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THE SOLUTION OF $y^2 \pm 2^n = x^3$

STANLEY RABINOWITZ[1]

ABSTRACT. All solutions to the diophantine equation

$$(*) \qquad y^2 + \gamma 2^n = x^3; \qquad \gamma = \pm 1,$$

are found.

The solution of $(*)$, with $n = \gamma = 1$, is due to Euler [4], [6, p. 103]. His was the first solution of a diophantine equation of the form $y^2 - k = x^3$, where the given value of k is neither the square nor the cube of an integer. Table I is from [5].

TABLE I. The solution of $(*)$ in some special cases

	$\gamma = 1$		$\gamma = -1$
n	$\langle x, \lvert y \rvert \rangle$	n	$\langle x, \lvert y \rvert \rangle$
0	$\langle 1, 0 \rangle$	0	$\langle -1, 0 \rangle, \langle 0, 1 \rangle, \langle 2, 3 \rangle$
1	$\langle 3, 5 \rangle$	1	$\langle -1, 1 \rangle$
2	$\langle 2, 2 \rangle, \langle 5, 11 \rangle$	2	$\langle 0, 2 \rangle$
3	$\langle 2, 0 \rangle$	3	$\langle -2, 0 \rangle, \langle 1, 3 \rangle, \langle 2, 4 \rangle, \langle 46, 312 \rangle$
4	no solutions	4	$\langle 0, 4 \rangle$

DEFINITIONS: Let $\theta = 2^{1/3}$; θ real. Then by [6, p. 105], $\Omega = \{a + b\theta + c\theta^2 | a, b, c \in Z\}$ is the ring of integers of $Q(\theta)$. The class number of Ω is 1 [1, p. 427] and therefore Ω is a unique factorization domain (U.F.D.).

Λ will be either Z or Ω. Hence Λ is real.

All Latin letters (except Z and Q) will represent elements of Z and all lower case Greek letters elements of Λ.

The units of Λ are $\pm \varepsilon^r$ $(r \in Z)$; $\varepsilon = 1$ for $\Lambda = Z$ and $\varepsilon = -1 + \theta$ for $\Lambda = \Omega$ [6, p. 112], [3, p. 304]. Note that $\varepsilon > 0$. Let $\gamma = \pm 1$.

$\alpha|_\Lambda \beta$ and $(\alpha, \beta)_\Lambda$ are read (respectively) as "α divides β in Λ" and "the greatest common divisor of α and β in Λ".

LEMMA 1. *If $\alpha \neq 0$ or $\beta \neq 0$, then $\alpha^2 + \alpha\beta + \beta^2 > 0$.*

PROOF. $4(\alpha^2 + \alpha\beta + \beta^2) = (2\alpha + \beta)^2 + 3\beta^2$.

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LEMMA 2. $(\alpha + \beta, \alpha^2 - \alpha\beta + \beta^2)_\Lambda|_\Lambda 3\beta^2$.

PROOF. $(2\beta - \alpha)(\alpha + \beta) + (\alpha^2 - \alpha\beta + \beta^2) = 3\beta^2$.

LEMMA 3. *If* $\varphi^2 = \alpha\beta$, $(\alpha, \beta)_\Lambda = 1$ *and* $\alpha > 0$, *then* $\alpha = \mu\xi^2$; $\mu = 1$ *or* ε.

PROOF. Since Λ is a U.F.D. and $\alpha > 0$, $\alpha = \varepsilon^r\psi^2$. If $r = 2t$, let $\mu = 1$, $\xi = \varepsilon^t\psi$. If $r = 2t + 1$, let $\mu = \varepsilon$, $\xi = \varepsilon^t\psi$.

LEMMA 4. *If* $as^2 + bs + c = 0$, *then* $b^2 - 4ac = d^2$.

PROOF. Let $d = 2as + b$.

LEMMA 5. *If* $(x, 3) = 1$, *then* $x^3 \equiv \pm 1 \pmod 9$.

PROOF. $x = \pm 1 + 3k$. Thus $x^3 = (\pm 1 + 3k)^3 \equiv (\pm 1)^3 = \pm 1 \pmod 9$.

LEMMA 6. *If* $(a, b) = 1$, *then* $(a, b)_\Omega = 1$.

PROOF. There exist integers e and f such that $ea + fb = 1$.

