

Fractals, complex equations, and polynomiographs.

Summary: The generation of Mandelbrot and Julia fractals will be revisited in this article. Emphasis will be placed on the way this fractals are created. A short overview and results of the use of the methods for creating fractals and other methods to determine the roots of complex polynomial equations will be discussed. The patterns (referred to as polynomiographs) generated with the method of Newton-Raphson and Muller will be discussed in more detail.

1. Successive substitution: Mandelbrot and Julia fractals, finding roots.

The method with which these fractals are created has been explained in Part 1 of this series of articles. Recapitulating: a Mandelbrot fractal is generated by varying the constant C in a two-dimensional grid representing the real values (X-axis) en imaginary values (Y-axis) using the equation $Z_{n+1} = F(Z_n) + C$. (Z and C are complex numbers). The initial or seed value of Z_n will have a fixed value and is mostly $(0,0)$. Julia fractals have a fixed C -value, while the varying seed values of Z will be associated with the pixels (640×480) of the screen that displays the results. In both cases the coordinate values of the screen (screen coordinates) will be translated to the coordinate values of Z in de real/imaginary coordinate system.

For my investigation I have used the following formula

$$F(Z) = Z^9 - C.Z^6 + C.Z^3 - Z + C = 0 \quad (1)$$

to generate Mandelbrot and Julia fractals.

To be able to use the method of successive substitution in order to create these fractals formula (1) is restated as:

$$Z_{n+1} = Z_n^9 - C.(Z_n^6 - Z_n^3 - 1) \quad (2)$$

The seed value of Z chosen for this exercise is $0.5 + 0.5i$ in three cases in which the values for C are respectively:

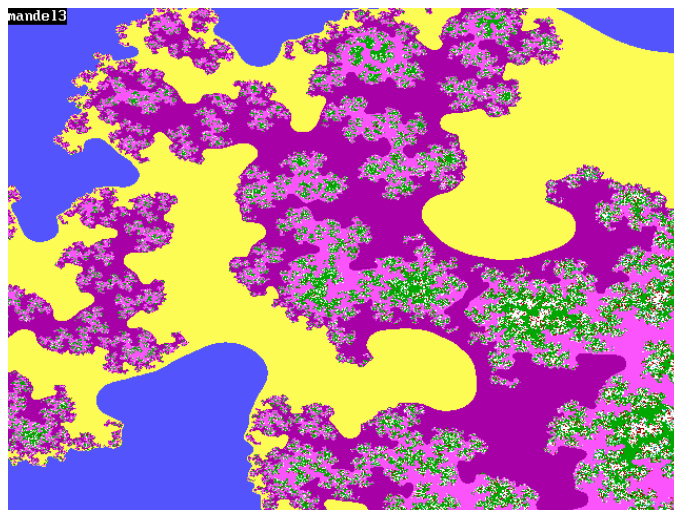
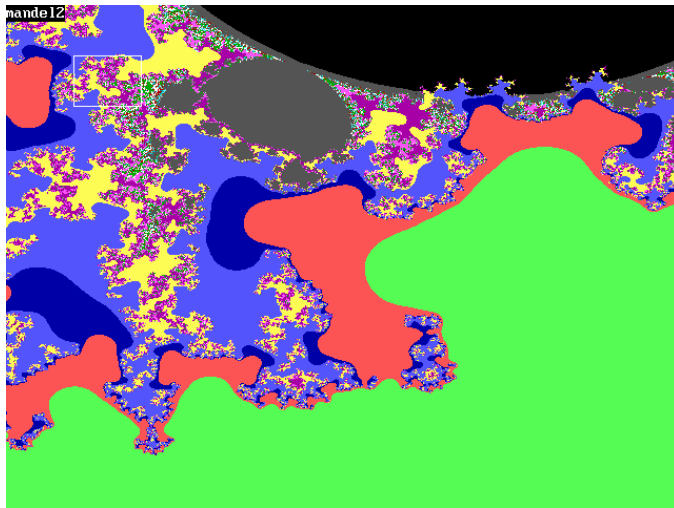
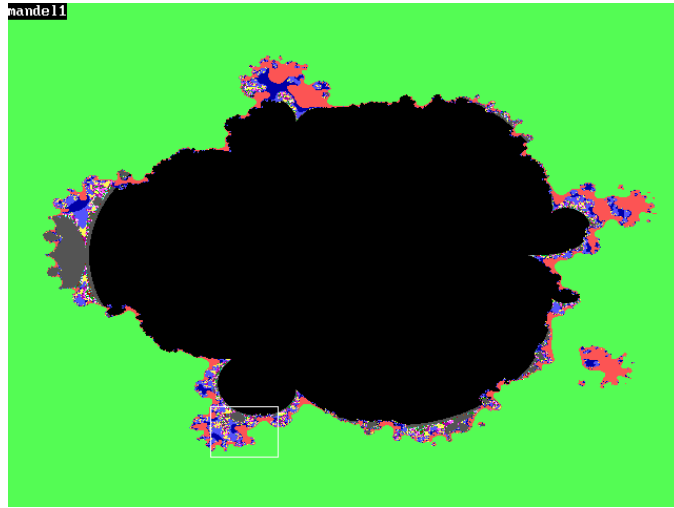
r_{min} , r_{max} , i_{max} , i_{min} (min real value, max real value, max imaginary value, min imaginary value) or in other words the top left real world value of the screen is $r_{min} + i_{max}.i$ and the bottom right real world value is $r_{max} + i_{min}.i$.

The fractals are named mandel1 for $C = -1, 1, 1, -1$

mandel2 for $C = -.4, -.2, -.6, -.8$, and

mandel3 for $C = -.38, -.36, -.62, -.64$

The black areas represent the complex values of Z for which the method of successive substitution does not diverge. These areas are referred to as the Mandelbrot set. The white rectangles in mandel1 identifies the fractal in mandel2 and the white rectangle in mandel2 to mandel3.



For generating Julia fractals use is made of three methods: successive substitution, modified successive substitution and a modified Wegstein method.

The formula's for these method are:

$$Z_{n+1} = F(Z_n) + Z_n \quad (3)$$

$$Z_{n+1} = \rho \cdot Z_n + (1-\rho) \cdot F(Z_n) \quad (4)$$

$$\alpha \cdot Z_{n+1} = F(Z_n) + (\alpha-1) \cdot Z_n \quad (5)$$

$$Z_{n+1} = \rho \cdot Z_n + (1-\rho) \cdot \{F(Z_n) + (\alpha-1) \cdot Z_n\} / \alpha \quad (6)$$

See also part 2 for further explanations about these methods. Formula (4) is known as Wegstein's method in which ρ is known as the relaxation factor. Formula's (4), (5), and (6) are not really intended to generate fractals. Formula (5) is a modified version of the method of successive substitution and can be used to make sure that the use of the method of successive substitution does converge to a root and does not diverge. Formula (5) can be used to assist or accelerating the iteration process in finding the roots of the original equation (1). However the resulting pictures display the characteristics of fractals. Due to the fact that these are not fractals in the real sense I refer to them as compromised fractals.

I shall refer to the formula (6) as the modified Wegstein method. In the unmodified version of the Wegstein method the value of $\alpha = 1$. I furthermore refer to the constant α as the modification factor.

I have generated Julia fractals with methods (3) and (6) and counted the times that a root (or more than one root) was found. Formula (3) generates normal Julia fractals. The application of formula (6) results in more roots (the seed values represented in the black areas converge to those roots), while the total picture represents a compromised fractal. The constant C is in all these four cases $-.37 - .63 \cdot i$. For julia1 the world coordinates of the seed values for Z are associated with the screen coordinates. Here Z contains the 640×480 complex numbers which are all located between $-1.6, 1.2, 1.6, -1.2$ (xleft,xrgt,ytop,ybtm) or (rmin, rmax, imax, imin). Here 3 times a root (probably the same) was found. Julia 2 is like julia1 but the modification factor $\alpha = 2$. This is a compromised fractal; julia3 is like julia1 with $\alpha = 3$ and a relaxation factor $\rho = 0.1$.

