

(See <https://cs.stanford.edu/~knuth/programs.html> for date.)

1. Intro. This program contains two implementations of the Koda–Ruskey algorithm for generating all ideals of a given forest poset [*Journal of Algorithms* **15** (1993), 324–340]. The common goal of both implementations is, in essence, to generate all binary strings $b_0 \dots b_{n-1}$ in which certain bits are required to be less than or equal to specified bits that lie to their right. (For some values of j there is a value of $k > j$ such that we don’t allow b_k to be 0 when $b_j = 1$.) Moreover, each binary string should differ from its predecessor in exactly one bit position; the algorithm therefore defines a generalized reflected Gray code.

The given forest is represented by n pairs of nested parentheses. For example, $()()()()()$ represents five independent bits, while $(((((()))))$ represents five bits with $b_0 \leq b_1 \leq b_2 \leq b_3 \leq b_4$. A more interesting example, $((())(())())$, represents six bits subject to the conditions $b_0 \leq b_1$, $b_1 \leq b_5$, $b_2 \leq b_4$, $b_3 \leq b_4$, $b_4 \leq b_5$. Each pair of parentheses corresponds to a bit that must not exceed the bit of its enclosing pair, if any, and the pairs are ordered by the appearances of their right parentheses.

The first implementation uses n coroutines, which call each other in a hierarchical fashion. The second uses multilinked data structures in a loopless way, so that each generation step performs a bounded number of operations to obtain the next element. I couldn’t resist writing this program, because both implementations turn out to be quite interesting and instructive.

Indeed, I think it’s a worthwhile challenge for people who study the science of computer programming to verify that these two implementations both define the same sequence of bitstrings. Even more challenging would be to derive the second implementation “automatically” from the first.

```
#include <stdio.h>
<Type definitions 4>
<Global variables 3>
int main(int argc, char *argv[])
{
    register int j, k, l;
    <Process the command line, parsing the given forest 2>;
    printf("Bitstrings generated from \"%s\":\n", argv[1]);
    <Generate the strings with a coroutine implementation 9>;
    printf("\nTrying again, looplessly:\n");
    <Generate the strings with a loopless implementation 15>;
    return 0;
}
```

2. In this step we parse the forest into an array of “scopes”: $scope[j]$ is the index of the smallest descendant of node j , including node j itself.

```
#define abort(m,i)
    { fprintf(stderr,m,argv[i]); return -1; }
#define stacksize 100    /* max levels in the forest */
#define forestsize 100   /* max nodes in the forest */
⟨ Process the command line, parsing the given forest 2 ⟩ ≡
    if (argc ≠ 2 ∨ argv[1][0] ≠ '(') abort("Usage: %s \\"nestedparens\\"\\n",0);
    for (j = k = l = 0; argv[1][k]; k++)
        if (argv[1][k] ≡ '(') {
            stack[l++] = j;
            if (l ≡ stacksize) abort("Stack_overflow_---\\\"%s\\\"_is_too_deep_for_me!\\n",1);
        } else if (argv[1][k] ≡ ')') {
            if (--l < 0) abort("Extra_right_parenthesis_in_\\\"%s\\\"!\\n",1);
            scope[j++] = stack[l];
            if (j ≡ forestsize) abort("Memory_overflow_---\\\"%s\\\"_is_too_big!\\n",1);
        } else abort("The_forest_spec_\\\"%s\\\"_should_contain_only_parentheses!\\n",1);
    if (l) abort("Missing_right_parenthesis_in_\\\"%s\\\"!\\n",1);
    nn = j;
```

This code is used in section 1.

3. ⟨ Global variables 3 ⟩ ≡

```
int stack[stacksize];    /* nodes preceding each open leftparen, while parsing */
int scope[forestsize];   /* table that exhibits each rightparen's influence */
int nn;                  /* the actual number of nodes in the forest */
```

See also sections 11 and 17.

This code is used in section 1.

4. The coroutine implementation. Our first implementation uses a system of n cooperating programs, each of which represents a node in the forest. For convenience we will call the associated record a “cnode.” If p points to a cnode, $p\text{-child}$ points to the cnode representing its rightmost child, and $p\text{-sib}$ points to the cnode representing its nearest sibling on the left, in the given forest.