LEMMA 7. *If* $2^x a + 2^y b + 2^z c = 0$, *where* $(abc, 2) = 1$, *and* $0 \leqslant x \leqslant y \leqslant z$, *then* $x = y < z$.

PROOF. $2^y | 2^x a$. Thus $x \geqslant y$.
If $y = z$, then $a + b + c = 0$. But $a + b + c$ is odd.
Note that if (*) holds, then, since $2^n = \gamma(x^3 - y^2)$, $n \geqslant 0$.

PROPOSITION 1.

$y^2 + 2^{3k} = x^3$; x *odd* $\Rightarrow \langle k, x, |y|\rangle = \langle 0, 1, 0\rangle$.

$y^2 - 2^{3k} = x^3$; x *odd* $\Rightarrow \langle k, x, |y|\rangle = \langle 0, -1, 0\rangle, \langle 1, 1, 3\rangle$ *or* $\langle 3, -7, 13\rangle$.

PROOF. Using Table I, we may assume that $k > 1$. Now

$$y^2 = ab; \qquad a = x - \gamma 2^k, \;\; b = x^2 + \gamma 2^k x + 2^{2k}.$$

Hence $(ab, 2) = 1$. By Lemma 1, $b > 0$. Therefore $a > 0$. By Lemma 2, $(a, b)|3 \cdot 2^{2k}$. Thus $(a, b) = 1$ or 3.

Suppose first that $(a, b) = 3$. Then $3|y$ and $(y/3)^2 = (a/3)(b/3)$. By Lemma 3, $a = 3u^2$ and $b = 3v^2$. Hence v is odd. Eliminating x from the latter two equations,

$$3u^4 + \gamma 3 \cdot 2^k u^2 + (2^{2k} - v^2) = 0.$$

Thus by Lemma 4, $12v^2 - 3 \cdot 2^{2k} = d^2$. Therefore $d = 2D$ and since $k > 1$, $3v^2 - D^2 = 3 \cdot 2^{2k-2} \equiv 0 \pmod 4$. But since v is odd, D is odd and, hence, $3v^2 - D^2 \equiv 2 \pmod 4$.

Thus $(a, b) = 1$. Therefore $a = u^2$ and $b = v^2$, implying $(uv, 2) = 1$. Eliminating x,

$$u^4 + 3 \cdot 2^k \gamma u^2 + (3 \cdot 2^{2k} - v^2) = 0. \tag{1}$$

By Lemma 4, $4v^2 - 3 \cdot 2^{2k} = d^2$. Thus $d = 2D$ and

$$v^2 - D^2 = 3 \cdot 2^{2k-2}. \tag{2}$$

Since $k \geqslant 2$ and v is odd, D is odd. Also $3|(v - D)(v + D)$. Let $V = \pm v$ where $3|V - D$. By (2), $V - D = 3 \cdot 2^s\delta$ and $V + D = 2^t\delta$; $s + t = 2k - 2$ and $\delta = \pm 1$. Since $(DV, 2) = 1$, $s \geqslant 1$ and $t \geqslant 1$. Hence

(3) $$D = \delta(2^{t-1} - 3 \cdot 2^{s-1}).$$

Thus either ($t > 1$ and $s = 1$) or ($t = 1$ and $s > 1$). Solving (1) for u^2,

(4) $$u^2 = -\gamma 3 \cdot 2^{k-1} \pm D.$$

Suppose first that $t > 1$ and $s = 1$. Hence $t = 2k - 3$ and by (3), $D = \delta(2^{2k-4} - 3)$. Thus $k > 2$ and by (4),

$$u^2 = -\gamma 3 \cdot 2^{k-1} \pm (2^{2k-4} - 3).$$

If $k > 3$, $u^2 \equiv \pm 3 \pmod 8$. Therefore $k = 3$ and $u^2 = \pm 12 \pm 1$, which is impossible.

Thus $t = 1$ and $s > 1$. Hence $s = 2k - 3$ and by (3), $D = \delta(1 - 3 \cdot 2^{2k-4})$. Thus $k > 2$ and by (4),

(5) $$u^2 = \pm(1 - 3 \cdot 2^{2k-4}) - \gamma 3 \cdot 2^{k-1}.$$

The first minus sign cannot hold modulo 3.

If $\gamma = 1$, then $u^2 < 0$. Hence $\gamma = -1$. By (5), $u^2 = 3(2^{k-1} - 2^{2k-4}) + 1$.

