maximum level so far achieved, to the levels on which choices are shown during verbose tracing;
- '`t`⟨positive integer⟩' causes the program to stop after this many solutions have been found;
- '`T`⟨integer⟩' sets *timeout* (which causes abrupt termination if $mems > timeout$ at the beginning of a level).

```
#define show_basics 1   /* vbose code for basic stats; this is the default */
#define show_choices 2   /* vbose code for backtrack logging */
#define show_details 4   /* vbose code for further commentary */
#define show_profile 128   /* vbose code to show the search tree profile */
#define show_full_state 256   /* vbose code for complete state reports */
#define show_tots 512   /* vbose code for reporting column totals at start and end */
#define show_warnings 1024   /* vbose code for reporting rows without primaries */
```

```
⟨Global variables 4⟩ ≡
  int random_seed = 0;   /* seed for the random words of gb_rand */
  int randomizing;   /* has 's' been specified? */
  int vbose = show_basics + show_warnings;   /* level of verbosity */
  int spacing;   /* solution k is output if k is a multiple of spacing */
  int show_choices_max = 1000000;   /* above this level, show_choices is ignored */
  int show_choices_gap = 1000000;   /* below level maxl − show_choices_gap, show_details is ignored */
  int show_levels_max = 1000000;   /* above this level, state reports stop */
  int maxl = 0;   /* maximum level actually reached */
  char buf[bufsize];   /* input buffer */
  ullng count;   /* core solutions found so far */
  double totcount;   /* total solutions found so far */
  int noncore;   /* does totcount exceed count? */
  ullng rows;   /* rows seen so far */
  ullng imems, mems;   /* mem counts */
  ullng updates;   /* update counts */
  ullng cleansings;   /* cleansing counts */
  ullng bytes;   /* memory used by main data structures */
  ullng nodes;   /* total number of branch nodes initiated */
  ullng thresh = 0;   /* report when mems exceeds this, if delta ≠ 0 */
  ullng delta = 0;   /* report every delta or so mems */
  ullng maxcount = #ffffffffffffffff;   /* stop after finding this many solutions */
  ullng timeout = #1fffffffffffffff;   /* give up after this many mems */
```

See also sections 9 and 27.

This code is used in section 3.

5. If an option appears more than once on the command line, the first appearance takes precedence.

```
⟨ Process the command line 5 ⟩ ≡
  for (j = argc − 1, k = 0; j; j−−)
    switch (argv[j][0]) {
    case 'v': k |= (sscanf(argv[j] + 1, ""O"d", &vbose) − 1); break;
    case 'm': k |= (sscanf(argv[j] + 1, ""O"d", &spacing) − 1); break;
    case 's': k |= (sscanf(argv[j] + 1, ""O"d", &random_seed) − 1), randomizing = 1; break;
    case 'd': k |= (sscanf(argv[j] + 1, ""O"lld", &delta) − 1), thresh = delta; break;
    case 'c': k |= (sscanf(argv[j] + 1, ""O"d", &show_choices_max) − 1); break;
    case 'C': k |= (sscanf(argv[j] + 1, ""O"d", &show_levels_max) − 1); break;
    case 'l': k |= (sscanf(argv[j] + 1, ""O"d", &show_choices_gap) − 1); break;
    case 't': k |= (sscanf(argv[j] + 1, ""O"lld", &maxcount) − 1); break;
    case 'T': k |= (sscanf(argv[j] + 1, ""O"lld", &timeout) − 1); break;
    default: k = 1;      /* unrecognized command-line option */
    }
  if (k) {
    fprintf(stderr, "Usage:␣"O"s␣[v<n>]␣[m<n>]␣[s<n>]␣[d<n>]""␣[c<n>]␣[C<n>]␣[l<n\
        >]␣[t<n>]␣[T<n>]␣<␣foo.dlx\n", argv[0]);
    exit(−1);
  }
  if (randomizing) gb_init_rand(random_seed);
```

This code is used in section 3.

6. The program doesn't compute or report *totcount* unless necessary.

```
⟨ Give statistics about the run 6 ⟩ ≡
  {
    fprintf(stderr, "Altogether␣"O"llu␣solution"O"s", count, count ≡ 1 ? "" : "s");
    if (noncore) fprintf(stderr, "␣("O".12g␣total)", totcount);
    fprintf(stderr, ",␣"O"llu+"O"llu␣mems,", imems, mems);
    fprintf(stderr, "␣"O"llu␣updates,␣"O"llu␣cleansings,", updates, cleansings);
    bytes = last_col ∗ sizeof(column) + last_node ∗ sizeof(node) + maxl ∗ sizeof(int);
    fprintf(stderr, "␣"O"llu␣bytes,␣"O"llu␣nodes.\n", bytes, nodes);
  }
```

This code is used in section 3.

7. Data structures. Each column of the input matrix is represented by a **column** struct, and each row is represented as a list of **node** structs. There's one node for each nonzero entry in the matrix.

More precisely, the nodes of individual rows appear sequentially, with "spacer" nodes between them. The nodes are also linked circularly within each column, in doubly linked lists. The column lists each include a header node, but the row lists do not. Column header nodes are aligned with a **column** struct, which contains further info about the column.

Each node contains four important fields. Two are the pointers *up* and *down* of doubly linked lists, already mentioned. A third points directly to the column containing the node. And the last specifies a color, or zero if no color is specified.

A "pointer" is an array index, not a C reference (because the latter would occupy 64 bits and waste cache space). The *cl* array is for **column** structs, and the *nd* array is for **node**s. I assume that both of those arrays are small enough to be allocated statically. (Modifications of this program could do dynamic allocation if needed.) The header node corresponding to $cl[c]$ is $nd[c]$.

Notice that each **node** occupies two octabytes. We count one mem for a simultaneous access to the *up* and *down* fields, or for a simultaneous access to the *col* and *color* fields.