Each cnode corresponds to a coroutine whose job is to generate all the ideals of the subforest it represents. Whenever the coroutine is invoked, it either changes one of the bits in its scope and returns *true*, or it changes nothing and returns *false*. Initially all the bits are 0; when it first returns *false*, it will have generated all legitimate bit patterns, ending with some nonzero pattern. Subsequently it will generate the patterns again in reverse order, ending with all 0s, after which it will return *false* a second time. Invoking it again and again will repeat the same process, going forwards and backwards, ad infinitum.

Each coroutine has the same basic structure, which can be described as follows in an ad hoc extension of C language:

```

coroutine p()
{
    while (1) {
        p-bit = 1; return true;
        while (p-child()) return true;
        return p-sib();
        while (p-child()) return true;
        p-bit = 0; return true;
        return p-sib();
    }
}

```

If either $p\text{-child}$ or $p\text{-sib}$ is Λ , the corresponding coroutine $\Lambda()$ is assumed to simply return *false*.

Suppose $p\text{-child}()$ first returns *false* after it has been called r times; thus $p\text{-child}()$ generates r different patterns, including the initial pattern of all 0s. Similarly, suppose that $p\text{-sib}()$ generates l different patterns before first returning *false*. Then the coroutine $p()$ itself will generate $l(r+1)$ patterns in between the times when it returns *false*. The final bit pattern for p will be the final bit pattern for $p\text{-sib}$, together with either $p\text{-bit} = 1$ and the final bit pattern of $p\text{-child}$ (if l is odd) or with $p\text{-bit} = 0$ and all 0s in $p\text{-child}$ (if l is even).

(Type definitions 4) \equiv

```

typedef enum {
    false, true
} boolean;

typedef struct cnode_struct {
    char bit; /* either 0 or 1; always 1 when a child's bit is set */
    char state; /* the current place in this cnode's coroutine */
    struct cnode_struct *child; /* rightmost child in the given forest */
    struct cnode_struct *sib; /* nearest left sibling in the given forest */
    struct cnode_struct *caller; /* which coroutine invoked this one */
} cnode;

```

See also section 14.

This code is used in section 1.

5. When coroutine p calls coroutine q , it sets p -state to an appropriate number and also sets q -caller = p . Then control passes to q at the place determined by q -state.

When coroutine q wants to return a boolean value, it sets *coresult* to this value; then it passes control to $p = q$ -caller at the place determined by p -state.

This program simulates coroutine linkage with a big switch statement. Actually the notion of “passing control” really means that we simply assign a value to the variable *cur_cnode*.

The value of q -caller for every cnode q is completely determined by the structure of the given forest, so we could set it once and for all during the initialization instead of setting it dynamically as done here. But what the heck.

```
#define cocall(q, s)
    { cur_cnode-state = s;
      if (q) q-caller = cur_cnode, cur_cnode = q;
      else coresult = false;
      goto cogo; }
#define bitchange(b, s)
    { cur_cnode-bit = b, coresult = true; coreturn(s); }
#define coreturn(s)
    { cur_cnode-state = s, cur_cnode = cur_cnode-caller;
      goto cogo; }

⟨ Repeatedly switch to the proper part of the current coroutine 5 ⟩ ≡
cogo: switch (cur_cnode-state) {
    ⟨ Cases for coroutine states 6 ⟩;
    default: abort("%s: Unknown state code (this can't happen)!\n", 0);
}
```

This code is used in section 9.

6. In its initial state 0, a coroutine turns its bit on, returns *true*, and enters state 1.

```
⟨ Cases for coroutine states 6 ⟩ ≡
case 0: bitchange(1, 1);
```

See also sections 7, 8, and 12.

This code is used in section 5.

7. The purpose of state 1 is to run through all bit patterns of the current node’s children, starting with all 0s and ending when they reach their final pattern. At that point we invoke the current node’s nearest left sibling and enter state 3. An intermediate state 2 is defined for the purpose of examining the result after calling the child coroutine.

