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GENERALIZED CANNONBALL PROBLEM

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ABSTRACT. The cannonball problem asks which numbers are both square and square pyramidal. In this paper I consider the cannonball problem for other r-regular polygons. I carried out a computer search and found a total of 858 solutions for polygons $3 \leq r \leq 10^5$. By using elliptic curves I also found that there are no solutions for $r = 5$ (pentagon), $r = 7$ (heptagon), and $r = 9$ (enneagon).

1. Introduction

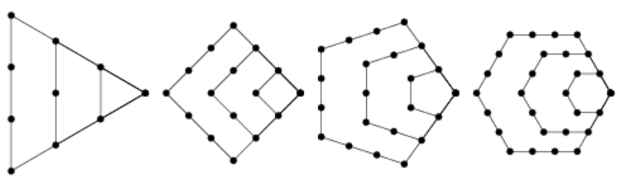
The general cannonball problem asks which r-regular polygons exist that are also an r-regular pyramidal (i.e. pyramids with an r-regular base). The case for a square and a square pyramidal was solved a long time ago: as early as 1918, G.N. Watson [1, 2] proved in the most elementary way that 1 and 4900 are the only solutions to the cannonball problem for a square.

In order to prove the above-mentioned result, this paper uses elliptic curves. The method to do this will be described later. The cannonball problem for a square looks for integer solutions to the following Diophantine equation: $a\,(a+1)\,(2a+1)\,/6 = b^2$. By means of a simple substitution $x = 12a$ and $y = 72b$, I obtain the following elliptic curve: $y^2 = x^3 + 18x^2 + 72x$. With SageMath, all the integer solutions of this elliptic curve can be found. Now, I see that integer solutions to x and y imply integer solutions to a and b. Filtering the solutions for situations when a and b are positive integers only gives the following: $(a, b) \in \{(1, 1), (24, 70)\}$. So, the only solutions that exist are when $b = 1$ and $b = 70$, which gives cannonball numbers of 1 and 4900, respectively.

The search for the solutions to the general cannonball problem started after Numberphile posted a video entitled: '90,525,801,730 Cannon Balls' [3, 4].

2. Methodology

Using MathWorld [5], I derived the formula for a polygonal number. A polygonal number is a type of figurate number that is a generalization of triangular, square, et cetera, to a b-gon for b, an arbitrary positive integer. The diagram [6] below graphically illustrates the process in which the polygonal numbers are built up.



Starting with the bth triangular number T_b, then

$$b + T_{b-1} = \mathrm{T}_b \tag{1}$$

Now, note that

$$b + 2T_{b-1} = b^2 \tag{2}$$

gives the bth square number,

$$b + 3T_{b-1} = \frac{b\left(3b-1\right)}{2} \tag{3}$$

gives the bth pentagonal number, and so on. The general polygonal number can be written in the following form:

$$p_b^r = \frac{b\left(b\left(r-2\right)+4-r\right)}{2} \tag{4}$$

where p_b^r is the bth r-gonal number. For example, taking $r = 3$ gives a triangular number, et cetera.

To get the pyramidal numbers from the polygonal numbers, the polygonal numbers need to be summed from 1 to a. This is logical because the pyramidal numbers are made from stacking polygonal numbers on top of each other. This relation is shown in Equation (5).

$$\frac{a\left(a+1\right)\left(a\left(r-2\right)+5-r\right)}{6} = \sum_{b=1}^{a} \frac{b\left(b\left(r-2\right)+4-r\right)}{2} \tag{5}$$

So, the general cannonball problem looks for integer solutions to the following Diophantine equation:

$$\# \coloneqq \frac{a\left(a+1\right)\left(a\left(r-2\right)+5-r\right)}{6} = \frac{b\left(b\left(r-2\right)+4-r\right)}{2} \tag{6}$$

A computer search was conducted to find solutions between $3 \leq r \leq 10^5$. In order to solve individual cases, I made use of a free open-source mathematics software package called SageMath. However, to use that software with the aim to find the integer points [7] of elliptic curves, our Equation (6) had to be transformed into a Weierstrass equation for an elliptic curve [8, 9].