Although the column-list pointers are called *up* and *down*, they need not correspond to actual positions of matrix entries. The elements of each column list can appear in any order, so that one row needn't be consistently "above" or "below" another. Indeed, when *randomizing* is set, we intentionally scramble each column list.

This program doesn't change the *col* fields after they've first been set up. But the *up* and *down* fields will be changed frequently, although preserving relative order.

Exception: In the node $nd[c]$ that is the header for the list of column c, we use the *col* field to hold the *length* of that list (excluding the header node itself). We also might use its *color* field for special purposes. The alternative names *len* for *col* and *aux* for *color* are used in the code so that this nonstandard semantics will be more clear.

A *spacer* node has $col \le 0$. Its *up* field points to the start of the preceding row; its *down* field points to the end of the following row. Thus it's easy to traverse a row circularly, in either direction.

The *color* field of a node is set to -1 when that node has been cleansed. In such cases its original color appears in the column header. (The program uses this fact only for diagnostic outputs.)

```
#define len col   /* column list length (used in header nodes only) */
#define aux color   /* an auxiliary quantity (used in header nodes only) */

⟨ Type definitions 7 ⟩ ≡
  typedef struct node_struct {
    int up, down;   /* predecessor and successor in column */
    int col;   /* the column containing this node */
    int color;   /* the color specified by this node, if any */
  } node;
```

See also section 8.

This code is used in section 3.

8. Each **column** struct contains five fields: The *name* is the user-specified identifier; *next* and *prev* point to adjacent columns, when this column is part of a doubly linked list; *bound* is the maximum number of rows from this column that can be added to the current partial solution; *slack* is the difference between this column's given upper and lower bounds. As computation proceeds, *bound* might change but *slack* will not.

A column can be removed from the active list of "unfinished columns" when its *bound* field is reduced to zero. A removed column is said to be "covered"; all of its remaining rows are then blocked from further participation. Furthermore, we will remove a column when we find that it has no unblocked rows; that situation can arise if $bound \le slack$.

As backtracking proceeds, nodes will be deleted from column lists when their row has been blocked by other rows in the partial solution. But when backtracking is complete, the data structures will be restored to their original state.

We count one mem for a simultaneous access to the *prev* and *next* fields, or for a simultaneous access to *bound* and *slack*.

The *bound* and *slack* fields of secondary columns are not used.

```
⟨Type definitions 7⟩ +≡
  typedef struct col_struct {
    char name[8];    /* symbolic identification of the column, for printing */
    int prev, next;    /* neighbors of this column */
    int bound, slack;    /* residual capacity of this column */
  } column;
```

9.
```
⟨Global variables 4⟩ +≡
  node nd[max_nodes];    /* the master list of nodes */
  int last_node;    /* the first node in nd that's not yet used */
  column cl[max_cols + 2];    /* the master list of columns */
  int second = max_cols;    /* boundary between primary and secondary columns */
  int last_col;    /* the first column in cl that's not yet used */
```

10. One **column** struct is called the root. It serves as the head of the list of columns that need to be covered, and is identifiable by the fact that its *name* is empty.

```
#define root 0    /* cl[root] is the gateway to the unsettled columns */
```

11. A row is identified not by name but by the names of the columns it contains. Here is a routine that prints a row, given a pointer to any of its nodes. It also prints the position of the row in its column, relative to a given head location.

```
⟨ Subroutines 11 ⟩ ≡
  void print_row(int p, FILE *stream, int head, int score)
  {
    register int k, q;
    if (p ≡ nd[head].col) fprintf(stream, "␣null␣"O".8s", cl[p].name);
    else {
      if (p < last_col ∨ p ≥ last_node ∨ nd[p].col ≤ 0) {
        fprintf(stderr, "Illegal␣row␣"O"d!\n", p);
        return;
      }
      for (q = p; ; ) {
        fprintf(stream, "␣"O".8s", cl[nd[q].col].name);
        if (nd[q].color) fprintf(stream, ":"O"c", nd[q].color > 0 ? nd[q].color : nd[nd[q].col].color);
        q++;
        if (nd[q].col ≤ 0) q = nd[q].up;      /* −nd[q].col is actually the row number */
        if (q ≡ p) break;
      }
    }
    for (q = head, k = 1; q ≠ p; k++) {
      if (q ≡ nd[p].col) {
        fprintf(stream, "␣(?)\n"); return;      /* row not in its column! */
      } else q = nd[q].down;
    }
    fprintf(stream, "␣("O"d␣of␣"O"d)\n", k, score);
  }

  void prow(int p)
  {
    print_row(p, stderr, nd[nd[p].col].down, nd[nd[p].col].len);
  }
```

See also sections 12, 13, 34, 35, 38, 39, 40, 41, 46, and 47.

This code is used in section 3.

12. When I'm debugging, I might want to look at one of the current column lists.

```
⟨Subroutines 11⟩ +≡
  void print_col(int c)
  {
    register int p;
    if (c < root ∨ c ≥ last_col) {
      fprintf(stderr, "Illegal␣column␣"O"d!\n", c);
      return;
    }
    fprintf(stderr, "Column␣"O".8s", cl[c].name);
    if (c < second) {
      if (cl[c].slack ∨ cl[c].bound ≠ 1)
        fprintf(stderr, "␣("O"d,"O"d)", cl[c].bound − cl[c].slack, cl[c].bound);
      fprintf(stderr, ",␣length␣"O"d,␣neighbors␣"O".8s␣and␣"O".8s:\n", nd[c].len,
          cl[cl[c].prev].name, cl[cl[c].next].name);
    } else fprintf(stderr, ",␣length␣"O"d:\n", nd[c].len);
    for (p = nd[c].down; p ≥ last_col; p = nd[p].down) prow(p);
  }
```