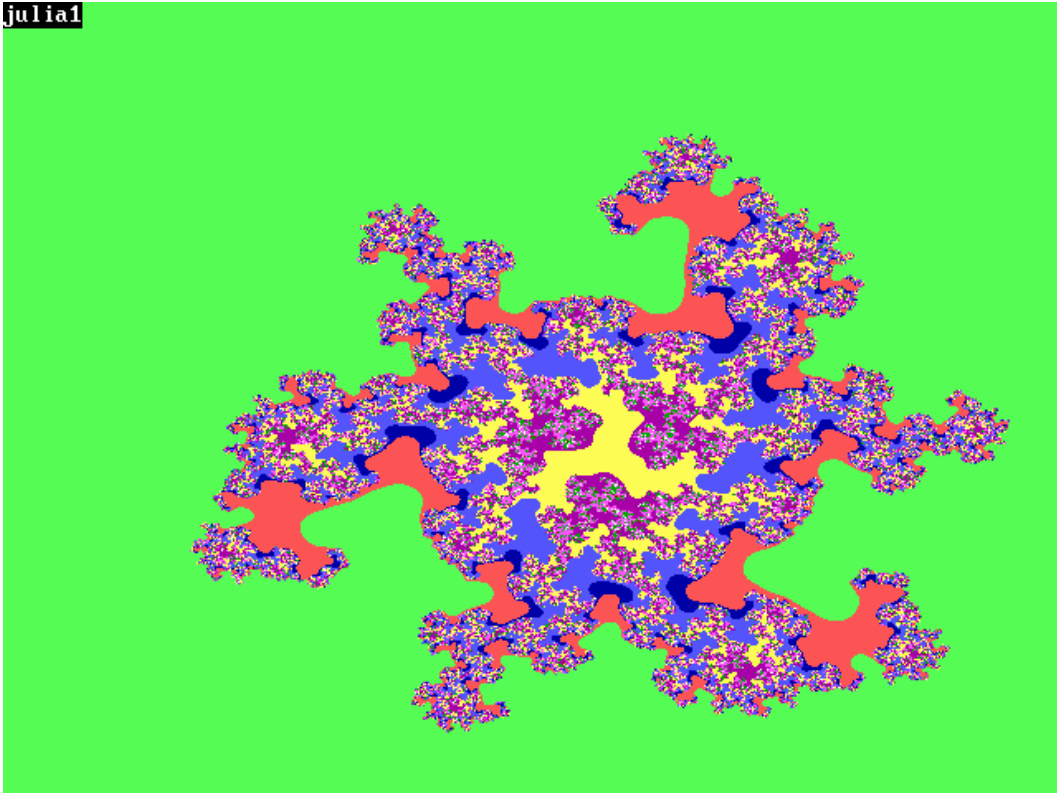
For julia 2 more than 120.000 times and for julia3 approx. 140.000 times roots were found.

Conjecture 1: There exist a combination of a value of α and a value of ρ for which certain roots of any higher degree complex polynomial can be found with the modified Wegstein method.

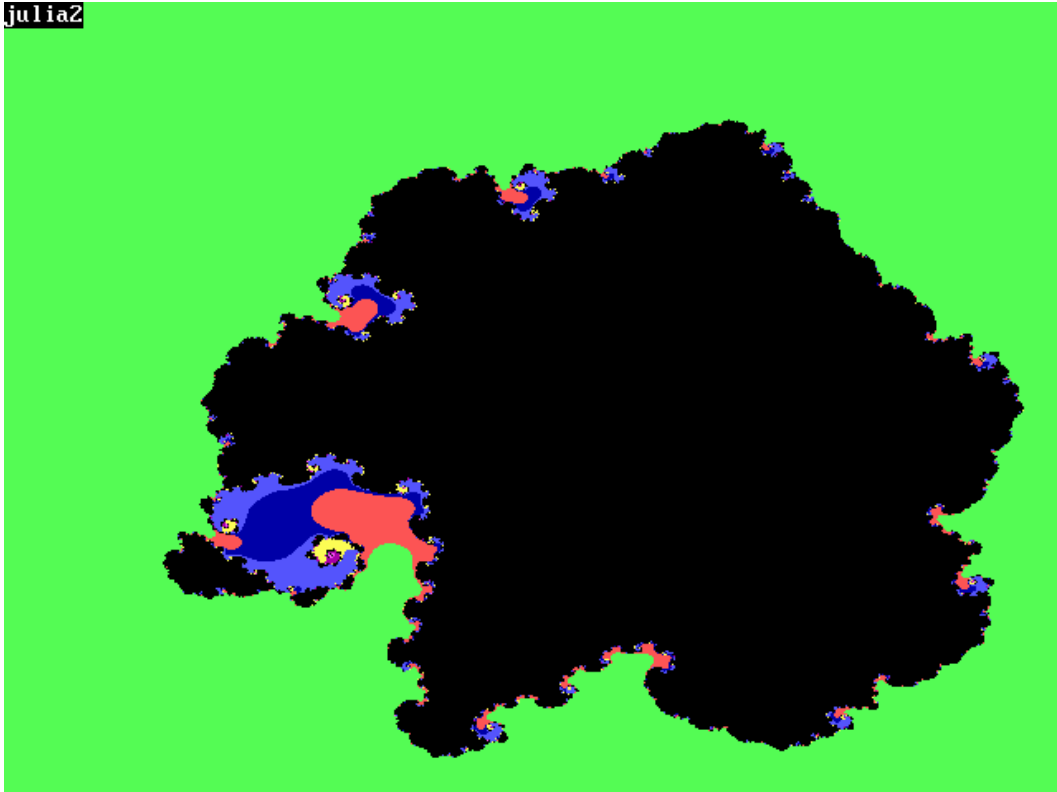
For julia 4 the window of the world coordinates is defined by the values $-1.04, -.48, -0.08, -.64$ (xleft,xrgt,ytop,ybtm) or (rmin, rmax, imax, imin). Here 82647 times roots were found. Julia4 also has a modification factor of 3 and a relaxation factor of 0.1.

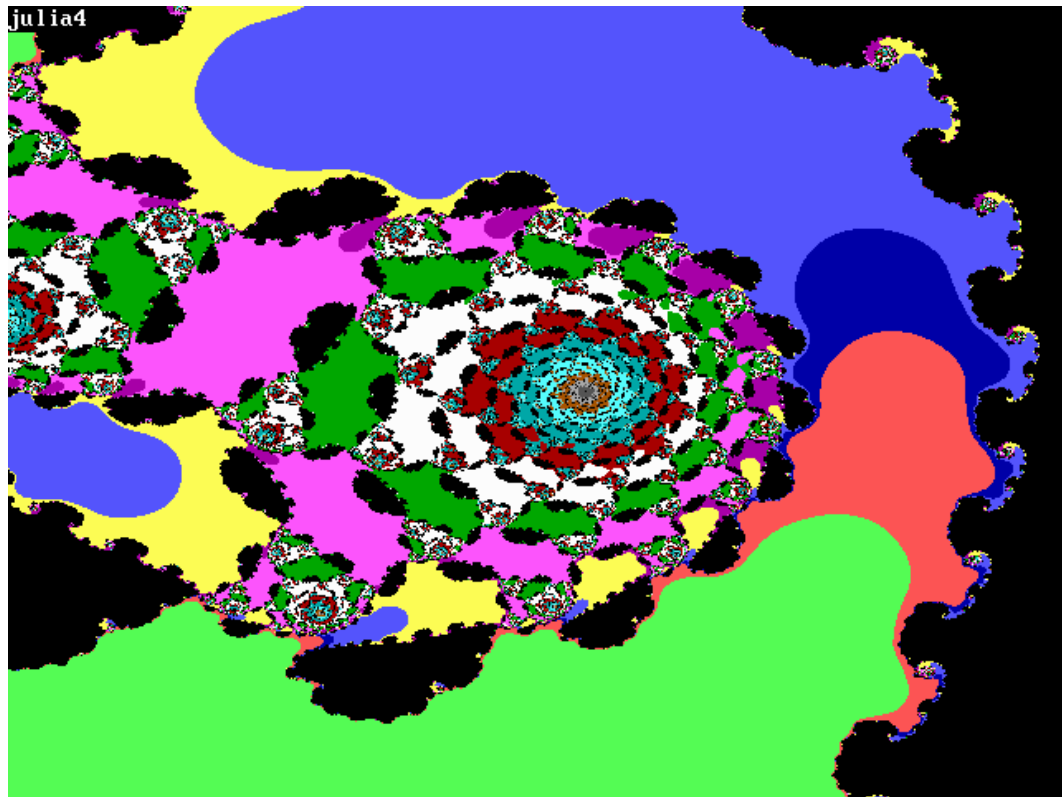
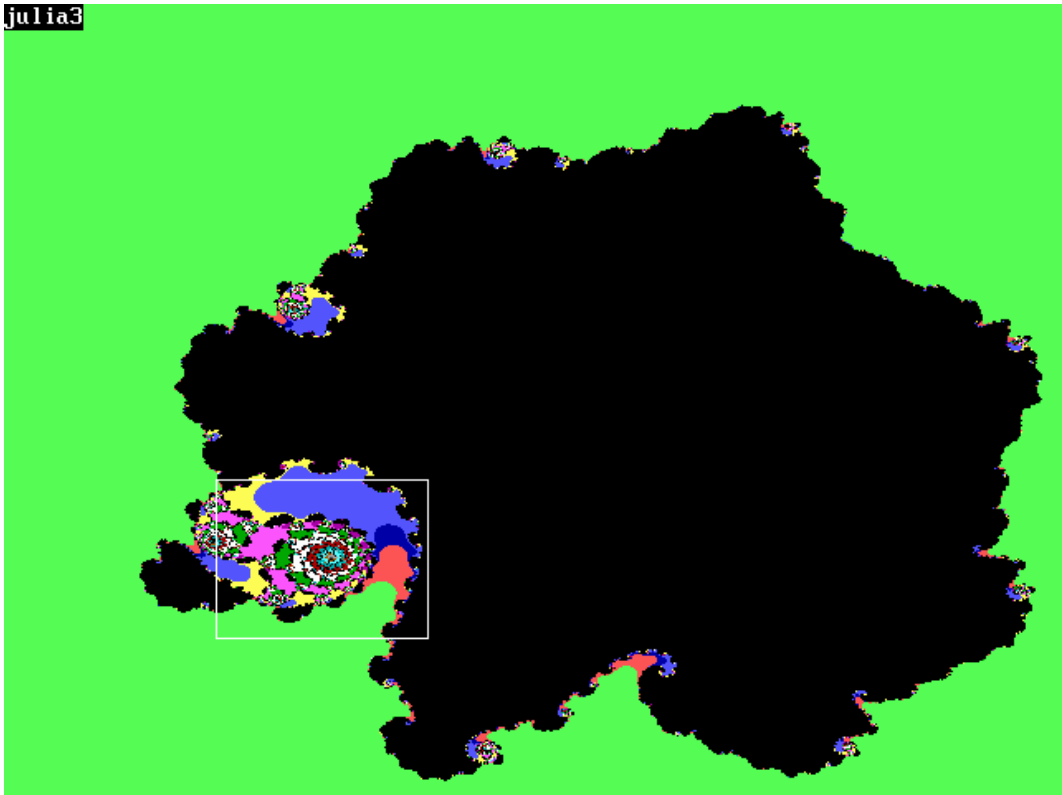
The white box in julia3 defines the dimensions of the total picture in julia4.