An elliptic curve over a field K is a projective nonsingular curve E defined over K of genus 1 together with a point $O \in E$ defined over K. Let K be an arbitrary field. A Weierstrass equation for an elliptic curve E/K is an equation of the following form [8, 9]:

$$b^2 + \beta_1 ab + \beta_3 b = a^3 + \beta_2 a^2 + \beta_4 a + \beta_6 \tag{7}$$

where $\beta_1, \beta_2, \beta_3, \beta_4, \beta_6$ are constants in K. The coefficients can be written as Weierstrass coefficients [8]:

$$[\beta_1, \beta_2, \beta_3, \beta_4, \beta_6] \tag{8}$$

When both the right-hand side and the left-hand side of Equation (6) are multiplied by 6, this equation turns into an elliptic curve. This elliptic curve has the following form:

$$\left(3r-6\right)b^2 + \left(12-3r\right)b = \left(r-2\right)a^3 + 3a^2 + \left(5-r\right)a \tag{9}$$

Let $x \coloneqq \left(3r-6\right)\left(r-2\right)a$ and $y \coloneqq \left(3r-6\right)^2\left(r-2\right)b$. With these substitutions, Equation (6) is written in the Weierstrass form as follows:

$$y^2 + \left(3r-6\right)\left(r-2\right)\left(12-3r\right)y = x^3 + 3\left(3r-6\right)x^2 + \left(3r-6\right)^2\left(r-2\right)\left(5-r\right)x \tag{10}$$

Notice that the substitutions that are done imply that integer solutions to x and y imply integer solutions to a and b. The coefficients from Equation (10) can now be written as the Weierstrass coefficients:

$$\left[0, 9\left(r-2\right), 9\left(4-r\right)\left(r-2\right)^2, 9\left(5-r\right)\left(r-2\right)^3, 0\right] \tag{11}$$

3. Results

With the help of a computer search, I looked for integer solutions to Equation (6), from $r = 3$ to $r = 10^5$. I found 858 solutions. Using C# I looked for solutions to Equation (6) by first solving this equation for b:

$$b = \frac{1}{r-2} \cdot \left\{ \frac{r}{2} + \frac{1}{6} \cdot \sqrt{3\left(3\left(r-4\right)^2 + 4a\left(r-2\right)\left(5+3a-r+a^2\left(r-2\right)\right)\right)} - 2 \right\} \tag{12}$$

and then I used a brute force method to check when:

$$3\left(3\left(r-4\right)^2 + 4a\left(r-2\right)\left(5+3a-r+a^2\left(r-2\right)\right)\right) \tag{13}$$

is a perfect square, so that the square and the square root cancel each other. Due to the nature of the used C#-code it is likely that not all solutions can be found that exist between the bounds.

Here, I present a brief selection of the results I found; a complete overview of all our results is presented below, following the reference section of this paper. For $r = 3$, I investigated if a triangle base pyramid (tetrahedron) would be equal to a triangle number. In this case, I found four non-trivial solutions, namely $(3, 4)$, $(8, 15)$, $(20, 55)$, and $(34, 119)$. For $r = 6$, I found one non-trivial solution: $(11, 22)$. Finally, for $r = 8$ I found four non-trivial solutions, namely $(10, 19)$, $(18, 45)$, $(49785, 6413415)$, and $(91839, 16068720)$.

However, for $3 \leq r \leq 10$ our search found no solutions for $r = 5$, $r = 7$, and $r = 9$. I will now prove that no solutions exist for $r = 5$, $r = 7$, and $r = 9$.

3.1. **Pentagon.** With $r = 5$ I obtain the following elliptic curve: $3b^2 - b = a^3 + a^2$. Using the substitutions $x = 27a$ and $y = 243b$, the elliptic curve is written in the following Weierstrass form: $y^2 - 81y = x^3 + 27x^2$. This means that I only need to consider integer solutions to x and y. I used SageMath to find the integer solutions to this elliptic curve. Transforming the solutions I found back to (a, b), I saw that the only integer solutions that exist are given by:

$$(a, b) \in \{(-1, 0), (0, 0), (1, 1), (4, -5), (6, -9)\} \tag{14}$$

This means that there is one positive trivial solution $(1, 1)$ and no non-trivial solutions. It shows that for a pentagon there are no solutions to the cannonball problem. □