13. Speaking of debugging, here's a routine to check if redundant parts of our data structure have gone awry.

```
#define sanity_checking 0      /* set this to 1 if you suspect a bug */
⟨Subroutines 11⟩ +≡
  void sanity(void)
  {
    register int k, p, q, pp, qq, t;
    for (q = root, p = cl[q].next; ; q = p, p = cl[p].next) {
      if (cl[p].prev ≠ q) fprintf(stderr, "Bad␣prev␣field␣at␣col␣"O".8s!\n", cl[p].name);
      if (p ≡ root) break;
      ⟨Check column p 14⟩;
    }
  }
```

14. ⟨Check column *p* 14⟩ ≡

```
  for (qq = p, pp = nd[qq].down, k = 0; ; qq = pp, pp = nd[pp].down, k++) {
    if (nd[pp].up ≠ qq) fprintf(stderr, "Bad␣up␣field␣at␣node␣"O"d!\n", pp);
    if (pp ≡ p) break;
    if (nd[pp].col ≠ p) fprintf(stderr, "Bad␣col␣field␣at␣node␣"O"d!\n", pp);
  }
  if (nd[p].len ≠ k) fprintf(stderr, "Bad␣len␣field␣in␣column␣"O".8s!\n", cl[p].name);
```

This code is used in section 13.

15. Inputting the matrix. Brute force is the rule in this part of the code, whose goal is to parse and store the input data and to check its validity.

```
#define panic(m)
        { fprintf(stderr, ""O"s!\n"O"d:␣"O".99s\n", m, p, buf); exit(−666); }

⟨Input the column names 15⟩ ≡
  if (max_nodes ≤ 2 ∗ max_cols) {
    fprintf(stderr, "Recompile␣me:␣max_nodes␣must␣exceed␣twice␣max_cols!\n");
    exit(−999);
  }    /∗ every column will want a header node and at least one other node ∗/
  while (1) {
    if (¬fgets(buf, bufsize, stdin)) break;
    if (o, buf[p = strlen(buf) − 1] ≠ '\n') panic("Input␣line␣way␣too␣long");
    for (p = 0; o, isspace(buf[p]); p++) ;
    if (buf[p] ≡ '|' ∨ ¬buf[p]) continue;    /∗ bypass comment or blank line ∗/
    last_col = 1;
    break;
  }
  if (¬last_col) panic("No␣columns");
  for ( ; o, buf[p]; ) {
    ⟨Scan a column name, possibly prefixed by bounds 16⟩;
    ⟨Initialize last_col to a new column with an empty list 19⟩;
    for (p += j + 1; o, isspace(buf[p]); p++) ;
    if (buf[p] ≡ '|') {
      if (second ≠ max_cols) panic("Column␣name␣line␣contains␣|␣twice");
      second = last_col;
      for (p++; o, isspace(buf[p]); p++) ;
    }
  }
  if (second ≡ max_cols) second = last_col;
  o, cl[root].prev = second − 1;    /∗ cl[second − 1].next = root since root = 0 ∗/
  last_node = last_col;    /∗ reserve all the header nodes and the first spacer ∗/
  o, nd[last_node].col = 0;
```

This code is used in section 3.

16. ⟨Scan a column name, possibly prefixed by bounds 16⟩ ≡

```
  if (second ≡ max_cols) stage = 0; else stage = 2;
start_name: for (j = 0; j < 8 ∧ (o, ¬isspace(buf[p + j])); j++) {
    if (buf[p + j] ≡ ':') {
      if (stage) panic("Illegal␣':'␣in␣column␣name");
      ⟨Convert the prefix to an integer, q 17⟩;
      r = q, stage = 1;
      goto start_name;
    } else if (buf[p + j] ≡ '|') {
      if (stage > 1) panic("Illegal␣'|'␣in␣column␣name");
      ⟨Convert the prefix to an integer, q 17⟩;
      if (q ≡ 0) panic("Upper␣bound␣is␣zero");
      if (stage ≡ 0) r = q;
      else if (r > q) panic("Lower␣bound␣exceeds␣upper␣bound");
      stage = 2;
      goto start_name;
    }
    o, cl[last_col].name[j] = buf[p + j];
  }
  switch (stage) {
  case 1: panic("Lower␣bound␣without␣upper␣bound");
  case 0: q = r = 1;
  case 2: break;
  }
  if (j ≡ 0) panic("Column␣name␣empty");
  if (j ≡ 8 ∧ ¬isspace(buf[p + j])) panic("Column␣name␣too␣long");
  ⟨Check for duplicate column name 18⟩;
```

This code is used in section 15.

17. ⟨Convert the prefix to an integer, q 17⟩ ≡

```
  for (q = 0, pp = p; pp < p + j; pp++) {
    if (buf[pp] < '0' ∨ buf[pp] > '9') panic("Illegal␣digit␣in␣bound␣spec");
    q = 10 * q + buf[pp] − '0';
  }
  p = pp + 1;
  while (j) cl[last_col].name[−−j] = 0;
```

This code is used in section 16.

18. ⟨Check for duplicate column name 18⟩ ≡

```
  for (k = 1; o, strncmp(cl[k].name, cl[last_col].name, 8); k++) ;
  if (k < last_col) panic("Duplicate␣column␣name");
```

This code is used in section 16.

19. ⟨Initialize *last_col* to a new column with an empty list 19⟩ ≡

```
  if (last_col > max_cols) panic("Too␣many␣columns");
  if (second ≡ max_cols) oo, cl[last_col − 1].next = last_col, cl[last_col].prev = last_col − 1, o,
        cl[last_col].bound = q, cl[last_col].slack = q − r;
  else o, cl[last_col].next = cl[last_col].prev = last_col;
  o, nd[last_col].up = nd[last_col].down = last_col;     /* nd[last_col].len = 0 */
  last_col++;
```

This code is used in section 15.