If $k > 3$, then $2k - 4 > k - 1$ and thus $u^2 < 0$. Hence $k = 3$ and $u^2 = 1$. Since $a = u^2$, $x = u^2 - 2^k = -7$. Therefore $y^2 = x^3 + 2^{3k} = 169$.

PROPOSITION 2.

$$y^2 + 2^{3k+1} = x^3; \quad x \text{ odd} \Rightarrow \langle k, x, |y|\rangle = \langle 0, 3, 5\rangle.$$

$$y^2 - 2^{3k+1} = x^3; \quad x \text{ odd} \Rightarrow \langle k, x, |y|\rangle = \langle 0, -1, 1\rangle \text{ or } \langle 2, 17, 71\rangle.$$

PROOF. Suppose $3|y$. Then $(x, 3) = 1$ and by Lemma 5,

$$0 \equiv y^2 = x^3 \pm 2 \cdot 8^k \equiv \pm 1 \pm 2 \pmod 9.$$

This contradiction shows that $(y, 3) = 1$. Obviously y is odd and so by Lemma 6, $(y, 6)_\Omega = 1$. By Table I we may assume that $k > 0$. Now

$$y^2 = \alpha\beta; \qquad \alpha = x - \gamma 2^k\theta, \quad \beta = x^2 + \gamma 2^k\theta x + (2^k\theta)^2.$$

By Lemma 1, $\beta > 0$ and thus $\alpha > 0$. By Lemma 2, $(\alpha, \beta)_\Omega|_\Omega 3(2^k\theta)^2$. But $(\alpha\beta, 6)_\Omega = 1$. Hence $(\alpha, \beta)_\Omega = 1$. By Lemma 3,

$$\alpha = \mu(a + b\theta + c\theta^2)^2; \qquad \mu = 1 \quad \text{or} \quad -1 + \theta.$$

We may assume that $c \geqslant 0$ since $\alpha = \mu(-a - b\theta - c\theta^2)^2$.

If $\mu = -1 + \theta$, we obtain

$$x = -a^2 - 4bc + 2b^2 + 4ac \quad (\Rightarrow a \text{ is odd})$$

and

$$-\gamma 2^k = -2c^2 - 2ab + a^2 + 4bc \quad (\Rightarrow a \text{ is even, since } k > 0).$$

Hence $\mu = 1$. Therefore

(6) $$x = a^2 + 4bc \quad (\Rightarrow a \text{ is odd}),$$

(7) $$-\gamma 2^{k-1} = c^2 + ab,$$

and

(8) $$0 = b^2 + 2ac \quad (\Rightarrow b \text{ is even}).$$

If $b = 0$, then by (8), $c = 0$. This contradicts (7). Thus $b = 2^s B$; $s \geqslant 1$ and B is odd. From (8), $c = 2^{2s-1}C$; C odd. $C > 0$, since $c \geqslant 0$. By (8) and (7),

(9) $$0 = B^2 + aC$$

and

(10) $$-\gamma 2^{k-1} = 2^{4s-2}C^2 + 2^s aB.$$

Let p be a prime of Z. If $p|C$, then by (9), $p|B$ and by (10), $p|2^{k-1}$. Therefore $C = 1$. Hence $a = -B^2$ and $-\gamma 2^{k-1} = 2^{4s-2} - 2^s B^3$. Since $s \geqslant 1$, $4s - 2 > s$. By Lemma 7, $k - 1 = s$. Hence $(-\gamma)^3 + B^3 = 2(2^{s-1})^3$. [2, pp. 70–72] gives $B = -\gamma = 2^{s-1}$. Thus $\gamma = -1$, $B = 1$, $s = 1$, $k = 2$, $a = -1$, $c = 2$ and $b = 2$. By (6), $x = 17$ and therefore $|y| = 71$.

PROPOSITION 3.

$$y^2 + 2^{3k+2} = x^3; \quad x \text{ odd} \Rightarrow \langle k, x, |y|\rangle = \langle 0, 5, 11\rangle.$$

$$y^2 - 2^{3k+2} = x^3; \quad x \text{ odd, has no solutions.}$$

PROOF. Assume $k > 0$ (see Table I).

$$y^2 = \alpha\beta; \qquad \alpha = x - \gamma 2^k\theta^2, \quad \beta = x^2 + \gamma 2^k\theta^2 x + (2^k\theta^2)^2.$$

As in Proposition 2, $\alpha = \mu(a + b\theta + c\theta^2)^2$; $\mu = 1$ or $-1 + \theta$ and $b \geqslant 0$.