3.2. **Heptagon.** With $r = 7$ I obtain the following elliptic curve: $15\mathrm{b}^2 - 9\mathrm{b} = 5\mathrm{a}^3 + 3\mathrm{a}^2 - 2\mathrm{a}$. Using the substitutions $x = 75a$ and $y = 1125b$, the elliptic curve is written in the following Weierstrass form: $y^2 - 675y = x^3 + 45x^2 - 2250x$. This means that I only need to consider integer solutions to x and y. I used SageMath to find the integer solutions to this elliptic curve. Transforming the solutions I found back to (a, b), I saw that the only integer solutions that exist are given by:

$$(a, b) \in \{(-1, 0), (0, 0), (1, 1)\} \tag{15}$$

This means that there is one positive trivial solution $(1, 1)$ and no non-trivial solutions. It shows that for a heptagon there are no solutions to the cannonball problem. □

3.3. **Enneagon.** With $r = 9$ I obtain the following elliptic curve: $21\mathrm{b}^2 - 15\mathrm{b} = 7\mathrm{a}^3 + 3\mathrm{a}^2 - 4\mathrm{a}$. Using the substitutions $x = 147a$ and $y = 3087b$, the elliptic curve is written in the following Weierstrass form: $y^2 - 2205y = x^3 + 63x^2 - 12348x$. This means that I only need to consider integer solutions to x and y. I used SageMath to find the integer solutions to this elliptic curve. Transforming the solutions I found back to (a, b), I saw that the only integer solutions that exist are given by:

$$(a, b) \in \{(-1, 0), (0, 0), (1, 1), (8, -13)\} \tag{16}$$

This means that there is one positive trivial solution $(1, 1)$ and no non-trivial solutions. It shows that for an enneagon there are no solutions to the cannonball problem. $\square$

4. Conclusion

To conclude, the cannonball problem can be generalized to r-regular polygons. Using elliptic curves I showed that no solution exists for $r = 5$, $r = 7$, and $r = 9$. With the help of a computer search I found a total of 858 solutions, with $3 \leq r \leq 10^5$.

