

A new algorithm for generating Pythagorean triples.

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1 Introduction

The following observation by one of us (RWDN) arose while investigating Pythagorean triples (x, y, z) with $y = x + 1$, and led to some interesting relationships which allow Pythagorean triples to be generated iteratively. In this article we obtain these and other algorithms which, as far as we are aware, have not been described before. In addition we show that some related relationships recently described by Hatch (1995) and by Mills (1996) are a consequence of these algorithms.

Let $z = y + b$. So $x^2 + y^2 = (y + b)^2$, and hence $y = (x^2 - b^2)/2b$. The triple can therefore be expressed as

$$x, \left(\frac{x^2 - b^2}{2b}\right), \left(\frac{x^2 + b^2}{2b}\right).$$

Let $y = x + a$. So $x + a = (x^2 - b^2)/2b$ and thus

$$x^2 - 2bx - (b^2 + 2ab) = 0. \tag{1}$$

2 Triples with $y = x + 1$

In this case we have $a = 1$, and equation 1 becomes

$$x^2 - 2bx - (b^2 + 2b) = 0. \tag{2}$$

If, also, $b = 1$ then equation 2 becomes

$$x^2 - 2x - 3 = (x - 3)(x + 1) = 0.$$

It follows that the two roots 3, -1 of this quadratic generate the triples 3, 4, 5 and $-1, 0, 1$ respectively.

In order to generate the next triple in the $a = 1$ sequence (ie. $y = x + 1$) using equation 2 it is necessary to know the next value of b . Now the next triple in the $a = 1$ sequence is 20, 21, 29, for which $b = 8$. Since $8 = 3 + 5$ the relationship $b_{n+1} = X_n + Z_n$ suggested itself as a possibility to be explored for determining subsequent values of b , where X_n, Y_n, Z_n represent the n^{th} Pythagorean triple of a sequence. Using this notation, $b_2 = 3 + 5 = 8$, and equation 2 becomes

$$x^2 - 16x - 80 = (x - 20)(x + 4) = 0,$$

which generates the second $a = 1$ triple 20, 21, 29. The first four triples in the $a = 1$ sequence can be generated using equation 2 as follows:

$$\begin{array}{llll} b_1 = 1 & \Rightarrow & x^2 - 2x - 3 = 0 = (x - 3)(x + 1) & \Rightarrow & 3, 4, 5 \\ b_2 = 3 + 5 & \Rightarrow & x^2 - 16x - 80 = 0 = (x - 20)(x + 4) & \Rightarrow & 20, 21, 29 \\ b_3 = 20 + 29 & \Rightarrow & x^2 - 98x - 2499 = 0 = (x - 119)(x + 21) & \Rightarrow & 119, 120, 169 \\ b_4 = 119 + 169 & \Rightarrow & x^2 - 576x - 83520 = 0 = (x - 696)(x + 120) & \Rightarrow & 696, 697, 985 \end{array}$$

When the working is laid out like this a clear pattern emerges which facilitates factorisation, namely that for the case where $y = x + 1$ then $(x + Y_{n-1})$ is a factor, and equation 2 factorises as follows:

$$x^2 - 2b_n x - (b_n^2 + 2b_n) = (x - X_n)(x + Y_{n-1}) = 0.$$

In view of these interesting heuristic relationships a more systematic approach was explored which led to a solution via Pell's equation (see Davenport, 1970), which we now present.

3 Triples where a is constant

Consider the triple X, Y, Z where $Y = X + a$ ($a > 0$). Then

$$X^2 + (X + a)^2 = Z^2.$$

Expanding and doubling both sides gives

$$\begin{array}{l} 4X^2 + 4aX + 2a^2 = 2Z^2, \\ \text{i.e.} \quad (2X + a)^2 + a^2 = 2Z^2, \\ \text{i.e.} \quad \left(\frac{2X + a}{a}\right)^2 + 1 = 2\left(\frac{Z}{a}\right)^2. \end{array}$$