20. I'm putting the row number into the spacer that follows it, as a possible debugging aid. But the program doesn't currently use that information.

```
⟨Input the rows 20⟩ ≡
  while (1) {
    if ($\neg fgets(buf, bufsize, stdin)$) break;
    if ($o, buf[p = strlen(buf) - 1] \neq$ '\n') panic("Row␣line␣too␣long");
    for ($p = 0$; $o, isspace(buf[p])$; $p$++) ;
    if ($buf[p] \equiv$ '|' $\vee \neg buf[p]$) continue;    /* bypass comment or blank line */
    $i = last\_node$;    /* remember the spacer at the left of this row */
    for ($pp = 0$; $buf[p]$; ) {
      for ($j = 0$; $j < 8 \wedge (o, \neg isspace(buf[p + j])) \wedge buf[p + j] \neq$ ':'; $j$++)
        $o, cl[last\_col].name[j] = buf[p + j]$;
      if ($\neg j$) panic("Empty␣column␣name");
      if ($j \equiv 8 \wedge \neg isspace(buf[p + j]) \wedge buf[p + j] \neq$ ':') panic("Column␣name␣too␣long");
      if ($j < 8$) $o, cl[last\_col].name[j] =$ '\0';
      ⟨Create a node for the column named in $buf[p]$ 21⟩;
      if ($buf[p + j] \neq$ ':') $o, nd[last\_node].color = 0$;
      else if ($k \geq second$) {
        if ($((o, isspace(buf[p + j + 1])) \vee (o, \neg isspace(buf[p + j + 2])))$)
          panic("Color␣must␣be␣a␣single␣character");
        $o, nd[last\_node].color = buf[p + j + 1]$;
        $p$ += 2;
      } else panic("Primary␣column␣must␣be␣uncolored");
      for ($p$ += $j + 1$; $o, isspace(buf[p])$; $p$++) ;
    }
    if ($\neg pp$) {
      if ($vbose$ & $show\_warnings$) fprintf(stderr, "Row␣ignored␣(no␣primary␣columns):␣"O"s", buf);
      while ($last\_node > i$) {
        ⟨Remove $last\_node$ from its column 23⟩;
        $last\_node$--;
      }
    } else {
      $o, nd[i].down = last\_node$;
      $last\_node$++;    /* create the next spacer */
      if ($last\_node \equiv max\_nodes$) panic("Too␣many␣nodes");
      $rows$++;
      $o, nd[last\_node].up = i + 1$;
      $o, nd[last\_node].col = -rows$;
    }
  }
```

This code is used in section 3.

21. ⟨Create a node for the column named in *buf*[*p*] 21⟩ ≡

```
for ($k = 0$; $o, strncmp(cl[k].name, cl[last\_col].name, 8)$; $k$++) ;
if ($k \equiv last\_col$) panic("Unknown␣column␣name");
if ($o, nd[k].aux \ge i$) panic("Duplicate␣column␣name␣in␣this␣row");
$last\_node$++;
if ($last\_node \equiv max\_nodes$) panic("Too␣many␣nodes");
$o, nd[last\_node].col = k$;
if ($k < second$) $pp = 1$;
$o, t = nd[k].len + 1$;
⟨Insert node last_node into the list for column k 22⟩;
```

This code is used in section 20.

22. Insertion of a new node is simple, unless we're randomizing. In the latter case, we want to put the node into a random position of the list.

We store the position of the new node into *nd*[*k*].*aux*, so that the test for duplicate columns above will be correct.

As in other programs developed for TAOCP, I assume that four mems are consumed when 31 random bits are being generated by any of the GB_FLIP routines.

⟨Insert node *last_node* into the list for column *k* 22⟩ ≡

```
$o, nd[k].len = t$;    /* store the new length of the list */
$nd[k].aux = last\_node$;    /* no mem charge for aux after len */
if ($\neg randomizing$) {
    $o, r = nd[k].up$;    /* the "bottom" node of the column list */
    $ooo, nd[r].down = nd[k].up = last\_node, nd[last\_node].up = r, nd[last\_node].down = k$;
} else {
    $mems$ += $4, t = gb\_unif\_rand(t)$;    /* choose a random number of nodes to skip past */
    for ($o, r = k$; $t$; $o, r = nd[r].down, t$−−) ;
    $ooo, q = nd[r].up, nd[q].down = nd[r].up = last\_node$;
    $o, nd[last\_node].up = q, nd[last\_node].down = r$;
}
```

This code is used in section 21.

23. ⟨Remove *last_node* from its column 23⟩ ≡

```
$o, k = nd[last\_node].col$;
$oo, nd[k].len$−−$, nd[k].aux = i - 1$;
$o, q = nd[last\_node].up, r = nd[last\_node].down$;
$oo, nd[q].down = r, nd[r].up = q$;
```

This code is used in section 20.

24. ⟨Report the successful completion of the input phase 24⟩ ≡

```
fprintf(stderr, "("O"lld␣rows,␣"O"d+"O"d␣columns,␣"O"d␣entries␣successfully␣read)\n",
        rows, second − 1, last_col − second, last_node − last_col);
```

This code is used in section 3.

25. The column lengths after input should agree with the column lengths after this program has finished. I print them (on request), in order to provide some reassurance that the algorithm isn't badly screwed up.

```
⟨ Report the column totals 25 ⟩ ≡
  {
    fprintf(stderr, "Column␣totals:");
    for (k = 1; k < last_col; k++) {
      if (k ≡ second) fprintf(stderr, "␣|");
      fprintf(stderr, "␣"O"d", nd[k].len);
    }
    fprintf(stderr, "\n");
  }
```

This code is used in section 3.

26. The dancing. Our strategy for generating all exact covers will be to repeatedly choose an active primary column and to branch on the ways to reduce the possibilities for covering that column. And we explore all possibilities via depth-first search.

The neat part of this algorithm is the way the lists are maintained. Depth-first search means last-in-first-out maintenance of data structures; and it turns out that we need no auxiliary tables to undelete elements from lists when backing up. The nodes removed from doubly linked lists remember their former neighbors, because we do no garbage collection.