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$r = 3$	$a = 3$	$b = 4$	$\# = 10$
$r = 3$	$a = 8$	$b = 15$	$\# = 120$
$r = 3$	$a = 20$	$b = 55$	$\# = 1540$
$r = 3$	$a = 34$	$b = 119$	$\# = 7140$
$r = 4$	$a = 24$	$b = 70$	$\# = 4900$
$r = 6$	$a = 11$	$b = 22$	$\# = 946$
$r = 8$	$a = 10$	$b = 19$	$\# = 1045$
$r = 8$	$a = 18$	$b = 45$	$\# = 5985$
$r = 8$	$a = 49785$	$b = 6413415$	$\# = 123395663059845$
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$r = 10$	$a = 5$	$b = 7$	$\# = 175$
$r = 10$	$a = 6511$	$b = 303336$	$\# = 368050005576$
$r = 11$	$a = 25$	$b = 73$	$\# = 23725$
$r = 11$	$a = 10044$	$b = 581175$	$\# = 1519937678700$
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$r = 62$	$a = 1198$	$b = 23941$	$\# = 17194450141$
$r = 65$	$a = 1321$	$b = 27721$	$\# = 24205450501$
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$r = 377$	$a = 46873$	$b = 5859001$	$\# = 6436478791921501$
$r = 383$	$a = 48385$	$b = 6144769$	$\# = 7192933280636545$
$r = 386$	$a = 49150$	$b = 6291073$	$\# = 7598897900740225$
$r = 392$	$a = 50698$	$b = 6590611$	$\# = 8470048625319061$
$r = 395$	$a = 51481$	$b = 6743881$	$\# = 8936805111705901$
$r = 398$	$a = 52270$	$b = 6899509$	$\# = 9425437080130765$
$r = 401$	$a = 53065$	$b = 7057513$	$\# = 9936792303244885$
$r = 404$	$a = 53866$	$b = 7217911$	$\# = 10471744636405921$
$r = 407$	$a = 54673$	$b = 7380721$	$\# = 11031194614952521$
$r = 410$	$a = 55486$	$b = 7545961$	$\# = 11616070060528201$
$r = 413$	$a = 56305$	$b = 7713649$	$\# = 12227326696522585$
$r = 416$	$a = 57130$	$b = 7883803$	$\# = 12865948772698045$
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$r = 431$	$a = 61345$	$b = 8772193$	$\# = 16506066998410705$
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$r = 491$	$a = 79705$	$b = 12991753$	$\# = 41268087286688845$
$r = 494$	$a = 80686$	$b = 13232341$	$\# = 43073329449785581$
$r = 497$	$a = 81673$	$b = 13475881$	$\# = 44945840437920181$
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$r = 911$	$a = 275425$	$b = 83453473$	$\# = 3165357101947555825$
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$r = 1145$	$a = 435481$	$b = 165917881$	$\# = 15732676664449335901$
$r = 1148$	$a = 437770$	$b = 167227759$	$\# = 16024015601178594265$
$r = 1151$	$a = 440065$	$b = 168544513$	$\# = 16319966672792640385$
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$r = 1154$	$a = 442366$	$b = 169868161$	$\# = 16620590564322433921$
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$r = 1166$	$a = 451630$	$b = 175232053$	$\# = 17871050434172356045$
$r = 1169$	$a = 453961$	$b = 176590441$	$\# = 18195971175113277781$
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$r = 1679$	$a = 937441$	$b = 524028961$	$\# = 230257425685236833521$
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$r = 1814$	$a = 1094446$	$b = 661044781$	$\# = 395904062855282665861$
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$r = 1826$	$a = 1108990$	$b = 674265313$	$\# = 414625945017013327585$
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$r = 1832$	$a = 1116298$	$b = 680941171$	$\# = 424268043079628655221$
$r = 1835$	$a = 1119961$	$b = 684295561$	$\# = 429160669541672690701$
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$r = 1844$	$a = 1130986$	$b = 694424791$	$\# = 444129952278446772481$
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$r = 1883$	$a = 1179385$	$b = 739473769$	$\# = 514285577769505366045$
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$r = 1889$	$a = 1186921$	$b = 746572681$	$\# = 525879318919005690661$
$r = 1895$	$a = 1194481$	$b = 753716881$	$\# = 537696367178045153401$
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$r = 1919$	$a = 1224961$	$b = 782749441$	$\# = 587269774109818673281$
$r = 1922$	$a = 1228798$	$b = 786430081$	$\# = 593733380655413450881$
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$r = 1967$	$a = 1287073$	$b = 843032161$	$\# = 698265917224488081361$
$r = 1970$	$a = 1291006$	$b = 846899281$	$\# = 705762577051281896401$
$r = 1973$	$a = 1294945$	$b = 850778209$	$\# = 713328118438472442865$
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$r = 2105$	$a = 1474201$	$b = 1033414201$	$\# = 1122944072650532905501$
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$r = 2387$	$a = 1896073$	$b = 1507377241$	$\# = 2709581978125550723941$
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$r = 2510$	$a = 2096686$	$b = 1752828661$	$\# = 3852804024591814050701$
$r = 2513$	$a = 2101705$	$b = 1759126249$	$\# = 3885176336073753076885$
$r = 2516$	$a = 2106730$	$b = 1765438903$	$\# = 3917785569706493902945$
$r = 2522$	$a = 2116798$	$b = 1778109481$	$\# = 3983708389053192758281$
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$r = 2531$	$a = 2131945$	$b = 1797228793$	$\# = 4084374620063126915605$
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$r = 2540$	$a = 2147146$	$b = 1816484671$	$\# = 4187213412308751825001$
$r = 2543$	$a = 2152225$	$b = 1822933729$	$\# = 4221982514389772263825$

$r = 2546$	$a = 2157310$	$b = 1829398033$	$\# = 4256998789194345381265$
$r = 2549$	$a = 2162401$	$b = 1835877601$	$\# = 4292263699278297361201$
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$r = 2558$	$a = 2177710$	$b = 1855408069$	$\# = 4399564970638818492445$
$r = 2561$	$a = 2182825$	$b = 1861948873$	$\# = 4435839186069107145925$
$r = 2564$	$a = 2187946$	$b = 1868505031$	$\# = 4472369453775743901361$
$r = 2567$	$a = 2193073$	$b = 1875076561$	$\# = 4509157278173949356761$
$r = 2570$	$a = 2198206$	$b = 1881663481$	$\# = 4546204170741909725401$
$r = 2573$	$a = 2203345$	$b = 1888265809$	$\# = 4583511650045617238665$
$r = 2576$	$a = 2208490$	$b = 1894883563$	$\# = 4621081241763768723085$
$r = 2579$	$a = 2213641$	$b = 1901516761$	$\# = 4658914478712722419621$
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$r = 2585$	$a = 2223961$	$b = 1914829561$	$\# = 4735378055406925640701$
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$r = 31265$	$a = 259$	$b = 2407$	$\# = 90525801730$
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