julia1



julia2





2. Newton-Raphson.

Newton-Raphson (NR) is an iterative method to find the roots of a (complex) polynomial equation. Its general formula is:

$$\begin{aligned} Z_{n+1} &= Z_n - F(Z_n)/F'(Z_n) && (7) \text{ or} \\ Z_{n+1} &= Z_n - \rho * F(Z_n)/F'(Z_n) && (7a) \end{aligned}$$

ρ is a relaxation factor (generally a number greater than 0 and smaller than 1) that helps to find roots in cases where basic Newton-Raphson (formula 7) cycles without finding a root. I refer to the method employing a relaxation factor as the modified Newton-Raphson method.

With this method we need to determine the first derivative. This makes the calculation a little more complex than is the case with successive substitution. However, according to my investigations, NR always produces all the roots of complex polynomial equations.

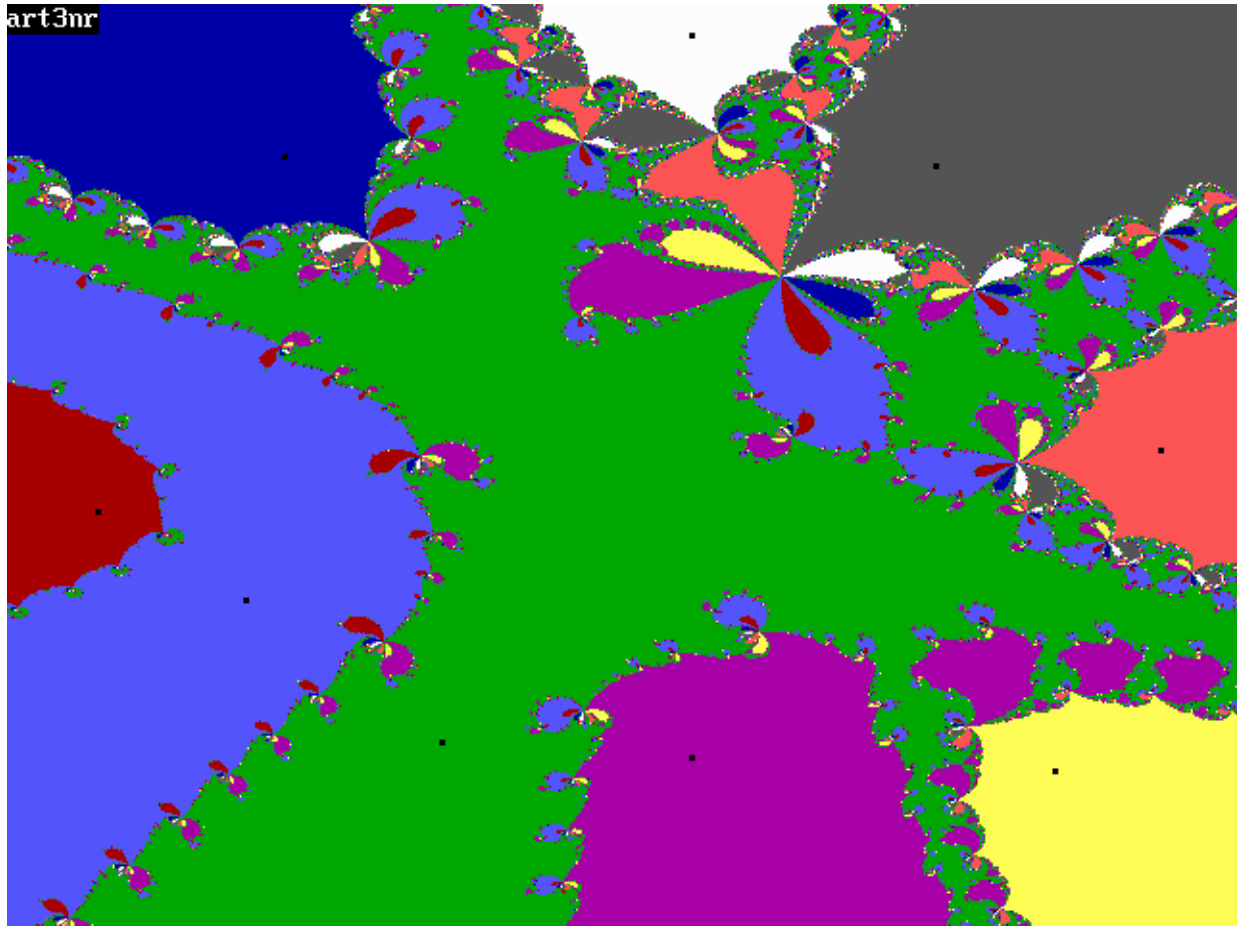
The roots are calculated by assigning world coordinates for complex numbers to the screen coordinates (640x480) or pixels. The choice of those coordinates may influence the fact whether or not all roots can be found. It is safe to specify them as an area that would include those roots. In reality it turns out that most choices will always find all roots. Exceptions will be treated later. We applied the NR-method by using all the complex numbers that are assigned to the pixels. As soon as a root is found it will be placed in an array, and when finding similar roots, these will be discarded. This process stops as soon as all roots are found.

With NR the roots of formula (1) and with $C = -.37 - .63i$, and using the world coordinates between (-1.2, 1.2, 1.2, -1.2) for respectively r_{min} , r_{max} , i_{max} and i_{min} , we find the following roots (stored in symbolic address `rtart3`):

```
Root1 = -.6596836704294642 + .8045808075081935i
Root2 = -.3541275391132120 - .7182412317552311i *)
Root3 = -.7348577419930283 - .3524344430808881i
Root4 = -1.023330372933215 - .1204092667014445i
Root5 = .1359958049606741 - .7578194705211022i
Root6 = .8427186349667669 - .7933247215131565i
Root7 = .1336872350533339 + 1.119929073163079i
Root8 = .6102546527271762 + .7788095958421002i
Root9 = 1.049342996739447 + .0389096570005479i
```

I also calculated the roots based on formula (6). For $\rho = 0$ and $\alpha = 2, 3, 5$ and 6 only one root is found in the window of the world coordinates (-1, 1, 1, -1). For $\rho = .9$ also the same root is found. Other tried combinations of ρ and α were so far unsuccessful. The found root is the 2nd root from the abovementioned list, indicated with *)

We now generate a picture in which nine different colours will be assigned to the found roots. This also means that we have to determine the roots using all seed values assigned to all 640x480 pixels. We use here the same world coordinates as used in finding the roots (-1.2, 1.2, 1.2, -1.2). The generated pictures are placed in symbolic address `art3nr`. The result is the following polionomiograph.



