

1. Intro. This program finds all odd n -bit palindromes x that are perfect squares, using roughly $2^{n/4}$ steps of computation. Thus I hope to use it for n well over 100. The idea is to try all 2^t combinations of the rightmost and leftmost $t + 3$ bits, for $t \approx n/4$, and to use number theory to rule out the bad cases rather quickly.

(When $n = 100$ I'll be using $t = 22$. This program is a big improvement over the one I wrote in 2013; that one used $t = 31$ when $n = 100$, and $t \approx n/3$ in general. Michael Coriand surprised me last week by claiming that he had a method using only about $n/4$. At first I was mystified, baffled, stumped. But aha, I woke up this morning with a good guess about what he'd discovered! He asked me to doublecheck his results; and I can't resist, even though I've got more than enough other things to do, because it's fun to write useless code like this.)

I haven't optimized this program for computational speed. My main goal was to get it right, with my personal time minimized. On the other hand I could easily have made it run a lot slower: I didn't pass up some "obvious" ways to avoid redundant computations.

```
#define maxn 180 /* I could go a little higher, but there won't be time */
#include <stdio.h>
#include <stdlib.h>
int n; /* the length of palindromes sought */
unsigned long long y[maxn/2], r[maxn/2]; /* table of partial square roots */
unsigned long long q[maxn/4], qq[maxn/4]; /* table of partial modular sqrts */
unsigned long long pretrial[2], trial[3], acc[6]; /* multiplication workspace */
main(int argc, char *argv[])
{
    register unsigned long long prod, sqrtxl, a, bit;
    register int j, k, t, p, jj, kk;
    <Process the command line 2>;
    printf("Binary palindromic squares with %d bits:\n", n);
    <Choose t and initialize the tables 12>;
    for (a = 0; a < 1LL << t; a++) <See if case a leads to any square palindromes 13>;
}

2. <Process the command line 2> ≡
if (argc ≠ 2 ∨ sscanf(argv[1], "%d", &n) ≠ 1) {
    fprintf(stderr, "Usage: %s\n", argv[0]);
    exit(-1);
}
if (n < 15 ∨ n > maxn) {
    fprintf(stderr, "Sorry: n should be between 15 and %d.\n", maxn);
    exit(-2);
}
```

This code is used in section 1.

3. Here's the theory: Let $a_1a_2 \dots a_t$ be a binary string, and suppose

$$x = 2^{n-1} + 2^{n-4}a_1 + 2^{n-5}a_2 + \dots + 2^{n-3-t}a_t + \dots + 2^{t+2}a_t + \dots + 2^4a_2 + 2^3a_1 + 1 = y^2.$$

Let $x_l = 2^{n-1} + 2^{n-4}a_1 + 2^{n-5}a_2 + \dots + 2^{n-3-t}a_t$ and $x_u = x_l + 2^{n-3-t}$.

It's easy to prove by induction on t that there's a unique integer q between 0 and 2^{t+2} such that $q \bmod 4 = 1$ and $q^2 \bmod 2^{t+3} = 2^{t+2}a_t + \dots + 2^4a_2 + 2^3a_1 + 1$, whenever $t > 0$. Hence the lower bits of the square root, $y \bmod 2^{t+2}$, must be either q or $2^{t+2} - q$.

On the other hand $x_l < x < x_u$; hence $\sqrt{x_l} < y < \sqrt{x_u}$. This tells us about the upper bits: We have $x_u = x_l(1 + \delta)$, where $\delta = 2^{n-3-t}/x_l$; hence $\sqrt{x_u} - \sqrt{x_l} = \sqrt{x_l}(\sqrt{1 + \delta} - 1) < \sqrt{x_l}\delta/2 = 2^{n-4-t}/\sqrt{x_l} \leq 2^{n-4-t}/2^{(n-1)/2} = 2^{n/2-7/2-t}$. The integers between $\sqrt{x_l}$ and $\sqrt{x_u}$ will therefore be distinct, modulo 2^{t+2} , if we have $n/2 - 7/2 - t \leq t + 2$.

It follows that we need only check two potential values of y , for each of the 2^t choices of $a_1a_2 \dots a_t$, when $t \geq (n - 11)/4$. Furthermore, this estimate is somewhat crude; there won't be many cases to try even if t is a bit smaller.

