An Observation on Rolle's problem

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In an earlier edition of the Gazette [3], Michael Hirschhorn considers the problem of finding three distinct integers a, b, c such that $a \pm b$, $a \pm c$, $b \pm c$ are all squares. In 1682 Rolle [2] had already provided a two parameter family of such 3-tuples,

$$\begin{aligned} a &= y^{20} + 21y^{16}z^4 - 6y^{12}z^8 - 6y^8z^{12} + 21y^4z^{16} + z^{20} \\ b &= 10y^2z^{18} - 24y^6z^{14} + 60y^{10}z^{10} - 24y^{14}z^6 + 10y^{18}z^2 \\ c &= 6y^2z^{18} + 24y^6z^{14} - 92y^{10}z^{10} + 24y^{14}z^6 + 6y^{18}z^2 \end{aligned}$$

however they did not cover all such solutions.

Hirschhorn sets these 6 squares to m^2, n^2, p^2, q^2, r^2, s^2 respectively and then goes on to show that this problem is equivalent to finding rational values k, l, Y such that

$$k(k^2 - 1)(l^4 - 1) = Y^2 \tag{1}$$

where $k = \frac{m+p}{q-n} = \frac{q+n}{m-p}$ and $l = \frac{p+q}{r-s} = \frac{r+s}{p-q}$. Hirschhorn completely solves the case of $k = l^2$.

When I first read the article and saw equation (1) I immediately thought of a parameterised elliptic curve (see [5]). As a result, the machinery developed there can be applied here. Set $l = \frac{u}{v}$ in equation (1) and then multiply by $v^4(u^4 - v^4)^2$ to obtain $[v^2(u^4 - v^4)Y]^2 = (u^4 - v^4)^3k^3 - (u^4 - v^4)^3k$. Now transform this by letting $x := (u^4 - v^4)k$ and $y := v^2(u^4 - v^4)Y$ to get

$$E[u, v] \quad : \quad y^2 = x^3 - (u^4 - v^4)^2 x \tag{2}$$

which is a two parameter elliptic curve equivalent to (1). Notice that (2) is symmetric in u, v so it is sufficient to consider the region $u > v \geq 1$. Furthermore, if $(u^4 - v^4)$ is divisible by a square, σ say, then we can transform $E[u, v]$, via $(x, y) \mapsto (\sigma^2 x, \sigma^3 y)$, to a curve of the same form with a smaller x coördinate. Hence we need only consider coprime pairs (u, v) with distinct squarefree $(u^4 - v^4)$ parts. Each particular choice of u and v corresponds to a specific elliptic curve and we show the rank of the first few in Table 1 (obtained using the techniques of [1] as implemented in `apecs`, a Maple package by Ian Connell). Note that each of these examples has rank ≥ 1 and so generates infinitely many solutions. For example we consider the curve $E[7, 1]$ or

u	v	$(u^4-v^4)^2$	$sqf(u^4-v^4)$	$rank(E[u,v](\mathbb{Q}))$
2	1	15^2	15	1
3	1	80^2	5	1
3	2	65^2	65	2
4	1	255^2	255	1
4	3	175^2	7	1
5	1	624^2	39	1
5	2	609^2	609	2
5	3	544^2	34	2
5	4	369^2	41	2
6	1	1295^2	1295	1
6	5	671^2	671	1
7	1	2400^2	6	1

Table 1: Rank of the first few curves $E[u,v](\mathbb{Q})$

$y^2 = x^3 - 2400^2 x$. Then map $(x,y) \mapsto (20^2\overline{x}, 20^3\overline{y})$ to obtain $\overline{y}^2 = \overline{x}^3 - 36\overline{x}$. The point $(\overline{x},\overline{y}) = (12,36)$ is a generator of the torsion-free part of the group of rational points on this latter curve. Thus we get $k = \frac{20^2 \cdot 12}{2400} = 2$ and substituting $(k,l) = (2,7)$ into Hisrchhorn's quadratic defining $\frac{p}{q}$ in terms of k, l, namely,

$$\begin{aligned}&\{(k^2+1)^2(l^4+1) - 2(k^4-6k^2+1)l^2\}(p/q)^2\\ -&2\{(k^2+1)^2(l^4-1) + 8k(k^2-1)l^2\}(p/q)\\ +&\{(k^2+1)^2(l^4+1) + 2(k^4-6k^2+1)l^2\} = 0\end{aligned}$$

gives the solutions $\frac{p}{q} = \frac{3}{4}$ or $\frac{4947}{3796}$. By using the defining equations for k and l one finds that the first is degenerate while the second leads to the solution

$$\begin{aligned}(m,n,p,q,r,s) &= (12010, 3360, 2\cdot 4947, 2\cdot 3796, 9306, 6808)\\ (a,b,c) &= (77764850, 66475250, 20126386).\end{aligned}$$

All multiples of $(12,36)$ in the group $E[7,1](\mathbb{Q})$ lead to solutions in the same way.

In the reverse direction it is known, from work on the congruent number problem [4], that the curves

$$E[n] \quad : \quad y^2 = x^3 - n^2 x$$

for $n = 1,2,3,4,8,9,10,11,12$ (as well as infinitely many others) have zero rank and hence only finitely many rational points (in fact, just $(0,0)$, $(\pm n, 0)$ and the point at infinity). For example, Fermat had already shown (by infinite descent) that the equation $u^4 - v^4 = w^2$ is impossible in non-trivial integers. Thus we conclude that the curves $E[u,v]$ which correspond (via the mapping above with $\sigma = w$) to $E[n]$ for the values $n = 1,4,9$ have only trivial solutions. Notice that none of the rank zero n values appear in the $sqf(u^4 - v^4)$ column of Table 1 while the missing values $n = 5, 6, 7$ do appear.

Finally, I ran a short search covering the region $1 \leq m, n, p, q, r, s \leq 1850$ to confirm Hirschhorn's suspicion that Euler had in fact found the smallest possible solution, namely the first row in the following table.

a	b	c
434657	420968	150568
733025	488000	418304
993250	949986	856350
1738628	1683872	602272

Table 2: Smallest four solutions to Rolle's problem

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References

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