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

1. Intro. Analyzing the graph created by TIC-TAC-TOE1.

I'm experimenting with a scoring system that includes "difficulty" as part of the desirability of a position. If you have to think harder to win, the position isn't quite as good as one in which no-brainer moves will take you home. Thus, one tries to move to positions that require the opponent to keep alert.

Furthermore, I consider it more desirable to win with lots of marks on the board than with fewer (because you have kindly refrained from humiliating your opponent).

```
#define rank z.I    /* number of moves made */
#define link y.V    /* next vertex of same rank */
#define head x.V    /* first vertex of given rank */
#define winner w.I    /* is this a winning position? */
#define bitcode v.I    /* binary representation of this position */
#define follower u.V    /* an optimal move goes here */
#define score w.I    /* the primary value of this position */
#define nobrainer u.I    /* immediate or threatened win */
#include "gb_graph.h"
#include "gb_save.h"
  Vertex *pos[1 ≪ 18];
  unsigned int diff[1 ≪ 18];    /* the difficulty factor */
  int count[9], win[9];
  main()
  {
    register j, k, s, t, tt, auts;
    register unsigned int d;
    Vertex *u, *v;
    Arc *a;
    Graph *g = restore_graph("/tmp/tictactoe.gb");
    ⟨Fill in the nobrainer fields 2⟩;
    for (k = 9; k ≥ 0; k−−)
      for (v = (g→vertices + k)→head; v; v = v→link) {
        pos[v→bitcode] = v;
        ⟨Compute the score and difficulty of v 3⟩;
      }
    for (k = 9; k ≥ 0; k−−)
      for (v = (g→vertices + k)→head; v; v = v→link) {
        ⟨Determine the equivalence class of v 4⟩;
      }
    for (k = 0; k ≤ 9; k++) printf("(%d,%d)␣classes␣after␣%d␣moves\n", count[k], win[k], k);
  }
```

2. The *nobrainer* field is set to +1 if there's a one-move win, and to −1 if the opponent has a one-move win that should be blocked.

⟨ Fill in the *nobrainer* fields 2 ⟩ ≡

```
for (k = 9; k ≥ 0; k−−)
  for (v = (g→vertices + k)→head; v; v = v→link) {
    for (a = v→arcs; a; a = a→next) {
      u = a→tip;
      if (u→winner) {
        v→nobrainer = 1;
        break;
      }
      if (u→nobrainer > 0) v→nobrainer = −1;     /* may be set +1 later */
    }
  }
```

This code is used in section 1.

3. The *score* field takes the place of what used to be called *winner*. Scores are computed from the standpoint of the `X` player: A score of +6 means that `X` can force a win at move six; a score of −9 means that `O` can win (or has won) at move nine. A score of zero means that a draw is the best possible outcome.

Positions with equal score are ranked secondarily by their *diff*, which is a sequence of 8 hexadecimal digits. The most significant digit is the number of nonoptimal moves facing the player at this position. The next digit is the *complement* of the number of nonoptimal moves facing the opponent, after the player has made an optimal move. And so on; even-numbered digits are complemented with respect to `f`.

⟨ Compute the *score* and difficulty of *v* 3 ⟩ ≡

```
if (v→winner) v→score = −v→rank, diff[v→bitcode] = #0f0f0f0f;
else if (v→rank ≡ 9) v→score = 0, diff[v→bitcode] = #0f0f0f0f;
else {
  for (s = 99, a = v→arcs; a; a = a→next) {
    u = a→tip;
    if (s > u→score ∨ (s ≡ u→score ∧ d < diff[u→bitcode])) s = u→score, d = diff[u→bitcode];
  }
  t = v→nobrainer;     /* the nobrainer field will become follower now */
  for (j = 0, a = v→arcs; a; a = a→next) {
    u = a→tip;
    if (s ≠ u→score ∨ d ≠ diff[u→bitcode]) j++;
    else v→follower = u;
  }
  if (t < 0 ∨ s ≡ −k − 1) j = 0;
  v→score = −s, diff[v→bitcode] = (j ≪ 28) + ((#fffffff − d) ≫ 4);
}
```

This code is used in section 1.

4. The tic-tac-toe board has eight automorphisms. So I can save a factor of roughly eight when I'm trying to understand this data.

```
⟨Determine the equivalence class of v 4⟩ ≡
  t = tt = v→bitcode, auts = 1;
  for (j = 1; j < 4; j++) {
    t = t ⊕ ((t ⊕ (t ≫ 2)) & #3f3f) ⊕ ((t ⊕ (t ≪ 6)) & #c0c0);      /* rotate 90° */
    if (t < tt) tt = t, auts = 1;
    else if (t ≡ tt) auts++;
  }
  t = t ⊕ ((t ⊕ (t ≫ 2)) & #3300) ⊕ ((t ⊕ (t ≪ 2)) & #cc00) ⊕ ((t ⊕ (t ≫ 4)) & #3) ⊕ ((t ⊕ (t ≪ 4)) & #30);
    /* reflect */
  if (t < tt) tt = t, auts = 1;
  else if (t ≡ tt) auts++;
  for (j = 1; j < 4; j++) {
    t = t ⊕ ((t ⊕ (t ≫ 2)) & #3f3f) ⊕ ((t ⊕ (t ≪ 6)) & #c0c0);      /* rotate 90° */
    if (t < tt) tt = t, auts = 1;
    else if (t ≡ tt) auts++;
  }
  if (tt ≡ v→bitcode) ⟨Print the best move from v 5⟩;
  if (v→score ≠ pos[tt]→score ∨ diff[v→bitcode] ≠ diff[pos[tt]→bitcode]) printf("I␣goofed!\n");
```

This code is used in section 1.

5. Whenever v is the leader of an equivalence class, I print out its characteristics.

```
⟨Print the best move from v 5⟩ ≡
  {
    count[v→rank]++;
    printf("%s␣has␣score␣%d(%08x),␣size␣%d", v→name, v→score, diff[v→bitcode] ⊕ #0f0f0f0f, 8/auts);
    if (v→follower) {
      printf(",␣->␣");
      for (j = 0; j ≤ 10; j++)
        printf("%c", v→follower→name[j] < 'A' ? v→follower→name[j] : 'X' + 'O' − v→follower→name[j]);
    } else win[k]++;
    printf("\n");
  }
```

This code is used in section 4.

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TICTACTOE2