For example, let's consider the case $n = 25$ and $t = 3$. In the first case $a_1a_2a_3 = 000$, we have $x_l = 2^{24}$ and $x_u = 2^{24} + 2^{19}$; so y lies between $(1000000000000)_2$ and $(1000000111111)_2$. Furthermore $y \bmod 2^5$ must be 1 or 31. So the only possible square roots of a binary palindrome having the form $(100000 \dots 000001)_2$ are

$$(10000000000001)_2, \quad (1000000011111)_2, \quad (1000000100001)_2, \quad (1000000111111)_2.$$

In the last case $a_1a_2a_3 = 111$, we have $x_l = 2^{24} + 2^{22} - 2^{19}$ and $x_u = 2^{24} + 2^{22}$; so y lies between $(1000110101001)_2$ and $(1000111100011)_2$. Furthermore $y \bmod 2^5$ must be 21 or 11. Again there are only four y 's to try:

$$(1000110101011)_2, \quad (1000110110101)_2, \quad (1000111001011)_2, \quad (1000111010101)_2.$$

(And the first of these actually works! Its square is $(1001110000010100000111001)_2$.)

The program below actually finds it convenient to try a few cases that could have been ruled out by the arguments above. For example, it will try also $(1000111101011)_2$ and $(100011110101)_2$ in the previous example.

4. We'll have to compute 2^t "modular square roots" q . Let $q[j]$ be the square root of $2^{j+2}a_j + \dots + 2^3a_1 + 1$ (modulo 2^{j+3}), and let $qq[j]$ be the rightmost $t + 2$ bits of its square. If $j < t$, $q[j + 1]$ will be either $q[j]$ or $q[j] + 2^{j+1}$, depending on the $(j + 2)$ nd bit of $qq[j]$.

When $a_1 \dots a_t = 0 \dots 0$, we have $q[j] = qq[j] = 1$ for all j . And when moving from any $a_1 \dots a_t$ to its successor, we need only recompute a few of the entries — $q[t]$ always, $q[t - 1]$ half the time, $q[t - 2]$ one-fourth of the time, etc.

⟨ Initialize the q and qq tables 4 ⟩ \equiv

for ($j = 1$; $j \leq t$; $j++$) $q[j] = qq[j] = 1$;

This code is used in section 12.

5. ⟨ Update q and qq when a_p changes from 0 to 1 5 ⟩ \equiv

$q[p] \oplus = 1_{LL} \ll (p + 1)$;

$qq[p] = q[p] * q[p]$;

for ($j = p + 1$; $j \leq t$; $j++$) {

if ($qq[j - 1] \& (1_{LL} \ll (j + 2))$) $q[j] = q[j - 1] \oplus (1_{LL} \ll (j + 1))$;

else $q[j] = q[j - 1]$;

$qq[j] = q[j] * q[j]$;

}

This code is used in section 13.

6. Similarly, we'll have to compute 2^t approximate square roots for the leading bits of y . Let $y[j]$ be bits m through j of $\sqrt{x_l}$, where $m = \lfloor n/2 \rfloor - 1$ is the index of the leading bit. The classical algorithm for square root extraction tells us how to go from $y[j]$ to $y[j-1]$: We have a “remainder” $r[j]$ representing the difference from the leading bits of x_l and $y[j]^2$, where $r[j] \leq 2y[j]$. To preserve this invariant when $a_1 \dots a_t = 0 \dots 0$, we set $y[j-1] = 2y[j]$ and $r[j-1] = 4r[j]$; if then $r[j-1] > 2y[j-1]$ we subtract $2y[j-1] + 1$ from $r[j-1]$ and increase $y[j-1]$ by 1. To preserve the invariant for other values of $a_1 \dots a_t$, the same steps apply except that $r[j-1] = 4r[j] + 2a_i + a_{i+1}$ for an appropriate value of i . The bits of the square root need only be computed for $j \geq t+2$; therefore all computations fit easily into a single **long long** register.

Once again it's easy to prime the pump when $a_1 \dots a_t = 0 \dots 0$, and to move to the successor by updating fewer than two entries on average (plus roughly $n/8$ entries “in the middle” where x_l has roughly $n/4$ zeros).

⟨ Initialize the y and r tables 6 ⟩ \equiv

```

if ( $n \& 1$ ) {
   $y[(n-3)/2] = 2, r[(n-3)/2] = 0;$ 
  for ( $j = (n-5)/2; j \geq t+2; j--$ )  $y[j] = 2 * y[j+1], r[j] = 0;$ 
} else {
   $y[n/2-1] = 1, r[n/2-1] = 1;$ 
  for ( $j = n/2-2; j \geq t+2; j--$ ) {
     $y[j] = 2 * y[j+1], r[j] = 4 * r[j+1];$ 
    if ( $r[j] > 2 * y[j]$ )  $r[j] -= 2 * y[j] + 1, y[j]++;$ 
  }
}

```

This code is used in section 12.

7. ⟨ Update y and r when a_p changes from 0 to 1 7 ⟩ \equiv

```

 $j = (n-3-p)/2;$ 
if ( $(n+p) \& 1$ )  $r[j] += 1;$ 
else  $r[j] = 4 * r[j+1] + 2, y[j] = 2 * y[j+1];$ 
if ( $r[j] > 2 * y[j]$ )  $r[j] -= 2 * y[j] + 1, y[j]++;$ 
for ( $j--; j \geq t+2; j--$ ) {
   $y[j] = 2 * y[j+1], r[j] = 4 * r[j+1];$ 
  if ( $r[j] > 2 * y[j]$ )  $r[j] -= 2 * y[j] + 1, y[j]++;$ 
}

```

This code is used in section 13.