The purpose of state 3 is simply to return to whoever called us, passing along the information in *coresult*, which tells whether any of our left siblings has changed one of its bits. Then we will continue in state 4.

```
⟨ Cases for coroutine states 6 ⟩ +=
case 1: cocall(cur_cnode-child, 2);
case 2: if (coresult) coreturn(1);
        cocall(cur_cnode-sib, 3);
case 3: coreturn(4);
```

8. State 4 is rather like state 1, except that the child coroutine is now running through its bit patterns in reverse order. Finally it reduces them all to 0s, and returns *false* the next time we attempt to invoke it. At that point we reset the current bit, return *true*, and enter state 6.

State 6 invokes the sibling coroutine, leading to state 7. And state 7 is like state 3, but it takes us back to state 0 instead of state 4.

```

⟨ Cases for coroutine states 6 ⟩ +≡
case 4: cocall(cur_cnode-child, 5);
case 5: if (coresult) coreturn(4);
        bitchange(0, 6);
case 6: cocall(cur_cnode-sib, 7);
case 7: coreturn(0);

```

9. Hey, the implementation is done already, except that we have to get it started and write the code that controls it at the outermost level.

```

⟨ Generate the strings with a coroutine implementation 9 ⟩ ≡
{
    register cnode *cur_cnode;
    ⟨ Initialize the cnode structure 10 ⟩;
    ⟨ Repeatedly switch to the proper part of the current coroutine 5 ⟩;
}

```

This code is used in section 1.

10. We allocate a special cnode to represent the external world outside of the given forest.

```

#define root_cnode cnode_table[nn].child
⟨ Initialize the cnode structure 10 ⟩ ≡
    scope[nn] = 0;
    for (k = 0; k ≤ nn; k++)
        if (scope[k] < k) {
            cnode_table[k].child = cnode_table + k - 1;
            for (j = k - 1; scope[j] > scope[k]; j = scope[j] - 1) cnode_table[j].sib = cnode_table + scope[j] - 1;
        }
    cur_cnode = cnode_table + nn;
    goto upward_step;

```

This code is used in section 9.

```

11. ⟨ Global variables 3 ⟩ +≡
    cnode cnode_table[forestsize + 1];    /* the cnodes */
    boolean coresult;    /* value returned by a coroutine */

```

12. States 8 and greater are reserved for the external (outermost) level, which simply invokes the coroutine for the entire forest and prints out the results, until the bit patterns have been generated in both the forward and reverse directions.

⟨ Cases for coroutine states 6 ⟩ +≡

```

case 8: if (coresult) {
    upward_step: ⟨ Print out all the current cnode bits 13 ⟩;
    cocall(root_cnode, 8);
}
printf("...and now we generate them in reverse:\n");
goto downward_step;
case 9: if (coresult) {
    downward_step: ⟨ Print out all the current cnode bits 13 ⟩;
    cocall(root_cnode, 9);
}
break;

```

13. ⟨ Print out all the current cnode bits 13 ⟩ ≡

```

for (k = 0; k < nn; k++) putchar('0' + cnode_table[k].bit);
putchar(' \n ');

```

This code is used in section 12.

14. The loopless implementation. Our coroutine implementation solves the generation problem in a nice and natural fashion, but it can be inefficient if the given forest has numerous nodes of degree one. For example, a one-tree forest like $((\dots())\dots)$ with n pairs of parentheses will need approximately $\binom{n}{2}$ coroutine invocations to generate $n + 1$ bitstrings.

Our second implementation reduces the work in such cases to $O(n)$; in fact, it needs only a bounded number of operations to generate each bitstring after the first. It does, however, need a slightly more complex data structure with four link fields.

The basic idea is to work with a dynamically varying list of nodes called the current *fringe* of the forest. The fringe consists of all node whose bit is 1, together with their children. We maintain it as a doubly linked list, so that $p\text{-left}$ and $p\text{-right}$ are the neighbors of p on the left and right. A special node *head* is provided to make the list circular; thus $head\text{-right}$ and $head\text{-left}$ are the leftmost and rightmost fringe nodes.

