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Collatz conjecture

Demonstration of the relationship between the numbers of even and odd steps before reaching 1, and the initial odd value of a Collatz sequence that converges

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Summary

The relationship between the numbers of even steps (P), the number of odd steps (I) and the odd initial value u_0 of a compressed Collatz sequence that converges is as follows:

$$I + P = E(\log_2(3^I * u_0)) + 1$$

This relation is equivalent to the expression below:

$$\left\{ \begin{array}{l} I + P = E(I * \log_2(3)) + E(\log_2(u_0)) + 1 \\ \text{or} \\ I + P = E(I * \log_2(3)) + E(\log_2(u_0)) + 2 \end{array} \right.$$

Where:

- $E(x)$ is the integer part of the real number x ;
- $\log_2(x)$ is the base two logarithm of the real number x ;
- $E(\log_2(u_0))$ is the exponent of the biggest power of 2 that is strictly less than the odd natural number u_0 ;
- I+P is the total stopping time of the compressed sequence.

1- Introduction

The Collatz conjecture (or Syracuse conjecture, Ulam conjecture or $3x+1$ problem) claims that the following sequence of natural numbers reaches the value 1 after a certain rank (or that the sequence of its odd numbers tends to 1).

For a natural number $s_0 \geq 1$ and for all natural number n :

$$s_n = \begin{cases} \frac{s_n}{2}, & \text{if } s_n \text{ is even} \\ 3s_n + 1, & \text{if } s_n \text{ is odd} \end{cases}$$

$3p+1$ being even if the natural number p is odd, the compressed sequence (c_n) of the sequence (s_n) is defined as follows:

For a natural number $c_0 \geq 1$ and for all natural number n :

$$c_n = \begin{cases} \frac{c_n}{2}, & \text{if } c_n \text{ is even} \\ \frac{3c_n+1}{2}, & \text{if } c_n \text{ is odd} \end{cases}$$

An uncompressed (or compressed) sequence that converges continues, after a certain rank, with the trivial cycle 1-4-2 (or 1-2) that is infinitely repeated.

2- General expression of an odd element of a compressed Collatz sequence

Considering the extracted sequence (u_n) composed of the odd elements of the sequence (s_n) , two successive elements have the following relationship:

$$u_n = \frac{3u_{n-1} + 1}{2^{k'_n}}$$

Where k'_n is the number of divisions by 2 that occur between u_{n-1} and u_n .

By developing the previous expression:

$$u_n = \frac{3^n u_0}{2^{\sum_{j=1}^n k'_j}} + \frac{3^{n-1}}{2^{\sum_{j=1}^n k'_j}} + \frac{3^{n-2}}{2^{\sum_{j=2}^n k'_j}} + \dots + \frac{3^0}{2^{k'_n}}$$

Then:

$$u_n = \frac{3^n u_0}{2^{\sum_{j=1}^n k'_j}} + \sum_{i=1}^n \frac{3^{n-i}}{2^{\sum_{j=i}^n k'_j}}$$

After factorization of the u_0 multiplier and simplification of the second term:

$$u_n = \frac{3^n}{2^{\sum_{j=1}^n k'_j}} \left[u_0 + \sum_{i=1}^n \left(3^{-i} * 2^{\sum_{j=1}^{i-1} k'_j} \right) \right]$$

Moreover, for all j : $k'_j = 1 + k_j$, because the successor of an odd element of (s_n) is always even; k_j is then the number of divisions by 2 between two successive odd elements of sequence (c_n) .

Therefore: $\sum_{j=1}^n k'_j = n + \sum_{j=1}^n k_j$ and $\sum_{j=1}^{i-1} k'_j = (i-1) + \sum_{j=1}^{i-1} k_j$

Notice also that:

$$u_n = \frac{3u_{n-1} + 1}{2^{1+k_n}}$$

$\sum_{j=1}^n k_j$ is the number of the even elements, at the rank j , of the compressed sequence (c_n) that follow u_0 .

By introducing k_j and after a new factorization, the expression of u_n becomes:

$$u_n = \left(\frac{3}{2}\right)^n * \frac{1}{2^{\sum_{j=1}^n k_j}} \left[u_0 + \frac{1}{3} \sum_{i=1}^n \left(\left(\frac{2}{3}\right)^{i-1} * 2^{\sum_{j=1}^{i-1} k_j} \right) \right]$$

After a shift on the index i , the expression of u_n , depending on an initial value u_0 , of n and of the first n elements of the sequence (k_n) , we have that:

$$u_n = \left(\frac{3}{2}\right)^n * \frac{1}{2^{\sum_{j=1}^n k_j}} \left[u_0 + \frac{1}{3} \sum_{i=0}^{n-1} \left(\left(\frac{2}{3}\right)^i * 2^{\sum_{j=1}^i k_j} \right) \right]$$

And hence:

$$\forall n \geq 0, \quad u_n = \frac{1}{a_n} \left(u_0 + \frac{x_n}{3} \right) \quad (1)$$

With:

$$x_n = \sum_{i=0}^{n-1} \left(\left(\frac{2}{3}\right)^i * 2^{\sum_{j=1}^i k_j} \right) \quad (2)$$

$$a_n = \left(\frac{2}{3}\right)^n * 2^{\sum_{j=1}^n k_j} \quad (3)$$

$\forall n \geq 1$, x_n and a_n are strictly positive. Therefore (k_n) is strictly increasing.