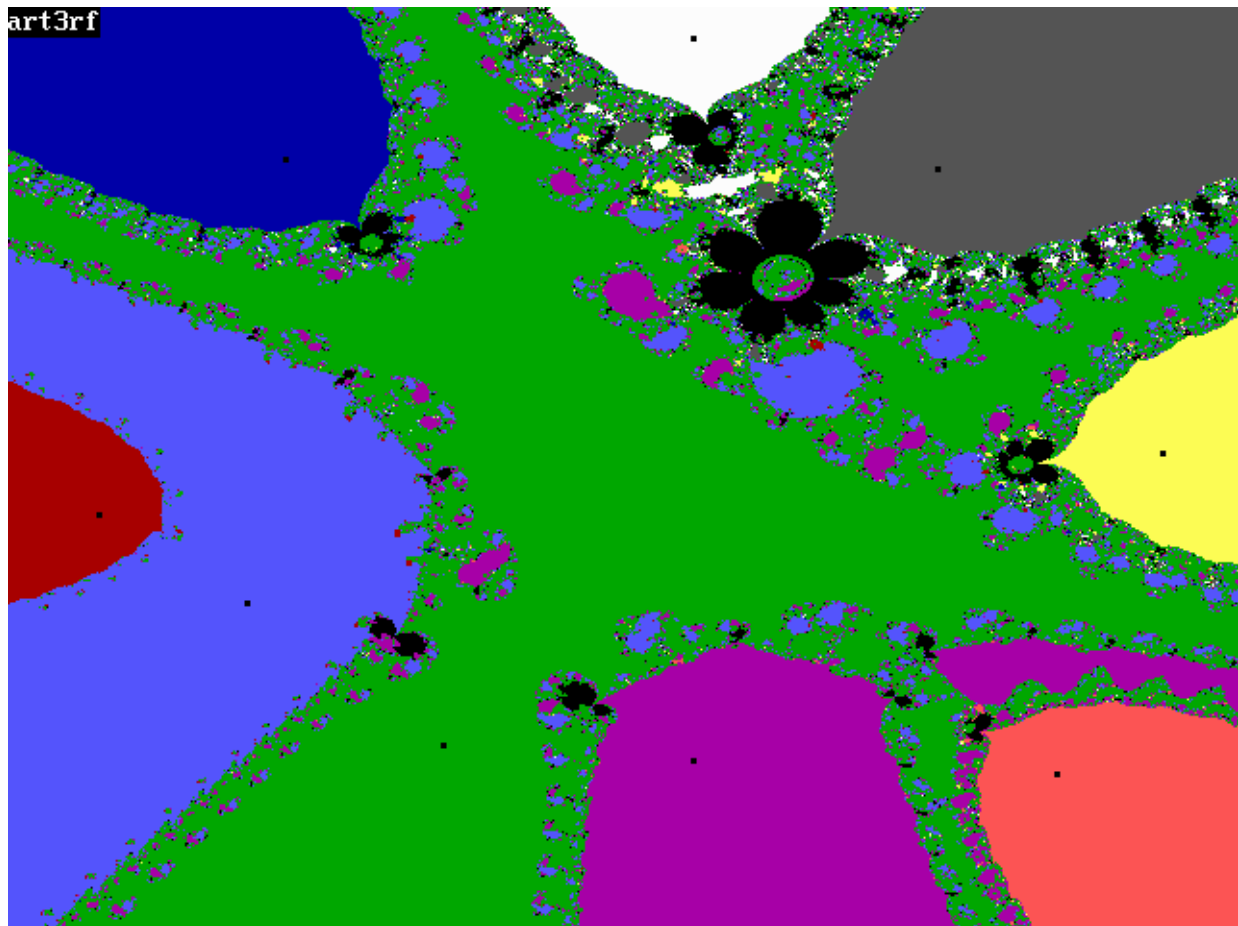
The black spots indicate the location of the nine roots. The large coloured areas would extend indefinitely if we would make the window of the world coordinates larger and it would then seem as if the boundaries of these areas follow straight lines. Each area with the same colour is the locus of all seed values that, when applying the NR-method, would converge to the same root. We will refer to these areas as “leaves” and discriminate between high-order leaves (the large areas of the picture) and lower-order leaves (the smaller areas in the picture). In many articles the pictures generated with this type of approach are referred to as fractals. In reality none of these is a result of fractional dimensions but is a result of the behaviour of the iteration process which can jump from leaf to leaf with the same colour. It is a behaviour that one would also find when finding the roots of a polynomial equation where these roots would be real (not complex) numbers. The generated picture consists thus of a set of loci of seed values that will iterate to a given root with the Newton-Raphson method. These kind of pictures are called a polynomiograph (a term coined by Prof. Bahman Kalantari) and I have distinguished between the pictures generated with the Newton-Raphson method and other methods mentioned in this article by inserting an indicator in front of “polynomiograph” that refers to the used method. In the case of Newton-Raphson the picture is identified with the term NR-polynomiograph.

3. Regula Falsi

A third method is the method of Regula Falsi. This method is also an iterative method. The new value of Z is calculated using two previously calculated or specified values of Z . The method can be formulated as:

$$Z_{n+1} = Z_n - F(Z_n) \cdot (Z_n - Z_{n-1}) / [F(Z_n) - F(Z_{n-1})] \quad (8)$$

The difficulty is that we have to start with two seed values, one for Z_n and one for Z_{n-1} . Since we are working here with the first difference between the functions of these two values, Regula Falsi has an iteration pattern that is similar to that of Newton-Raphson were we work with the first derivative of the function of Z . Using the same roots of formula (1) and the same world coordinates as used in the previous chapter the RF-polynomiograph (Regula Falsi polynomiograph) becomes



In this RF-polynomiograph the black leaves (black areas other than the small black squares that indicate the locations of the roots) means that Regula Falsi did not converge there to any root. This may have been influenced by the choice of the initial two seed values of Z_n and Z_{n-1} . The RF-polynomiograph is stored under the name art3rf.

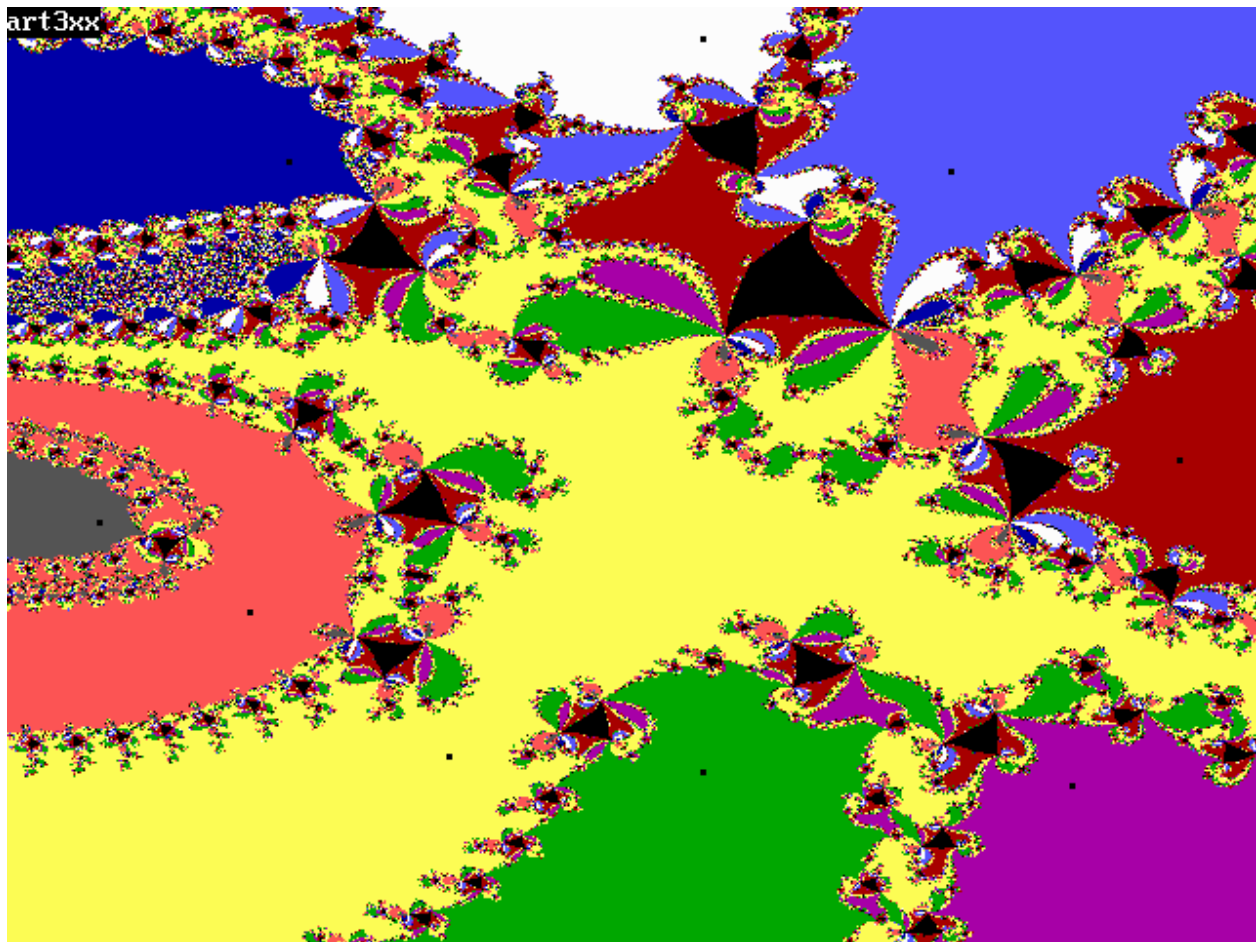
4. Extended Newton-Raphson.

In the extended Newton-Raphson method a term with the second derivative has been added to the original Newton-Raphson formula and reads as follows:

$$Z_{n+1} = Z_n - F(Z_n)/F'(Z_n) - F(Z_n)^2 * F''(Z_n) / 2 * F'(Z_n)^3 \quad (9)$$

The method is applied to the equation of formula (1). In a real/imaginary window of coordinates defined by (-1, 1, 1, -1) (rmin, rmax, imax, imin) and a screen of 640x480 pixels all 9 roots were found. The roots are placed in the storage address rtxx, and the visual representation in art3xx. The roots are the same as the roots shown on page 6, but have not been calculated in the same order as the roots found with the normal Newton-Raphson method.