A fringe node is said to be either *active* or *passive*. Every node is active when it joins the fringe, but it becomes passive for at least a short time when its bit changes value; at such times the node is essentially shifting direction between going forward or backward, as in the coroutine implementation. (A passive node corresponds roughly to a coroutine that is asking its siblings to make the next move.) We save time jumping across such call-chains by using a special link field called the *focus*: If p is a passive fringe node whose righthand neighbor $p\text{-right}$ is active, $p\text{-focus}$ is the rightmost active node to the left of p in the fringe; otherwise $p\text{-focus} = p$. (The special *head* node is always considered to be active, for purposes of this definition, but it is not strictly speaking a member of the fringe.)

The loopless implementation works with records called lnodes, just as the coroutine implementation worked with cnodes. Besides the dynamic *bit* and *left* and *right* and *focus* fields already mentioned, each lnode also has a static field called *lchild*, representing its leftmost child. (There is no need for an *rchild* field, since $p\text{-rchild} = p - 1$ when $p\text{-lchild} \neq \Lambda$.)

If p is not in the fringe, $p\text{-focus}$ should equal p . Also, $p\text{-left}$ and $p\text{-right}$ are assumed to equal the nearest siblings of p to the left and right, respectively, if such siblings exist; otherwise $p\text{-left}$ and/or $p\text{-right}$ are undefined.

⟨ Type definitions 4 ⟩ \equiv

```
typedef struct lnode_struct {
    char bit;          /* either 0 or 1; always 1 when a child's bit is set */
    struct lnode_struct *left, *right; /* neighbors in the forest and/or fringe */
    struct lnode_struct *lchild;      /* leftmost child */
    struct lnode_struct *focus;      /* red-tape cutter for efficiency */
} lnode;
```

15. Here now is the basic outline of the loopless implementation:

```

⟨Generate the strings with a loopless implementation 15⟩ ≡
{
  register lnode *p, *q, *r;
  ⟨Initialize the lnode structure, putting all roots into the fringe 16⟩;
  while (1) {
    ⟨Print out all the current lnode bits 22⟩;
    ⟨Set p to the rightmost active node of the fringe, and activate everything to its right 18⟩;
    if (p ≠ head) {
      if (p→bit ≡ 0) {
        p→bit = 1; /* moving forward */
        ⟨Insert the children of p after p in the fringe 19⟩;
      } else {
        p→bit = 0; /* moving backward */
        ⟨Delete the children of p from the fringe 20⟩;
      }
    } else if (been_there_and_done_that) break;
    else {
      printf("...and now we generate them in reverse:\n");
      been_there_and_done_that = true; continue;
    }
    ⟨Make node p passive 21⟩;
  }
}

```

This code is used in section 1.

16. Initialization of the lnodes is similar to initialization of the cnodes, but more links need to be set up.

```

#define head (lnode_table + nn)
⟨Initialize the lnode structure, putting all roots into the fringe 16⟩ ≡
for (k = 0; k ≤ nn; k++) {
  lnode_table[k].focus = lnode_table + k;
  if (scope[k] < k) {
    for (j = k - 1; scope[j] > scope[k]; j = scope[j] - 1) {
      lnode_table[j].left = lnode_table + scope[j] - 1;
      lnode_table[scope[j] - 1].right = lnode_table + j;
    }
    lnode_table[k].lchild = lnode_table + j;
  }
}
head→left = head - 1, (head - 1)→right = head;
head→right = head→lchild, head→lchild→left = head;

```

This code is used in section 15.

17. ⟨Global variables 3⟩ +≡
 lnode lnode_table[forestsize + 1]; /* the lnodes */
 boolean been_there_and_done_that;

18. \langle Set p to the rightmost active node of the fringe, and activate everything to its right 18 $\rangle \equiv$
 $q = \text{head-left};$
 $p = q\text{-focus};$
 $q\text{-focus} = q;$

This code is used in section 15.

19. \langle Insert the children of p after p in the fringe 19 $\rangle \equiv$
if ($p\text{-lchild}$) {
 $q = p\text{-right};$
 $q\text{-left} = p - 1, (p - 1)\text{-right} = q;$
 $p\text{-right} = p\text{-lchild}, p\text{-lchild-left} = p;$
}

This code is used in section 15.