The basic operation is "covering a column." This means removing it from the list of columns needing to be covered, and "blocking" its rows: removing nodes from other lists whenever they belong to a row of a node in this column's list. We cover the chosen column when it has *bound* = 1 and *slack* = 0.

There's also an auxiliary operation called "tweaking a column," used when covering is inappropriate. In that case we simply block the topmost row in the column's list; we also remove that row temporarily from the list. (The tweaking operation, whose beauties will be described below, is a new dance step! It was introduced in the MDANCE program of 2004.)

```
⟨Solve the problem 26⟩ ≡
  level = 0;
forward: nodes++;
  if (vbose & show_profile) profile[level]++;
  if (sanity_checking) sanity();
  ⟨Do special things if enough mems have accumulated 28⟩;
  ⟨Set best_col to the best column for branching, and let score be its branching degree 42*⟩;
  if (score ≤ 0) goto backdown;      /* not enough rows left in this column */
  if (score ≡ infty) ⟨Record a solution and goto backdown 43⟩;
  scor[level] = score, first_tweak[level] = 0;      /* for diagnostics only, so no mems charged */
  oo, cur_node = choice[level] = nd[best_col].down;
  o, cl[best_col].bound−−;      /* one mem will be charged later */
  if (cl[best_col].bound ≡ 0 ∧ cl[best_col].slack ≡ 0) cover(best_col, 1);
  else {
    o, first_tweak[level] = cur_node;
    if (cl[best_col].bound ≡ 0) {
      o, p = cl[best_col].prev, q = cl[best_col].next;
      oo, cl[p].next = q, cl[q].prev = p;      /* deactivate best_col */
    }
  }
advance: ⟨If cur_node is off limits, goto backup; also tweak if needed 32⟩;
  if ((vbose & show_choices) ∧ level < show_choices_max) ⟨Report the current move 30⟩;
  if (cur_node > last_col) ⟨Cover or partially cover all other columns of cur_node's row 36⟩;
  ⟨Increase level and goto forward 29⟩;
backup: ⟨Restore the original state of best_col 33⟩;
backdown: if (level ≡ 0) goto done;
  level−−;
  oo, cur_node = choice[level], best_col = nd[cur_node].col, score = scor[level];
  if (cur_node < last_col) ⟨Reactivate best_col and goto backup 31⟩;
  ⟨Uncover or partially uncover all other columns of cur_node's row 37⟩;
  oo, cur_node = choice[level] = nd[cur_node].down; goto advance;
```

This code is used in section 3.

27. ⟨ Global variables 4 ⟩ +≡

```
int level;  /* number of choices in current partial solution */
int choice[max_level];  /* the node chosen on each level */
ullng profile[max_level];  /* number of search tree nodes on each level */
int first_tweak[max_level];  /* original top of column before tweaking */
int scor[max_level];  /* for reports of progress */
```

28. ⟨ Do special things if enough *mems* have accumulated 28 ⟩ ≡

```
if (delta ∧ (mems ≥ thresh)) {
  thresh += delta;
  if (vbose & show_full_state) print_state( );
  else print_progress( );
}
if (mems ≥ timeout) {
  fprintf(stderr, "TIMEOUT!\n"); goto done;
}
```

This code is used in section 26.

29. ⟨ Increase *level* and **goto** *forward* 29 ⟩ ≡

```
if (++level > maxl) {
  if (level ≥ max_level) {
    fprintf(stderr, "Too␣many␣levels!\n");
    exit(−4);
  }
  maxl = level;
}
goto forward;
```

This code is used in section 26.

30. ⟨ Report the current move 30 ⟩ ≡

```
{
  fprintf(stderr, "L"O"d:", level);
  if (cl[best_col].bound ≡ 0 ∧ cl[best_col].slack ≡ 0)
    print_row(cur_node, stderr, nd[best_col].down, score);
  else print_row(cur_node, stderr, first_tweak[level], score);
}
```

This code is used in section 26.

31. ⟨ Reactivate *best_col* and **goto** *backup* 31 ⟩ ≡

```
{
  best_col = cur_node;
  o, p = cl[best_col].prev, q = cl[best_col].next;
  oo, cl[p].next = cl[q].prev = best_col;  /* reactivate best_col */
  goto backup;
}
```

This code is used in section 26.

32. In the normal cases treated by DLX1 and DLX2, we want to back up after trying all rows in the column; this happens when *cur_node* has advanced to *best_col*, the column's header node.

In the other cases, we've been tweaking this column. Then we back up when fewer than $bound + 1 - slack$ rows remain in the column's list. (The current value of *bound* is one less than its original value on entry to this level.)

Notice that we might reach a situation where the list is empty (that is, $cur\_node = best\_col$), yet we don't want to back up. This can happen when $bound - slack < 0$. In such cases the move at this level is null: No row is added to the solution, and the column becomes inactive.

```
⟨If cur_node is off limits, goto backup; also tweak if needed 32⟩ ≡
  if ((o, cl[best_col].bound ≡ 0) ∧ (cl[best_col].slack ≡ 0)) {
    if (cur_node ≡ best_col) goto backup;
  } else if (oo, nd[best_col].len ≤ cl[best_col].bound − cl[best_col].slack) goto backup;
  else if (cur_node ≠ best_col) tweak(cur_node);
  else if (cl[best_col].bound ≠ 0) {
    o, p = cl[best_col].prev, q = cl[best_col].next;
    oo, cl[p].next = q, cl[q].prev = p;      /* deactivate best_col */
  }
```
This code is used in section 26.

33. ⟨Restore the original state of *best_col* 33⟩ ≡

```
  if ((o, cl[best_col].bound ≡ 0) ∧ (cl[best_col].slack ≡ 0)) uncover(best_col, 1);
  else o, untweak(best_col, first_tweak[level]);
  oo, cl[best_col].bound++;
```
This code is used in section 26.

34. When a row is blocked, it leaves all lists except the list of the column that is being covered. Thus a node is never removed from a list twice.