The NRX-polynomiograph (Newton-Raphson eXtended polynomiograph) is shown below. The roots are the same as roots 1, 2, 3, 5 and 8 on page 6 and their location is shown in the NRX-polynomiograph as little square black dots. The larger black areas are areas of seed values with which no roots were determined.



5. Other methods and conclusions.

Amongst other methods that we have not investigated (due to their complexity) are those of Bairstow, Graeffe, and the QD-method (Quotient-Difference method). Bairstow's method divides the original formula by a quadratic equation, determines corrections to the result and expands this in Taylor series. The Q-D method, constructed by Stiefel, Rutishauser, and Henrici, can be used for the determination of eigen values of matrices and finding roots. The method is based on constructing a rhombic pattern of numbers, using the higher order differences between those numbers, and solving a set of two equations. The method of Muller is based on determining three points on the curve of the equation and constructing a parabola through those points. This method is discussed in chapter 7. We are dealing here with choosing three points, whereas in Regula Falsi two points would be sufficient for finding the roots of the equation.

The convergence exponents of the methods with the exception of Bairstow's method and the Q-D method are:

| | |
|-----------------------------|------|
| 1. Successive substitution: | 1 |
| 2. Regula Falsi | 1.62 |
| 3. Muller | 1.84 |
| 4. Newton-Raphson | 2 |
| 5. Newton-Raphson extended | 3 |

The easiest of these methods is the first. However, as we have demonstrated, it is difficult to find all the roots. In my used examples this method only found one root of a nine-degree complex equation. Methods 2 and 3 needs initial values of resp. 2 and 3 points, while for methods 4 and 5 resp. the first derivative, and the first and second derivative have to be determined.

It turns out that the fastest method is slowed down by having to calculate a complicated third term that involves a multiplication and a division using the original function, its first and second derivative. As shown, it determines not all the roots that we want to find. The Regula Falsi method will find all the roots, is slightly slower than Newton-Raphson, but generates RF-polynomiographs with areas in which roots can't be found (black areas). This also happens with the Newton-Raphson method but less frequently. I am convinced that in most cases it finds all the roots and generates complete NR-polynomiographs, no matter whether the initial or seed values are extremely large or extremely small. In case Newton-Raphson fails, the modified method (7a) will do the trick, provided that a suitable value for the relaxation factor ρ is used. We have tried this method with world coordinates of (-100000, 100000, 100000, -100000) (rmin, rmax, imax, imin). The convergence process slows down the larger these coordinates becomes, but it will converge to the correct roots and creates complete NR-polynomiographs. The smallest coordinates used cover an area that is 10^{-26} smaller than the smallest area that contains the roots. We might have been able to try even smaller areas, where it not that the hardware of my computer does not support the use of values that define such small areas.

Conjecture 2: For any given seed value, excluding the one that coincides with the origin, the method of Newton-Raphson or the modified Newton-Raphson method will find a root.

Conjecture 3: All roots of a complex polynomial can be found with the method of Newton-Raphson or the modified Newton-Raphson method, provided that enough seed values and an appropriate value for the relaxation value are used.

It is argued in the literature that the iterations in the basic Newton-Raphson method could cycle. If this happens it can be resolved by using the modified version of Newton-Raphson. Another problem is the fact that the first derivative of the formula representing the NR-method can become zero. In my programs I have managed to stay clear of this situation.

As mentioned, a large number of polynomial equations were investigated. The following chapter: Example, shows the results of one of them. From all these calculations it becomes clear that there the highest order leafs (represented in the polynomiographs with the symbolic names ga05aa and ga0500) are open leafs. That means that they will continue to infinity and have boundaries that can be viewed as two diverging straight lines. Note that these lines contain infinite sets of lower-order leafs. The open highest-order leafs also contain the roots associated with these leafs. All lower-order leafs have closed boundaries. Note that each closed leaf is surrounded by a barrier of leafs with an order that is one level lower than the leaf within this barrier. Investigations show that these boundaries serve as barriers. If one wants to move from one leaf to the next adjacent one with very small steps, one enters such a barrier that acts as a minefield. Jumping over this barrier is the only way to move from the set of loci associated with one particular root to the set of loci of another root, where this second set of loci has the appearance of being a direct neighbour of the first set of loci. These barriers consist basically of a chain of a bundle of leafs and in which these leafs represent the leafs associated with the roots of the original equation (1). Whether we defined the real/imaginary coordinates extremely large or extremely small, this pattern of open and closed leafs will reappear, as shown in the example of the next paragraph. The only handicap in this process is the limited way in which real numbers can be represented with our computer equipment. All the performed calculations shows polynomiographs of which we have drawn the following conclusions:

Conjecture 4: An NR-polynomiograph consists of open leafs in which the roots of a polynomial equation are located, and an infinitely large amount of closed leafs.

Conjecture 5: Leafs of the same order are separated from each other by a barrier of leafs of a lower order. No two leafs of the same order are directly adjacent to each other.

6. Example.

Consider the equation $\sum_{m=0}^{m=9} C_m Z^m = 0$

where $C_0 = 4 + 6.i$; $C_1 = .3 - 1.i$; $C_2 = .8 - .5.i$; $C_3 = -.25 + .5.i$; $C_4 = .5 + .5.i$;
 $C_5 = .7 - .75.i$; $C_6 = -.35 + .75.i$; $C_7 = .45 - .25.i$; $C_8 = -.65 + .25.i$; $C_9 = 1$

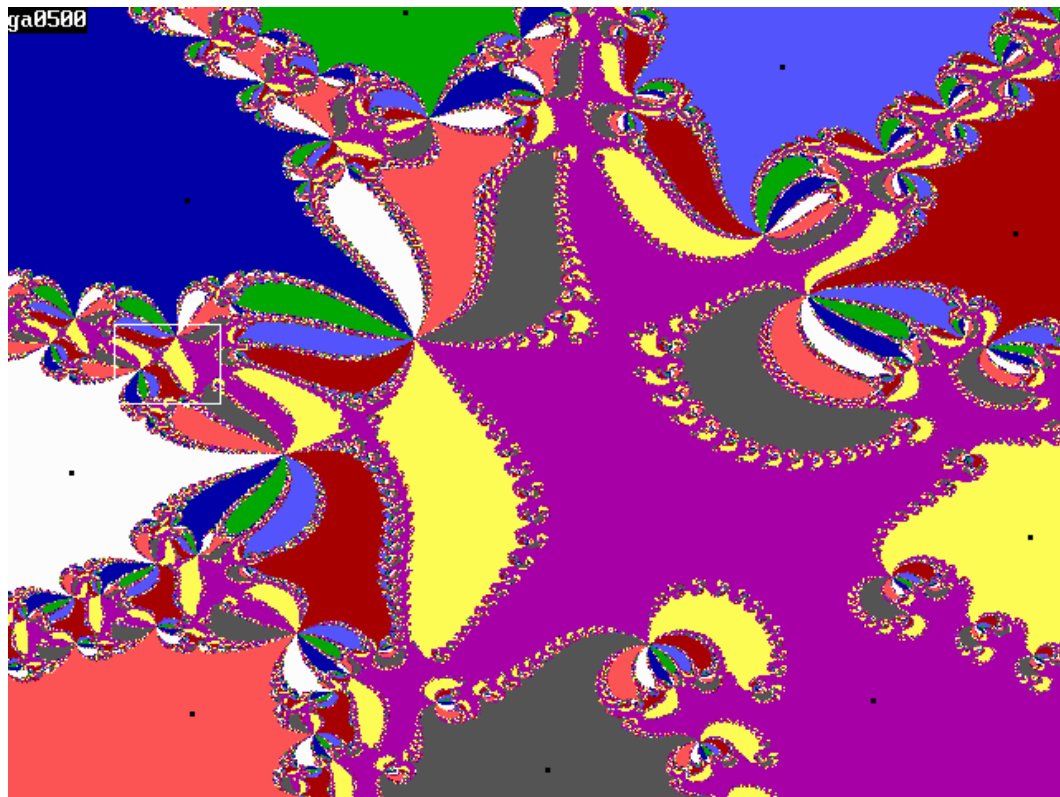
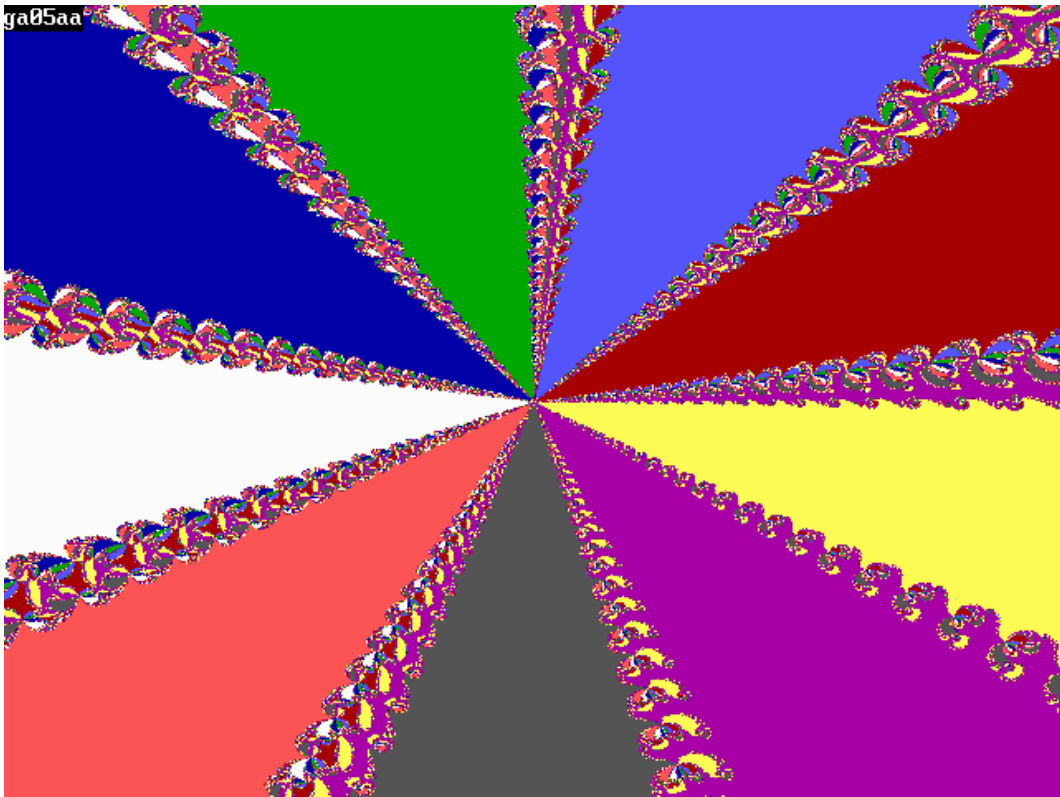
The roots are (calculated with an accuracy of 0.0001):