Moreover:

$$a_n = x_{n+1} - x_n \quad \text{and} \quad x_n = \sum_{i=0}^{n-1} a_i$$

a_n is the general term of serie (x_n) .

We also can write that, for all natural number n:

$$a_n = \left(\frac{2}{3}\right)^n * 2^{P(n)} \quad (4)$$

And:

$$x_n = \sum_{i=0}^{n-1} \left(\frac{2}{3}\right)^i * 2^{P(i)}$$

With: $\forall i \in [1, n], P(i) = \sum_{j=1}^i k_j$

P(i) is the number of even elements, at rank i, of the compressed sequence (c_n) that follow u_0 , the corresponding number of odd elements being of course i.

Note also that: $x_0 = 0$ and $a_0 = x_1 = 1$.

3- Relation between the numbers of even steps, odd steps and u_0

a. Expression of I+P as a function of I and a_I

Considering Collatz sequence (u_n) composed of the odd elements of the sequence (s_n), that converges to 1, i.e. $\lim_{n \rightarrow +\infty} (u_n) = 1$.

This sequence being digital, it exists a rank I for which $u_I = 1$.

Therefore, the formula (1) gives: $u_I = \frac{1}{a_I} \left(u_0 + \frac{x_I}{3}\right) = 1$; then:

$$a_I = u_0 + \frac{x_I}{3} \quad (5)$$

According to (4): $a_I = \left(\frac{2}{3}\right)^I * 2^{P(I)}$

We can note $P=P(I)$; I and P are respectively the odd and even steps of the sequence (c_n) before reaching 1, I+P being then its total stopping time.

By applying the base two logarithms of the two terms of the previous equation, we have that:

$$I + P = \log_2(3^I * a_I) = \log_2 \left[3^I * \left(u_0 + \frac{x_I}{3}\right) \right] = I * \log_2(3) + \log_2 \left(u_0 + \frac{x_I}{3}\right)$$

I+P is an integer that is the sum of the two last terms of this equality, each of them being non integer real numbers. Consequently, by using $E(x)$ as the integer part of the real number x:

$$E(I + P) = I + P = E(I * \log_2(3)) + E\left(\log_2 \left(u_0 + \frac{x_I}{3}\right)\right) + 1 \quad (6)$$

b. Expression of $E(\log_2(a_I))$ as a function of $n_0 = E(\log_2(u_0))$

We have: $u_0 = 2^{n_0} + r_0$, r_0 being a natural number ; n_0 is the exponent of the biggest power of 2 that is strictly less than the odd natural number u_0 .

We can apply the two following inequalities:

- $2^{n_0} \leq u_0 < 2^{n_0+1} \Rightarrow n_0 \leq \log_2(u_0) < n_0 + 1 \Rightarrow n_0 = E(\log_2(u_0))$ by definition of the integer part function of a real number ;
- $0 \leq r_0 < 2^{n_0}$.

Notice that, u_0 being odd, the two above inequalities are strict.

According to (5), $a_I > u_0$ because $x_I > 0$; therefore: $\log_2(u_0) < \log_2(a_I)$; then $n_0 \leq E(\log_2(a_I))$, the logarithm and integer part functions being increasing.

Moreover, it is obvious that, according to (4):

$$\forall n \geq 0, a_{I+n} = \left(\frac{2}{3}\right)^{I+n} * 2^{P(I+n)} = \left(\frac{2}{3}\right)^{I+n} * 2^{P+n} = \left(\frac{4}{3}\right)^n * a_I$$

Because $P(I+n) = P(I) + P(n) = P + n$, $P(n)$ being incremented by 1 from a_{I+n} to a_{I+n+1} .

$$\text{Then: } \forall n \geq 0, \log_2(a_{I+n}) = n * \log_2\left(\frac{4}{3}\right) + \log_2(a_I) \quad (7)$$

(a_{I+n}) is an increasing sequence, with the integer part of the base two logarithm of its first term a_I being greater or equal to n_0 .

We have that: $\log_2\left(\frac{4}{3}\right) \approx 0,415$.