We can save time by not removing nodes from secondary columns that have been purified. (Such nodes have *color* < 0. Note that *color* and *col* are stored in the same octabyte; hence we pay only one mem to look at them both.)

```
⟨ Subroutines 11 ⟩ +≡
  void cover(int c, int deact)
  {
    register int cc, l, r, rr, nn, uu, dd, t;
    if (deact) {
      o, l = cl[c].prev, r = cl[c].next;
      oo, cl[l].next = r, cl[r].prev = l;
    }
    updates++;
    for (o, rr = nd[c].down; rr ≥ last_col; o, rr = nd[rr].down)
      for (nn = rr + 1; nn ≠ rr; ) {
        if (o, nd[nn].color ≥ 0) {
          o, uu = nd[nn].up, dd = nd[nn].down;
          cc = nd[nn].col;
          if (cc ≤ 0) {
            nn = uu;
            continue;
          }
          oo, nd[uu].down = dd, nd[dd].up = uu;
          updates++;
          o, t = nd[cc].len − 1;
          o, nd[cc].len = t;
        }
        nn++;
      }
  }
```

35. I used to think that it was important to uncover a column by processing its rows from bottom to top, since covering was done from top to bottom. But while writing this program I realized that, amazingly, no harm is done if the rows are processed again in the same order. So I'll go downward again, just to prove the point. Whether we go up or down, the pointers execute an exquisitely choreographed dance that returns them almost magically to their former state.

```
⟨Subroutines 11⟩ +≡
  void uncover(int c, int deact)
  {
    register int cc, l, r, rr, nn, uu, dd, t;
    for (o, rr = nd[c].down; rr ≥ last_col; o, rr = nd[rr].down)
      for (nn = rr + 1; nn ≠ rr; ) {
        if (o, nd[nn].color ≥ 0) {
          o, uu = nd[nn].up, dd = nd[nn].down;
          cc = nd[nn].col;
          if (cc ≤ 0) {
            nn = uu;
            continue;
          }
          oo, nd[uu].down = nd[dd].up = nn;
          o, t = nd[cc].len + 1;
          o, nd[cc].len = t;
        }
        nn++;
      }
    if (deact) {
      o, l = cl[c].prev, r = cl[c].next;
      oo, cl[l].next = cl[r].prev = c;
    }
  }
```

36.
```
⟨Cover or partially cover all other columns of cur_node's row 36⟩ ≡
  for (pp = cur_node + 1; pp ≠ cur_node; ) {
    o, cc = nd[pp].col;
    if (cc ≤ 0) o, pp = nd[pp].up;
    else {
      if (cc < second) {
        oo, cl[cc].bound−−;
        if (cl[cc].bound ≡ 0) cover(cc, 1);
      } else {
        if (¬nd[pp].color) cover(cc, 1);
        else if (nd[pp].color > 0) purify(pp);
      }
      pp++;
    }
  }
```
This code is used in section 26.

37. We must go leftward as we uncover the columns, because we went rightward when covering them.

```
⟨ Uncover or partially uncover all other columns of cur_node's row 37 ⟩ ≡
  for (pp = cur_node − 1; pp ≠ cur_node; ) {
    o, cc = nd[pp].col;
    if (cc ≤ 0) o, pp = nd[pp].down;
    else {
      if (cc < second) {
        if (o, cl[cc].bound ≡ 0) uncover(cc, 1);
        o, cl[cc].bound++;
      } else {
        if (¬nd[pp].color) uncover(cc, 1);
        else if (nd[pp].color > 0) unpurify(pp);
      }
      pp−−;
    }
  }
```

This code is used in section 26.

38. When we choose a row that specifies colors in one or more columns, we "purify" those columns by removing all incompatible rows. All rows that want the chosen color in a purified column are temporarily given the color code −1 so that they won't be purified again.

```
⟨ Subroutines 11 ⟩ +≡
  void purify(int p)
  {
    register int cc, rr, nn, uu, dd, t, x;
    o, cc = nd[p].col, x = nd[p].color;
    nd[cc].color = x;      /* no mem charged, because this is for print_row only */
    cleansings++;
    for (o, rr = nd[cc].down; rr ≥ last_col; o, rr = nd[rr].down) {
      if (o, nd[rr].color ≠ x) {
        for (nn = rr + 1; nn ≠ rr; ) {
          o, uu = nd[nn].up, dd = nd[nn].down;
          o, cc = nd[nn].col;
          if (cc ≤ 0) {
            nn = uu; continue;
          }
          if (nd[nn].color ≥ 0) {
            oo, nd[uu].down = dd, nd[dd].up = uu;
            updates++;
            o, t = nd[cc].len − 1;
            o, nd[cc].len = t;
          }
          nn++;
        }
      } else if (rr ≠ p) cleansings++, o, nd[rr].color = −1;
    }
  }
```

39. Just as *purify* is analogous to *cover*, the inverse process is analogous to *uncover*.

```
⟨Subroutines 11⟩ +≡
  void unpurify(int p)
  {
    register int cc, rr, nn, uu, dd, t, x;
    o, cc = nd[p].col, x = nd[p].color;      /* there's no need to clear nd[cc].color */
    for (o, rr = nd[cc].up; rr ≥ last_col; o, rr = nd[rr].up) {
      if (o, nd[rr].color < 0) o, nd[rr].color = x;
      else if (rr ≠ p) {
        for (nn = rr − 1; nn ≠ rr; ) {
          o, uu = nd[nn].up, dd = nd[nn].down;
          o, cc = nd[nn].col;
          if (cc ≤ 0) {
            nn = dd; continue;
          }
          if (nd[nn].color ≥ 0) {
            oo, nd[uu].down = nd[dd].up = nn;
            o, t = nd[cc].len + 1;
            o, nd[cc].len = t;
          }
          nn−−;
        }
      }
    }
  }
```