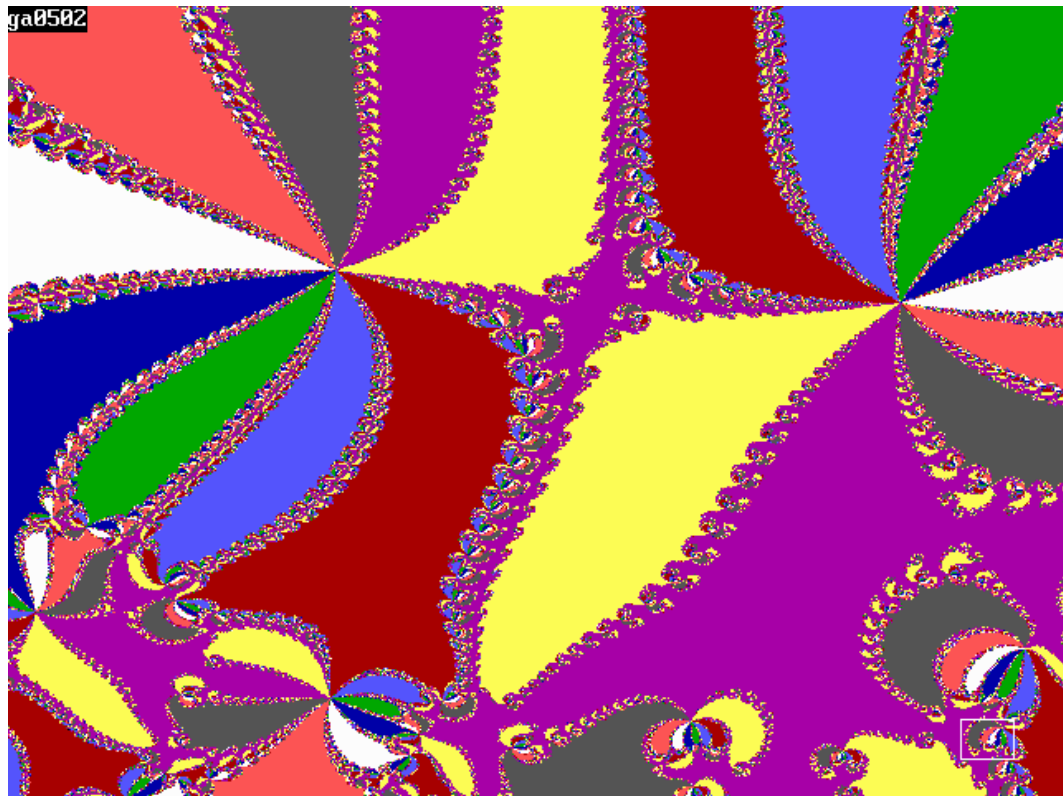
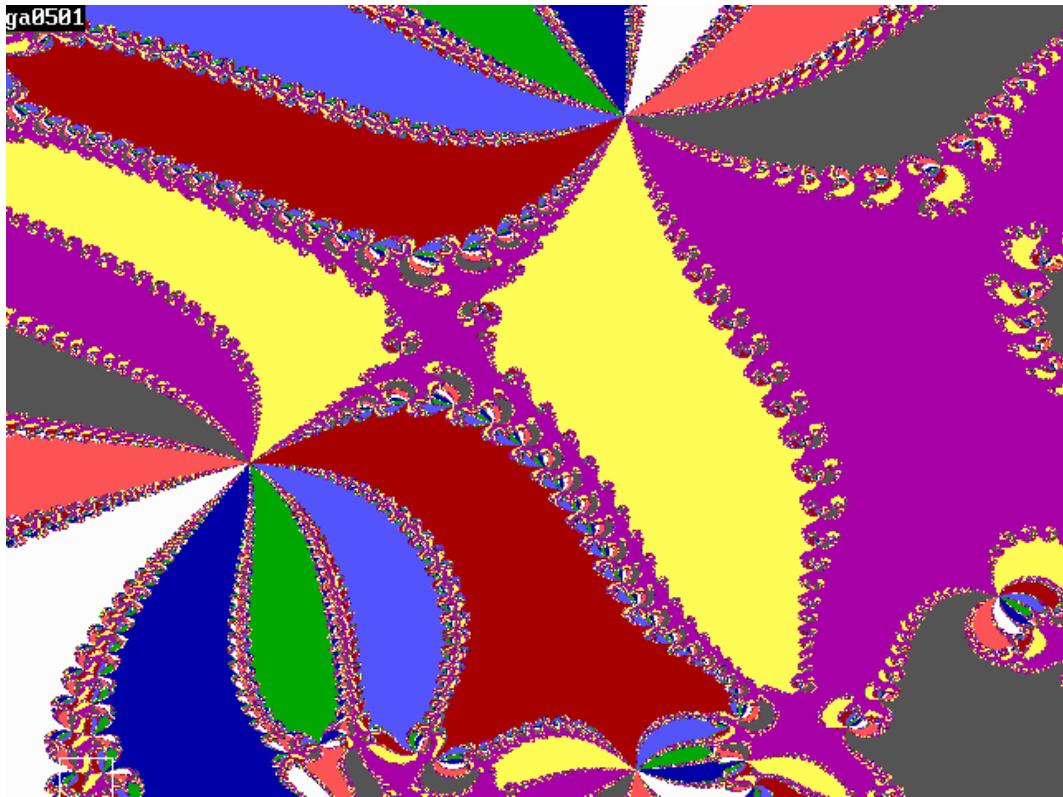
Root1: $-.8606220286249983 + .6659487704078041*i$ (blue)
Root2: $-.3260056834276752 + 1.283126586328105 *i$ (green)
Root3: $.5992787509712372 + 1.103682709656271*i$ (light blue)
Root4: $1.1734550366744960 + .5590327452828046*i$ (red)
Root5: $.8245803640955177 - .9748311601773331*i$ (magenta)
Root6: $1.2101329495036600 - .4380346718883291*i$ (yellow)
Root7: $-1.1452672657445820 - .2252986466412862 *i$ (white)
Root8: $.0247114547197130 - 1.203766313565029 *i$ (gray)
Root9: $-.8502635781658199 - 1.019860019403639 *i$ (light red)