8. Now comes the boring stuff. I hope I don't mess up here. To make the final test, I'll need to square a number of up to 90 bits. I simply treat it as three 32-bit chunks, and multiply by the textbook method.

```
#define m32 0xffffffff /* 32-bit mask */
```

⟨ Square the contents of *trial* 8 ⟩ ≡

```
for (j = 0; j < 3; j++) {
    prod = trial[j] * trial[0];
    if (j) prod += acc[j];
    acc[j] = prod & m32;
    prod >>= 32;
    prod += trial[j] * trial[1];
    if (j) prod += acc[j + 1];
    acc[j + 1] = prod & m32;
    prod >>= 32;
    prod += trial[j] * trial[2];
    if (j) prod += acc[j + 2];
    acc[j + 2] = prod & m32;
    acc[j + 3] = prod >> 32;
}
```

This code is used in section 14.

9. To manufacture the *trial*, I need to shift the leading digits appropriately and combine them with the trailing digits. First, I put the leading digits into *pretrial* and *trial*. (This can be tricky: If $n = 129$ or 130 , so that $t = 29$, there are 34 leading digits; one of them will go into *trial*[0], 32 into *trial*[1], and one into *trial*[2].)

⟨ Shift the leading digits 9 ⟩ ≡

```
if (t + 2 < 32) pretrial[0] = (sqrtd << (t + 2)) & m32, pretrial[1] = (sqrtd >> (30 - t)) & m32;
else pretrial[0] = 0, pretrial[1] = (sqrtd << (t - 30)) & m32;
trial[2] = sqrtd >> (62 - t);
```

This code is used in section 13.

10. ⟨ Add $q[t]$ to the *trial* 10 ⟩ ≡

```
if (t + 2 ≤ 32) trial[0] = pretrial[0] + q[t], trial[1] = pretrial[1];
else trial[0] = q[t] & m32, trial[1] = pretrial[1] + (q[t] >> 32);
```

This code is used in section 13.

11. #define comp(x) ((1LL << (t + 2)) - (x))

⟨ Add the complement of $q[t]$ to the *trial* 11 ⟩ ≡

```
if (t + 2 ≤ 32) trial[0] = pretrial[0] + comp(q[t]), trial[1] = pretrial[1];
else trial[0] = comp(q[t]) & m32, trial[1] = pretrial[1] + (comp(q[t]) >> 32);
```

This code is used in section 13.

12. I make $t = \lfloor (n - 11)/4 \rfloor$. (It will be between 1 and 42.)

⟨ Choose t and initialize the tables 12 ⟩ ≡

```
t = (n - 11)/4;
⟨ Initialize the  $q$  and  $qq$  tables 4 ⟩;
⟨ Initialize the  $y$  and  $r$  tables 6 ⟩;
```

This code is used in section 1.

13. And now at last the denouement, where we put everything together.

```

⟨ See if case a leads to any square palindromes 13 ⟩ ≡
{
    sqrtrl = y[t + 2];
    for (p = t, bit = 1; a & bit; p--, bit <= 1) ;
    ⟨ Update y and r when ap changes from 0 to 1 7 ⟩;
    if (y[t + 2] ≥ sqrtrl + 4) fprintf(stderr, "Something's wrong in case %llx!\n", a);
    for ( ; sqrtrl ≤ y[t + 2]; sqrtrl++) {
        ⟨ Shift the leading digits 9 ⟩;
        ⟨ Add q[t] to the trial 10 ⟩;
        ⟨ Check if trial is a solution 14 ⟩;
        ⟨ Add the complement of q[t] to the trial 11 ⟩;
        ⟨ Check if trial is a solution 14 ⟩;
    }
    ⟨ Update q and qq when ap changes from 0 to 1 5 ⟩
}

```

This code is used in section 1.

```

14. ⟨ Check if trial is a solution 14 ⟩ ≡
⟨ Square the contents of trial 8 ⟩;
for (j = 0, k = n - 1; j < k; j++, k--) {
    jj = ((acc[j] >> 5) & (1 << (j & #1f))) ≠ 0);
    kk = ((acc[k] >> 5) & (1 << (k & #1f))) ≠ 0);
    if (jj ≠ kk) break;
}
if (j ≥ k) /* solution! */
    printf("%08llx%08llx%08llx^2=%08llx%08llx%08llx%08llx%08llx\n", trial[2], trial[1],
        trial[0], acc[5], acc[4], acc[3], acc[2], acc[1], acc[0]);

```

This code is used in section 13.

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SQUAREPAL

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