20. \langle Delete the children of p from the fringe 20 $\rangle \equiv$
if ($p\text{-lchild}$) {
 $q = (p - 1)\text{-right};$
 $p\text{-right} = q, q\text{-left} = p;$
}

This code is used in section 15.

21. At this point we know that $p\text{-right}$ is active.

\langle Make node p passive 21 $\rangle \equiv$
 $p\text{-focus} = p\text{-left-focus};$
 $p\text{-left-focus} = p\text{-left};$

This code is used in section 15.

22. \langle Print out all the current lnode bits 22 $\rangle \equiv$
for ($k = 0; k < nn; k++$) $\text{putchar}('0' + \text{lnode_table}[k].\text{bit});$
 $\text{putchar}('\n');$

This code is used in section 15.

23. I used the following code when debugging.

#define $\text{rel}(f)$ ($\text{lnode_table}[k].f ? \text{lnode_table}[k].f - \text{lnode_table} : -1$)
 \langle Print out the whole lnode structure 23 $\rangle \equiv$
for ($k = 0; k \leq nn; k++$) {
 $\text{printf}(\text{"lnode_}\square\text{d:}\square\text{bit=}\square\text{d,}\square", k, \text{lnode_table}[k].\text{bit});$
 $\text{printf}(\text{"focus=}\square\text{d,}\square\text{left=}\square\text{d,}\square\text{right=}\square\text{d,}\square\text{lchild=}\square\text{d}\backslash\text{n"} , \text{rel}(\text{focus}), \text{rel}(\text{left}), \text{rel}(\text{right}), \text{rel}(\text{lchild}));$
}

24. Index.

abort: [2](#), [5](#).
argc: [1](#), [2](#).
argv: [1](#), [2](#).
been_there_and_done_that: [15](#), [17](#).
bit: [4](#), [5](#), [13](#), [14](#), [15](#), [22](#), [23](#).
bitchange: [5](#), [6](#), [8](#).
boolean: [4](#), [11](#), [17](#).
caller: [4](#), [5](#).
child: [4](#), [7](#), [8](#), [10](#).
cnode: [4](#), [9](#), [11](#).
cnode_struct: [4](#).
cnode_table: [10](#), [11](#), [13](#).
cocall: [5](#), [7](#), [8](#), [12](#).
cogo: [5](#).
coresult: [5](#), [7](#), [8](#), [11](#), [12](#).
coreturn: [5](#), [7](#), [8](#).
cur_cnode: [5](#), [7](#), [8](#), [9](#), [10](#).
downward_step: [12](#).
false: [4](#), [5](#), [8](#).
focus: [14](#), [16](#), [18](#), [21](#), [23](#).
forestsize: [2](#), [3](#), [11](#), [17](#).
fprintf: [2](#).
head: [14](#), [15](#), [16](#), [18](#).
j: [1](#).
k: [1](#).
l: [1](#).
lchild: [14](#), [16](#), [19](#), [20](#), [23](#).
left: [14](#), [16](#), [18](#), [19](#), [20](#), [21](#), [23](#).
lnode: [14](#), [15](#), [17](#).
lnode_struct: [14](#).
lnode_table: [16](#), [17](#), [22](#), [23](#).
main: [1](#).
nn: [2](#), [3](#), [10](#), [13](#), [16](#), [22](#), [23](#).
p: [15](#).
printf: [1](#), [12](#), [15](#), [23](#).
putchar: [13](#), [22](#).
q: [15](#).
r: [15](#).
rchild: [14](#).
rel: [23](#).
right: [14](#), [16](#), [19](#), [20](#), [21](#), [23](#).
root_cnode: [10](#), [12](#).
scope: [2](#), [3](#), [10](#), [16](#).
sib: [4](#), [7](#), [8](#), [10](#).
stack: [2](#), [3](#).
stacksize: [2](#), [3](#).
state: [4](#), [5](#).
stderr: [2](#).
true: [4](#), [5](#), [6](#), [8](#), [15](#).
upward_step: [10](#), [12](#).