Write $(2X + a)/a = U$ and $Z/a = T$. Then

$$U^2 + 1 = 2T^2.$$

If $a = 1$ then we have an equation in integers ($U, T \in \mathbb{Z}$), and therefore this is a case of Pell's equation for which it is known that the n^{th} solution U_n, T_n in positive integers is given by

$$U_n + T_n\sqrt{2} = (1 + \sqrt{2})^{2n-1}.$$

Thus

$$\begin{aligned}
 U_{n+1} + T_{n+1}\sqrt{2} &= (1 + \sqrt{2})^{2(n+1)-1} \\
 &= (1 + \sqrt{2})^2(1 + \sqrt{2})^{2n-1} \\
 &= (1 + \sqrt{2})^2(U_n + T_n\sqrt{2}) \\
 &= (3 + 2\sqrt{2})(U_n + T_n\sqrt{2}) \\
 &= (3U_n + 4T_n) + (2U_n + 3T_n)\sqrt{2}.
 \end{aligned}$$

Equating $\sqrt{2}$ and non- $\sqrt{2}$ parts gives

$$T_{n+1} = 2U_n + 3T_n \tag{3}$$

$$U_{n+1} = 3U_n + 4T_n. \tag{4}$$

Although these recurrence relations have been reached using Pell’s equation for integers, we wish to highlight the following observation. Suppose that U_n, T_n are determined recursively by equations 3 and 4, whether or not they are integers. Then direct calculation gives

$$\begin{aligned}
 2T_{n+1}^2 - U_{n+1}^2 &= 2(2U_n + 3T_n)^2 - (3U_n + 4T_n)^2 \\
 &= 2T_n^2 - U_n^2.
 \end{aligned}$$

Thus, provided $2T_1^2 - U_1^2 = 1$, the pairs U_n, T_n are solutions of $2T^2 - U^2 = 1$, whether or not U_1, T_1 are integers.

Substituting for T and U with $T = Z/a$ and $U = (2X + a)/a$ in equations 3 and 4 (bearing in mind that the full set of Pythagorean triple solutions is given only for the case where $a = 1$) gives respectively

$$\left(\frac{Z_{n+1}}{a}\right) = 2\left(\frac{2X_n + a}{a}\right) + \left(\frac{3Z_n}{a}\right),$$

and

$$\left(\frac{2X_{n+1} + a}{a}\right) = 3\left(\frac{2X_n + a}{a}\right) + \left(\frac{4Z_n}{a}\right),$$

which reduce to

$$Z_{n+1} = 4X_n + 3Z_n + 2a, \tag{5}$$

$$X_{n+1} = 3X_n + 2Z_n + a. \tag{6}$$

Since $Y_n = X_n + a$ we can rearrange equation 6 to obtain

$$X_{n+1} = 2(X_n + Z_n) + Y_n. \tag{7}$$

Subtracting equation 6 from equation 5 gives

$$\begin{aligned}
 Z_{n+1} - X_{n+1} &= Z_n + X_n + a, \\
 \text{i.e.} \quad b_{n+1} + a &= Z_n + X_n + a, \\
 \text{i.e.} \quad b_{n+1} &= Z_n + X_n,
 \end{aligned} \tag{8}$$

the relationship conjectured above in Section 2.

4 Triples where b is constant

Similar relationships can be obtained for the case where b is constant, as follows:

$$a_{n+1} = X_n + Y_n, \tag{9}$$

$$X_{n+1} = X_n + 2b, \tag{10}$$

$$Y_{n+1} = 2X_n + Y_n + 2b, \tag{11}$$

$$Z_{n+1} = 2X_n + Z_n + 2b. \tag{12}$$

We leave it to the interested reader to verify that these do give a sequence of triples, and that in this case equation 1 factorises as follows:

$$x^2 - 2bx - (b^2 + 2ba_n) = (x - X_n)(x + X_{n-1}) = 0.$$

5 Conclusion

We have therefore shown that the following relationships generate Pythagorean triples X, Y, Z

$$\text{For } a = \text{constant } (X_n + a = Y_n) \quad \begin{cases} X_{n+1} = 3X_n + 2Z_n + a \\ b_{n+1} = X_n + Z_n \end{cases}$$

$$\text{For } b = \text{constant } (Z_n = Y_n + b) \quad \begin{cases} Z_{n+1} = 2X_n + Z_n + 2b \\ a_{n+1} = X_n + Y_n \end{cases}$$

In the special cases $a = 1$ ($a = \text{constant}$) and $b = 1$ ($b = \text{constant}$) then the above recurrence relationships generate *all* the relevant corresponding Pythagorean triples. However, for all other cases the above relationships necessarily give only some of the triples, since the recurrence relations (equations 3 and 4) do not, from any initial U_1, T_1 generate all fractional solutions of Pell's equation.