Consequently, a maximum of 3 consecutive terms of the increasing sequence $(E(\log_2(a_{I+n})))$ may be equal.

If we consider the first natural number n_1 for which:

$$E(\log_2(a_{I+n_1})) = n_0 + 1$$

According to (7): $\log_2(a_{I+n_1}) = n_1 * \log_2\left(\frac{4}{3}\right) + \log_2(a_I) = N_1 + \log_2(a_I)$

By noting: $N_1 = n_1 * \log_2\left(\frac{4}{3}\right)$.

By deduction, we get:

$$\begin{cases} E(\log_2(a_{I+n_1})) = E(N_1) + E(\log_2(a_I)) \\ \text{or} \\ E(\log_2(a_{I+n_1})) = E(N_1) + E(\log_2(a_I)) + 1 \end{cases}$$

And then:

$$\begin{cases} n_0 + 1 = E(N_1) + E(\log_2(a_I)) \\ \text{or} \\ n_0 + 1 = E(N_1) + E(\log_2(a_I)) + 1 \end{cases}$$

By taking account the inequality $n_0 \leq E(\log_2(a_I))$, we obtain the two possible following inequalities:

$$\begin{cases} n_0 + 1 \geq E(N_1) + n_0 \\ \text{or} \\ n_0 + 1 \geq E(N_1) + n_0 + 1 \end{cases}$$

Then:

$$\begin{cases} E(N_1) \leq 1 \\ \text{or} \\ E(N_1) \leq 0 \Rightarrow E(N_1) = 0 \end{cases}$$

The integer part of a positive real number being positive or equal to 0, but not negative, we have: $E(N_1) = 0$ or $E(N_1) = 1$. Therefore, the possible values of n_1 are : 0, 1, 2, 3 or 4 (see table below).

n1	N1=n1*log2(4/3)	E(N1)
0	0,00	0
1	0,42	0
2	0,83	0
3	1,25	1
4	1,66	1
5	2,08	2

Investigate the different cases:

Case 1: if $n_1 = 0$, then $E(\log_2(a_I)) = n_0 + 1$ by hypothesis.

Case 2: if $n_1 = 1$, then $E(\log_2(a_I)) = n_0$, because $n_0 \leq E(\log_2(a_I))$ and a_{I+1} is the first term of sequence (a_{I+n}) for which $E(\log_2(a_{I+1})) = n_0 + 1$.

Case 3: if $n_1 = 2$, then $E(\log_2(a_{I+2})) = n_0 + 1$; then $E(\log_2(a_I)) = E(\log_2(a_{I+1})) = n_0$, because $n_0 \leq E(\log_2(a_I))$ and a_{I+2} is the first term of sequence (a_{I+n}) for which $E(\log_2(a_{I+2})) = n_0 + 1$.

Case 4: if $n_1 = 3$, then $E(\log_2(a_{I+3})) = n_0 + 1$; therefore, like for case 3, $E(\log_2(a_I)) = E(\log_2(a_{I+1})) = E(\log_2(a_{I+2})) = n_0$.

Case 5: if $n_1 = 4$, then $E(\log_2(a_{I+4})) = n_0 + 1$; **this case is impossible** because that would imply that $E(\log_2(a_I)) = E(\log_2(a_{I+1})) = E(\log_2(a_{I+2})) = E(\log_2(a_{I+3})) = n_0$, and then that 4 consecutive terms of the sequence $(E(\log_2(a_{I+n})))$ would be equal, the maximum being 3 like precised above (a maximum of 3 consecutive terms of the increasing sequence $(E(\log_2(a_{I+n})))$ can be equal).

Therefore:

$$\begin{cases} E(\log_2(a_I)) = n_0 \\ \text{or} \\ E(\log_2(a_I)) = n_0 + 1 \end{cases}$$

4- Conclusion

The relations (5) and (6) imply that:

$$\begin{cases} I + P = E(I * \log_2(3)) + E(\log_2(u_0)) + 1 \\ \text{or} \\ I + P = E(I * \log_2(3)) + E(\log_2(u_0)) + 2 \end{cases}$$

Which is equivalent to:

$$I + P = E(\log_2(3^I * u_0)) + 1$$

I+P is then the « ceiling » function of the real number $\log_2(3^I * u_0)$.

This last formula it the same that in Ruggiero[2] related to sequence (s_n) , if we add I at each of the two terms of the equation above.

Bibliography

[1] J. C. Lagarias, "The $3x+1$ problem and its generalizations", The American Mathematical Monthly, vol. 92, no. 1, pp. 3–23, 1985.

[2] Rafael Ruggiero, "The relationship between stopping time and number of odd terms in Collatz sequences", arXiv: 1911.01229v2, [math.GM] 6 Nov. 2019.