- ⟨ Cases for coroutine states [6](#), [7](#), [8](#), [12](#) ⟩ Used in section [5](#).
- ⟨ Delete the children of p from the fringe [20](#) ⟩ Used in section [15](#).
- ⟨ Generate the strings with a coroutine implementation [9](#) ⟩ Used in section [1](#).
- ⟨ Generate the strings with a loopless implementation [15](#) ⟩ Used in section [1](#).
- ⟨ Global variables [3](#), [11](#), [17](#) ⟩ Used in section [1](#).
- ⟨ Initialize the cnode structure [10](#) ⟩ Used in section [9](#).
- ⟨ Initialize the lnode structure, putting all roots into the fringe [16](#) ⟩ Used in section [15](#).
- ⟨ Insert the children of p after p in the fringe [19](#) ⟩ Used in section [15](#).
- ⟨ Make node p passive [21](#) ⟩ Used in section [15](#).
- ⟨ Print out all the current cnode bits [13](#) ⟩ Used in section [12](#).
- ⟨ Print out all the current lnode bits [22](#) ⟩ Used in section [15](#).
- ⟨ Print out the whole lnode structure [23](#) ⟩
- ⟨ Process the command line, parsing the given forest [2](#) ⟩ Used in section [1](#).
- ⟨ Repeatedly switch to the proper part of the current coroutine [5](#) ⟩ Used in section [9](#).
- ⟨ Set p to the rightmost active node of the fringe, and activate everything to its right [18](#) ⟩ Used in section [15](#).
- ⟨ Type definitions [4](#), [14](#) ⟩ Used in section [1](#).

KODA-RUSKEY

	1	2
	12	13
	14	15
	16	17
	18	19
	20	21
	22	23
	24	25
	26	27
	28	29
	30	31
	32	33
	34	35
	36	37
	38	39
	40	41
	42	43
	44	45
	46	47
	48	49
	50	51
	52	53
	54	55
	56	57
	58	59
	60	61
	62	63
	64	65
	66	67
	68	69
	70	71
	72	73
	74	75
	76	77
	78	79
	80	81
	82	83
	84	85
	86	87
	88	89
	90	91
	92	93
	94	95
	96	97
	98	99
	100	101
	102	103
	104	105
	106	107
	108	109
	110	111
	112	113
	114	115
	116	117
	118	119
	120	121
	122	123
	124	125
	126	127
	128	129
	130	131
	132	133
	134	135
	136	137
	138	139
	140	141
	142	143
	144	145
	146	147
	148	149
	150	151
	152	153
	154	155
	156	157
	158	159
	160	161
	162	163
	164	165
	166	167
	168	169
	170	171
	172	173
	174	175
	176	177
	178	179
	180	181
	182	183
	184	185
	186	187
	188	189
	190	191
	192	193
	194	195
	196	197
	198	199
	200	201
	202	203
	204	205
	206	207
	208	209
	210	211
	212	213
	214	215
	216	217
	218	219
	220	221
	222	223
	224	225
	226	227
	228	229
	230	231
	232	233
	234	235
	236	237
	238	239
	240	241
	242	243
	244	245
	246	247
	248	249
	250	251
	252	253
	254	255
	256	257
	258	259
	260	261
	262	263
	264	265
	266	267
	268	269
	270	271
	272	273
	274	275
	276	277
	278	279
	280	281
	282	283
	284	285
	286	287
	288	289
	290	291
	292	293
	294	295
	296	297
	298	299
	300	301
	302	303
	304	305
	306	307
	308	309
	310	311
	312	313
	314	315
	316	317
	318	319
	320	321
	322	323
	324	325
	326	327
	328	329
	330	331
	332	333
	334	335
	336	337
	338	339
	340	341
	342	343
	344	345
	346	347
	348	349
	350	351
	352	353
	354	355
	356	357
	358	359
	360	361
	362	363
	364	365
	366	367
	368	369
	370	371
	372	373
	374	375
	376	377
	378	379
	380	381
	382	383
	384	385
	386	387
	388	389
	390	391
	392	393
	394	395
	396	397
	398	399
	400	401
	402	403
	404	405
	406	407
	408	409
	410	411
	412	413
	414	415
	416	417
	418	419
	420	421
	422	423
	424	425
	426	427
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