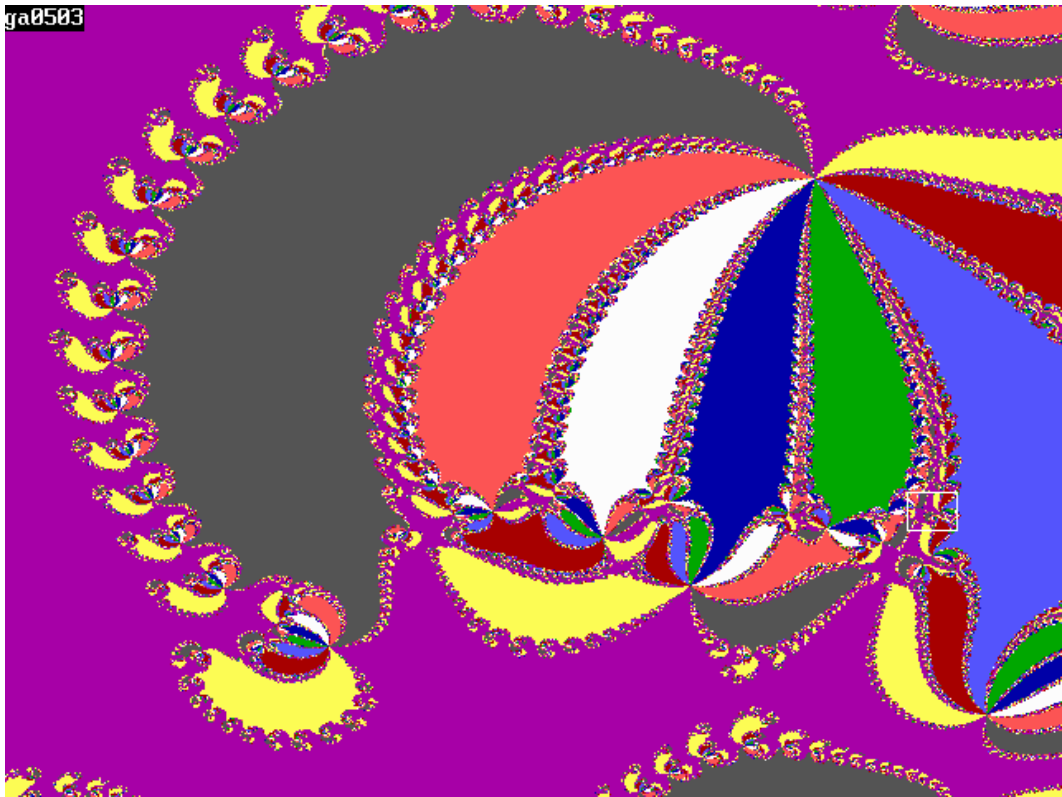
We have generated various NR-polynomiographs with the following with windows defined by the following world coordinates (rmin, rmax, imax, imin):

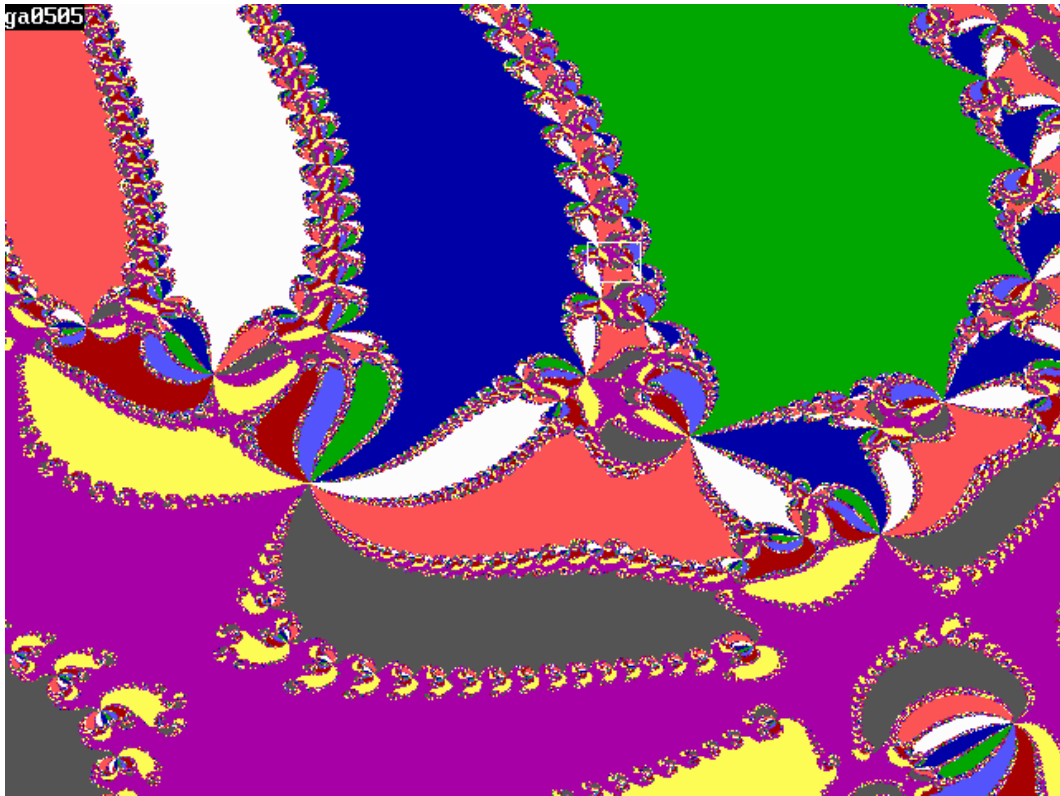
ga05aa: -100, 100, 100, -100
ga0500: -1.3 1.3, 1.3 -1.3 (here the locations of the roots are identified with small black squares)
ga0501: -1.04, -.78, .26, 0
ga0502: -1.027, -1.014, 0.013, 0
ga0503: -1.0153, -1.01465, 0.0013, 0.00065
ga0504: -1.014745, -1.014715, 0.0009, 0.00087
ga0505: -1.014718, -1.014715, 0.000876, 0.000873
ga0506: -1.01471635, -1.01471620, 0.00087510, 0.00087495
ga0507: -1.01471632, -1.014716305, 0.00087501, 0.000874995
ga0508: -1.014716308, -1.0147163075, 0.0008750085, 0.000875008
ga0509: -1.0147163079, -1.0147163076, 0.0008750085, 0.0008750082
ga0510: -1.01471630779; -1.01471630778, 0.00087500824, 0.00087500823
ga0511: -1.014716307782, -1.014716307781, 0.000875008239, 0.000875008238

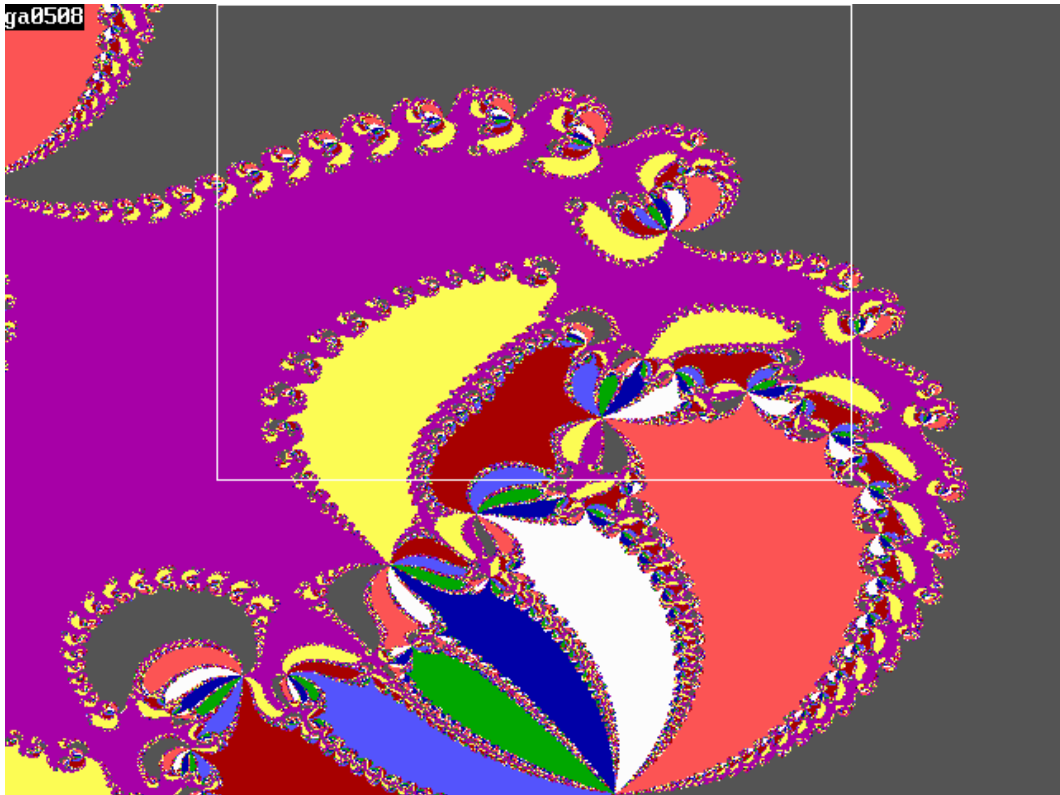
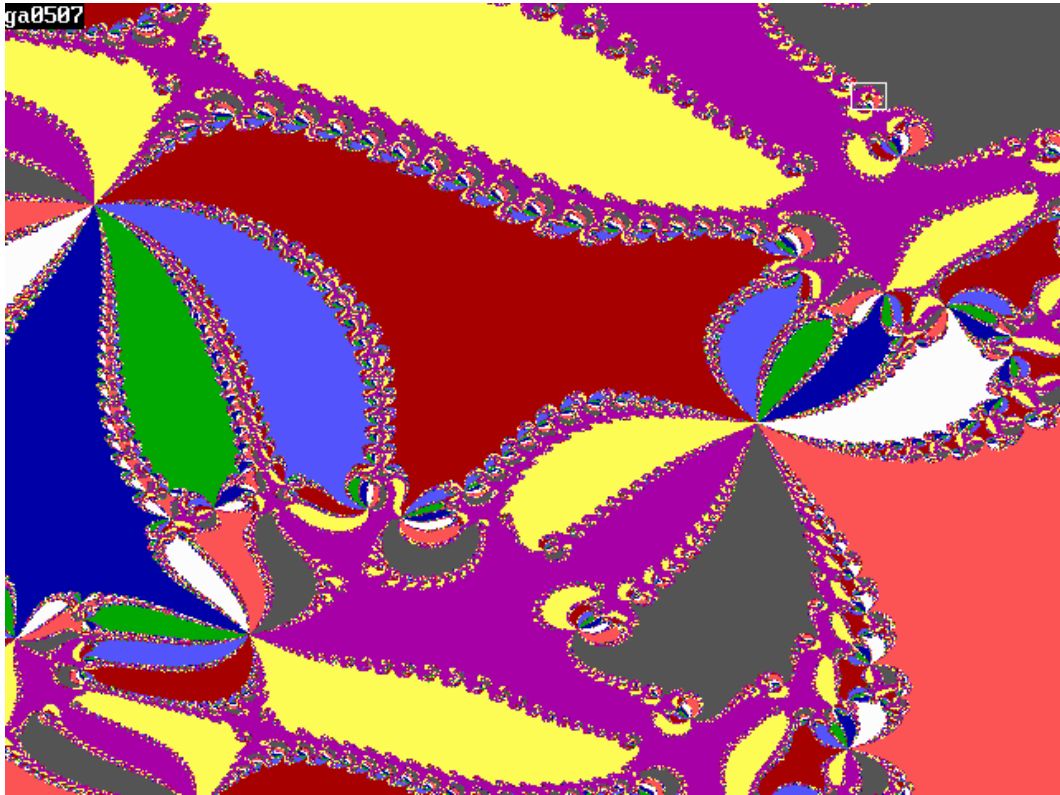
Note that the surface of the largest polynomiograph (ga05aa) is 40,000 units and the surface of the smallest polynomiograph (ga0510) is 10^{-24} units.