A significant feature of these algorithms is that if the initial triple is primitive, then *every* member of the generated sequence is also primitive. For example, consider the $a = \text{constant}$ case. Suppose $h|X_{n+1}$ and $h|Y_{n+1}$, then $h^2|(X_{n+1}^2 + Y_{n+1}^2)$, and hence $h|Z_{n+1}$. Also, $h|(Y_{n+1} - X_{n+1})$, and so $h|a$. From equations 5 and 6 it follows that $h|(4X_n + 3Z_n)$ and $h|(3X_n + 2Z_n)$; by taking linear combinations of these we see that $h|Z_n$ and $h|X_n$, from which it follows that $h|Y_n$, as $Y_n = X_n + a$. It follows, therefore, that if the triple $X_{n+1}, Y_{n+1}, Z_{n+1}$ is not primitive, then neither is X_n, Y_n, Z_n ; and so on down to X_1, Y_1, Z_1 . A similar argument for the $b = \text{constant}$ case applies with equations 10, 11, 12.

6 Examples

Constant a ($a = 1$)

Suppose we start with the primitive Pythagorean triple 119, 120, 169 and wish to generate subsequent triples in the sequence. Using equation 6 we obtain

$$X_2 = 3X_1 + 2Z_1 + a = 3(119) + 2(169) + 1 = 696,$$

and so the next triple is 696, 697, 985.

Constant a ($a = 7$)

Start with the primitive Pythagorean triple 5, 12, 13 ($a = 7$). In this case our algorithm generates $X_2 = 48$, and hence the triple 48, 55, 73, which misses the triple 21, 28, 35.

Constant b ($b = 2$)

Start with the primitive Pythagorean triple 8, 15, 17. Using equation (10) we obtain

$$Z_2 = 2X_1 + Z_1 + 2b = 2(8) + 17 + 2(2) = 37,$$

and so our next triple is 12, 35, 37, which misses the triple 10, 24, 26.

7 Alternative relationships for X_{n+1} and Z_{n+1}

The empirical relationship $X_{n+1} = 6X_n - X_{n-1} + 2$, described in a recent article by Hatch (1995) for the case when $a = 1$, is in fact a particular case of a more general relationship which follows directly from our approach, as follows.

From equation 6

$$X_n = 3X_{n-1} + 2Z_{n-1} + a = 2(X_{n-1} + Z_{n-1}) + X_{n-1} + a. \tag{13}$$

From equation 8

$$b_n = X_{n-1} + Z_{n-1}. \tag{14}$$

Eliminating $(X_{n-1} + Z_{n-1})$ between equations 13 and 14 gives

$$X_n = 2b_n + X_{n-1} + a.$$

But $X_n + a + b_n = Z_n$, so

$$X_n = (2Z_n - 2X_n - 2a) + X_{n-1} + a = 2Z_n - 2X_n + X_{n-1} - a.$$

Eliminating $(2Z_n)$ using equation 6 gives

$$\begin{aligned} X_n &= (X_{n+1} - 3X_n - a) - 2X_n + X_{n-1} - a, \\ \text{i.e. } X_{n+1} &= 6X_n - X_{n-1} + 2a. \end{aligned} \tag{15}$$

When $a = 1$ then this is Hatch's equation

$$X_{n+1} = 6X_n - X_{n-1} + 2;$$

as required.

Finally, a similar argument shows that the relationship $Z_{n+1} = 6Z_n - Z_{n-1}$ discussed by Mills (1996) for a sequence with a constant, also follows from our approach.

From equation 5

$$2Z_{n+1} = 8X_n + 6Z_n + 4a. \tag{16}$$

From equation 6

$$3X_{n+1} = 9X_n + 6Z_n + 3a. \tag{17}$$

Eliminating Z_n between equations 16 and 17 gives

$$2Z_{n+1} = 3X_{n+1} - X_n + a.$$

Using the corresponding equations for Z_n and Z_{n-1} we see that

$$2(Z_{n+1} - 6Z_n + Z_{n-1}) = 3(X_{n+1} - 6X_n + X_{n-1}) - (X_n - 6X_{n-1} + X_{n-2}) - 4a,$$

which, by equation 15, gives

$$2(Z_{n+1} - 6Z_n + Z_{n-1}) = 3(2a) - 2a - 4a = 0.$$

Thus

$$Z_{n+1} = 6Z_n - Z_{n-1};$$

as required.

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