40. Now let's look at tweaking, which is deceptively simple. When this subroutine is called, node n is the topmost in its column. Tweaking is important because the column remains active and on a par with all other active columns.

```
⟨Subroutines 11⟩ +≡
  void tweak(int n)
  {
    register int cc, nn, uu, dd, t;
    for (nn = n + 1; ; ) {
      if (o, nd[nn].color ≥ 0) {
        o, uu = nd[nn].up, dd = nd[nn].down;
        cc = nd[nn].col;
        if (cc ≤ 0) {
          nn = uu;
          continue;
        }
        oo, nd[uu].down = dd, nd[dd].up = uu;
        updates++;
        o, t = nd[cc].len − 1;
        o, nd[cc].len = t;
      }
      if (nn ≡ n) break;
      nn++;
    }
  }
```

41. The punch line occurs when we consider untweaking. Consider, for example, a column c whose rows from top to bottom are x, y, z. Then the *up* fields for (c,x,y,z) are initially (z,c,x,y), and the *down* fields are (x,y,z,c). After we've tweaked x, they've become (z,c,c,y) and (y,y,z,c); after we've subsequently tweaked y, they've become (z,c,c,c) and (z,y,z,c). Notice that x still points to y, and y still points to z. So we can restore the original state if we restore the *up* pointers in y and z, as well as the *down* pointer in c. The value of x has been saved in the *first_tweak* array for the current level; and that's sufficient to solve the puzzle.

We also have to resuscitate the rows by reinstating them in their columns. That can be done top-down, as in *uncover*; in essence, a sequence of tweaks is like a partial covering.

```
⟨ Subroutines 11 ⟩ +≡
  void untweak(int c, int x)
  {
    register int z, cc, nn, uu, dd, t, k, rr, qq;
    oo, z = nd[c].down, nd[c].down = x;
    for (rr = x, k = 0, qq = c; rr ≠ z; o, qq = rr, rr = nd[rr].down) {
      o, nd[rr].up = qq, k++;
      for (nn = rr + 1; nn ≠ rr; ) {
        if (o, nd[nn].color ≥ 0) {
          o, uu = nd[nn].up, dd = nd[nn].down;
          cc = nd[nn].col;
          if (cc ≤ 0) {
            nn = uu;
            continue;
          }
          oo, nd[uu].down = nd[dd].up = nn;
          o, t = nd[cc].len + 1;
          o, nd[cc].len = t;
        }
        nn++;
      }
    }
    o, nd[rr].up = qq;      /* rr = z */
    oo, nd[c].len += k;
  }
```

42* The “best column” is considered to be a column that minimizes the branching degree. If there are several candidates, we choose the leftmost — unless we’re randomizing, in which case we select one of them at random.

Consider a column that has four rows $\{w, x, y, z\}$, and suppose its *bound* is 3. If the *slack* is zero, we’ve got to choose either w or x, so the branching degree is 2. But if $slack = 1$, we have three choices, w or x or y; if $slack = 2$, there are four choices; and if $slack \ge 3$, there are five, including the “null” choice.

In general, the branching degree turns out to be $l + s - b + 1$, where l is the length of the column, b is the current bound, and s is the minimum of b and the slack. This formula gives degree ≤ 0 if and only if l is too small to satisfy the column constraint; in such cases we will backtrack immediately. (It would have been possible to detect this condition early, before updating all the data structures and increasing *level*. But that would make the downdating process much more difficult and error-prone. Therefore I wait to discover such anomalies until column-choosing time.)

Let’s assign the score $l + s - b + 1$ to each column. If two columns have the same score, I prefer the one with smaller s, because slack columns are less constrained. If two columns with the same s have the same score, I (counterintuitively) prefer the one with larger b (hence larger l), because that tends to reduce the size of the final search tree.

Consider, for instance, the following example taken from MDANCE: If we want to choose 2 rows from 4 in one column, and 3 rows from 5 in another, where all slacks are zero, and if the columns are otherwise independent, it turns out that the number of nodes per level if we choose the smaller column first is $(1, 3, 6, 6 \cdot 3, 6 \cdot 6, 6 \cdot 10)$. But if we choose the larger column first it is $(1, 3, 6, 10, 10 \cdot 3, 10 \cdot 6)$, which is smaller in the middle levels.

Another special case also deserves mention: A column is completely unconstrained when $s = b \ge l$. Such columns are *never* selected as “best”; if all columns have this property, we’ve found a core solution, as mentioned above.

```
#define infty max_nodes    /* the “score” of a completely unconstrained column */
⟨Set best_col to the best column for branching, and let score be its branching degree 42*⟩ ≡
  score = infty;
  if ((vbose & show_details) ∧ level < show_choices_max ∧ level ≥ maxl − show_choices_gap)
    fprintf(stderr, "Level␣"O"d:", level);
  for (o, k = cl[root].next; k ≠ root; o, k = cl[k].next) {
    o, s = cl[k].slack; if (s > cl[k].bound) s = cl[k].bound;
    if ((vbose & show_details) ∧ level < show_choices_max ∧ level ≥ maxl − show_choices_gap) {
      if (cl[k].bound ≠ 1 ∨ s ≠ 0) fprintf(stderr, "␣"O".8s("O"d:"O"d,"O"d)", cl[k].name,
            cl[k].bound − s, cl[k].bound, nd[k].len + s − cl[k].bound + 1);
      else fprintf(stderr, "␣"O".8s("O"d)", cl[k].name, nd[k].len);
    }
    if ((o, nd[k].len > cl[k].bound) ∨ (s < cl[k].bound)) {
      t = nd[k].len + s − cl[k].bound + 1;
      if (score ≡ infty ∨ t ≤ 1 ∨ (t ≤ score ∧ cl[k].name[0] ≡ '#')) {
        if (t < score ∨ s < best_s ∨ (s ≡ best_s ∧ nd[k].len > best_l))
          score = t, best_col = k, best_s = s, best_l = nd[k].len, p = 1;
        else if (score ∧ s ≡ best_s ∧ nd[k].len ≡ best_l) {
          p++;    /* this many columns achieve the min */
          if (randomizing ∧ (mems += 4, ¬gb_unif_rand(p))) best_col = k;
        }
      }
    }
  }
  if ((vbose & show_details) ∧ level < show_choices_max ∧ level ≥ maxl − show_choices_gap) {
    if (score < infty) fprintf(stderr, "␣branching␣on␣"O".8s("O"d)\n", cl[best_col].name, score);
    else fprintf(stderr, "␣core␣solution\n");
  }
```

This code is used in section 26.