If $\mu = -1 + \theta$, then

$$x = -a^2 - 4bc + 2b^2 + 4ac \quad (\Rightarrow a \text{ is odd})$$

and

$$0 = -2c^2 - 2ab + a^2 + 4bc \quad (\Rightarrow a \text{ is even}).$$

Thus $\mu = 1$ and

(11) $$x = a^2 + 4bc \quad (\Rightarrow a \text{ is odd}),$$

(12) $$0 = c^2 + ab,$$

and

(13) $$-\gamma 2^k = b^2 + 2ac \quad (\Rightarrow b \text{ is even}).$$

By (12), c is even.

If $c = 0$, then by (12), $b = 0$. But this contradicts (13). Thus $c = 2^s C$; $s \geqslant 1$ and C odd. By (12), $b = 2^{2s}B$; B odd. Therefore $B > 0$. By (12) and (13), $0 = C^2 + aB$ and

$$-\gamma 2^k = 2^{4s}B^2 + 2^{s+1}aC.$$

As in Proposition 2, $B = 1$. Hence $a = -C^2$ and $-\gamma 2^k = 2^{4s} - 2^{s+1}C^3$. Since $4s > s + 1$, $k = s + 1$ and $(-\gamma)^3 + C^3 = 4(2^{s-1})^3$. This equation has no solutions by [2, pp. 70–72].

THEOREM. *All the solutions of* $(*)$ *are given in the following table with* $x = 2^g e$ *and* $y = \pm 2^h f$.

EXPLANATION OF TABLE II. If $e = 0$ (respectively $f = 0$), then the value of g (respectively h) is irrelevant. n is given modulo 6 and is nonnegative.

The solutions are numbered for reference in the proof.

TABLE II

$\gamma = 1$

n (modulo 6)	$3g$	e	$2h$	f	Solution Number
0	n	1	–	0	1
1	$n-1$	3	$n-1$	5	2
2	$n+1$	1	n	1	3
2	$n-2$	5	$n-2$	11	4
3	n	1	–	0	5

$\gamma = -1$

n (modulo 6)	$3g$	e	$2h$	f	Solution Number
0	n	-1	–	0	6
0	–	0	n	1	7
0	$n+3$	1	n	3	8
1	$n-1$	-1	$n-1$	1	9
1 ($n > 7$)	$n-7$	17	$n-7$	71	10
2	–	0	n	1	11
3 ($n > 9$)	$n-9$	-7	$n-9$	13	12
3	n	-1	–	0	13
3	$n-3$	1	$n-3$	3	14
3	n	1	$n+1$	1	15
3	n	23	$n+3$	39	16
4	–	0	n	1	17

PROOF. By direct calculation the above can be shown to be solutions. Suppose now that $(*)$ holds.

If $x = 0$, then $\gamma = -1$ and $y^2 = 2^n$. Therefore n is even implying solution 7, 11 or 17.

If $y = 0$, then $3|n$ yielding solution 1, 5, 6 or 13.

Suppose now that $xy \neq 0$. Therefore $x = 2^g e$ and $|y| = 2^h f$; ef odd. By $(*)$,

$$2^{2h} f^2 + \gamma 2^n = 2^{3g} e^3. \tag{14}$$

By Lemma 7,

$$2h = 3g < n, \tag{15}$$

$$2h = n < 3g, \tag{16}$$

or

$$(17) \qquad 3g = n < 2h.$$

If (15), then $2h = 3g = 6q$ and by (14), $f^2 + \gamma 2^{n-6q} = e^3$. Propositions 1, 2 and 3 imply solution 2, 4, 14, 12, 9 or 10.

If (16), then $n = 6w + 2i$; $i = 0$, 1 or 2. So $(2^i f)^2 + \gamma 2^{2i} = (2^{g-2w}e)^3$. Table I gives solution 3 or 8.

If (17), then $n = 6w + 3j$; $j = 0$ or 1. So $(2^{h-3w}f)^2 + \gamma 2^{3j} = (2^j e)^3$. Table I yields solution 15 or 16.

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Current address: Department of Mathematics and Computer Science, Kingsborough Community College (CUNY), Brooklyn, New York 11235.