43. ⟨ Record a solution and **goto** *backdown* 43 ⟩ ≡

```
{
  count++;
  ⟨ Set p to the number of rows remaining 44 ⟩;
  if (p ∧ ¬noncore) noncore = 1, totcount = count − 1;
  if (noncore) {
    register double f = 1.0;
    while (p > 60) f *= 1_LL ≪ 60, p −= 60;
    f *= 1_LL ≪ p;
    totcount += f;
  }
  if (spacing ∧ (count mod spacing ≡ 0)) {
    printf(""O"lld:\n", count);
    for (k = 0; k < level; k++) {
      pp = choice[k];
      cc = pp < last_col ? pp : nd[pp].col;
      if (¬first_tweak[k]) print_row(pp, stdout, nd[cc].down, scor[k]);
      else print_row(pp, stdout, first_tweak[k], scor[k]);
    }
    if (p) ⟨ Print the free rows 45 ⟩;
    fflush(stdout);
  }
  if (count ≥ maxcount) goto done;
  goto backdown;
}
```

This code is used in section 26.

44. ⟨ Set *p* to the number of rows remaining 44 ⟩ ≡

```
for (o, p = 0, cc = cl[root].next; cc ≠ root; o, cc = cl[cc].next) {
  o, p += nd[cc].len;
  cover(cc, 0);
}
for (cc = cl[root].prev; cc ≠ root; o, cc = cl[cc].prev) uncover(cc, 0);
```

This code is used in section 43.

45. ⟨ Print the free rows 45 ⟩ ≡

```
{
  printf("␣and␣"O"d␣free␣row"O"s:\n", p, p ≡ 1 ? "" : "s");
  for (cc = cl[root].next; cc ≠ root; cc = cl[cc].next) {
    for (r = nd[cc].down; r ≠ cc; r = nd[r].down) print_row(r, stdout, nd[cc].down, nd[cc].len);
    cover(cc, 0);
  }
  for (cc = cl[root].prev; cc ≠ root; cc = cl[cc].prev) uncover(cc, 0);
}
```

This code is used in section 43.

46. ⟨ Subroutines 11 ⟩ +≡

```
void print_state(void)
{
  register int l, p, c, q;
  fprintf(stderr, "Current␣state␣(level␣"O"d):\n", level);
  for (l = 0; l < level; l++) {
    p = choice[l];
    c = (p < last_col ? p : nd[p].col);
    if (¬first_tweak[l]) print_row(p, stderr, nd[c].down, scor[l]);
    else print_row(p, stderr, first_tweak[l], scor[l]);
    if (l ≥ show_levels_max) {
      fprintf(stderr, "␣...\n");
      break;
    }
  }
  fprintf(stderr, "␣"O"lld␣"O"ssols,␣"O"lld␣mems,␣and␣max␣level␣"O"d␣so␣far.\n", count,
      noncore ? "core␣" : "", mems, maxl);
}
```

47. During a long run, it's helpful to have some way to measure progress. The following routine prints a string that indicates roughly where we are in the search tree. The string consists of character pairs, separated by blanks, where each character pair represents a branch of the search tree. When a node has d descendants and we are working on the kth, the two characters respectively represent k and d in a simple code; namely, the values 0, 1, ..., 61 are denoted by

`0, 1, ..., 9, a, b, ..., z, A, B, ...,Z.`

All values greater than 61 are shown as '`*`'. Notice that as computation proceeds, this string will increase lexicographically.

Following that string, a fractional estimate of total progress is computed, based on the naïve assumption that the search tree has a uniform branching structure. If the tree consists of a single node, this estimate is .5; otherwise, if the first choice is 'k of d', the estimate is $(k-1)/d$ plus $1/d$ times the recursively evaluated estimate for the kth subtree. (This estimate might obviously be very misleading, in some cases, but at least it grows monotonically.)

```
⟨ Subroutines 11 ⟩ +≡
  void print_progress(void)
  {
    register int l, k, d, c, p;
    register double f, fd;
    fprintf(stderr, "␣after␣"O"lld␣mems:␣"O"lld␣sols,", mems, count);
    for (f = 0.0, fd = 1.0, l = 0; l < level; l++) {
      p = choice[l], d = scor[l];
      c = (p < last_col ? p : nd[p].col);
      if (¬first_tweak[l]) p = nd[c].down;
      else p = first_tweak[l];
      for (k = 1; p ≠ choice[l]; k++, p = nd[p].down) ;
      fd *= d, f += (k − 1)/fd;      /* choice l is k of d */
      fprintf(stderr, "␣"O"c"O"c", k < 10 ? '0' + k : k < 36 ? 'a' + k − 10 : k < 62 ? 'A' + k − 36 : '*',
          d < 10 ? '0' + d : d < 36 ? 'a' + d − 10 : d < 62 ? 'A' + d − 36 : '*');
      if (l ≥ show_levels_max) {
        fprintf(stderr, "...");
        break;
      }
    }
    fprintf(stderr, "␣"O".5f\n", f + 0.5/fd);
  }
```

48. ⟨ Print the profile 48 ⟩ ≡

```
  {
    fprintf(stderr, "Profile:\n");
    for (level = 0; level ≤ maxl; level++) fprintf(stderr, ""O"3d:␣"O"lld\n", level, profile[level]);
  }
```

This code is used in section 3.

49.* Index.

The following sections were changed by the change file: 42, 49.

DLX3-SHARP