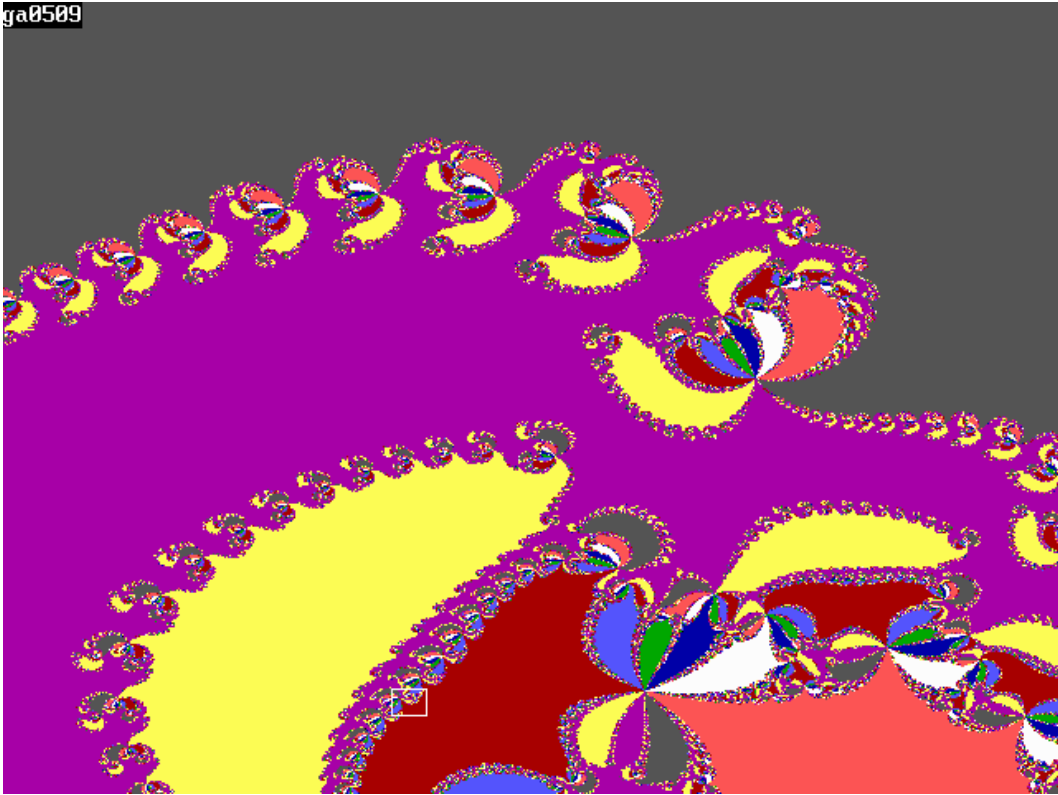






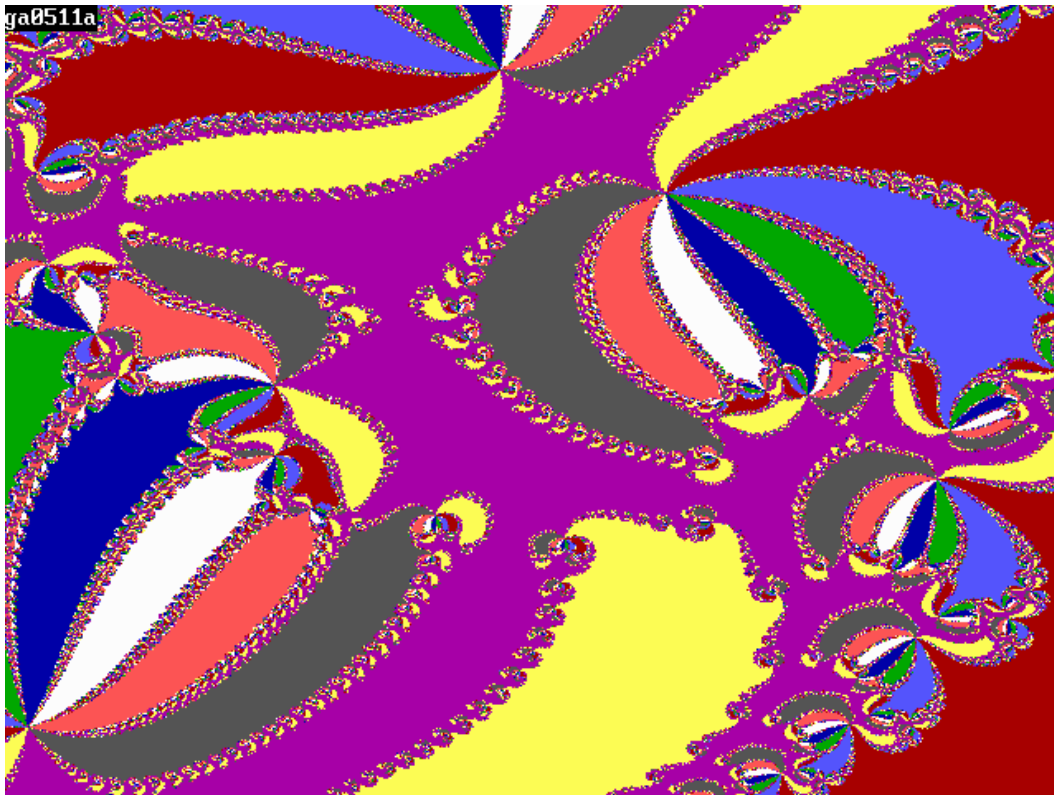


ga0509



ga0510





This is one of the smallest polynomiograph I was able to generate. Polynomiographs that are 10% smaller tend to become irregular due to the loss of significance in the presentation of floating point numbers. I am convinced that with more powerful machines and/or computers of which the representation of floating point numbers are more accurate will be able to generate *ad infinitum* the same kind of patterns.

Observations

1. With the previously described methods certain problems may arise. That is especially the case if a complex polynomial has one or more roots that are identical. With our root-finding approach we will miss those roots, despite the fact that we are using all the seed values that are associated with the pixel values of the display screen.

If, using the Newton-Raphson method, we find a number of roots that is smaller than the degree of the polynomial, it is quite certain that we are dealing with identical roots. To find these roots we can apply the following strategy.

Assume that the degree of the polynomial is n and that we find k roots ($k < n$) We will divide the original polynomial by a polynomial of the form $(Z-Z_1).(Z-Z_2).....(Z-Z_k)$. The newly generated polynomial is of the order $m = n-k$ and of the form:

$$F_{\text{new}}(Z) = \sum_{j=0}^{j=n} C_j Z^j / \prod_{i=1}^{i=k} (Z - Z_i) \quad (10)$$

If $m = 2$ or 3 we can easily solve the new equation with analytical means. It means we are dealing with 2 or 3 roots that have identical values. If m is larger than 3 we have to solve the roots of this new function in the same way as we did with the original polynomial.

2. One must be careful with the definition of the frame within which one tries to determine the roots. It is possible to define that frame too small resulting in covering an area in a leaf that will determine the root associated to that leaf only.

3. Once a seed value has been selected that is located in a specific closed leaf of any order (other than the highest order), the iteration process will determine new starting values that will always be located in leaves (probably of different order) that belong to the same class of leaves or stated differently: leaves that are associated with the same root. The process jumps from leaf to leaf where all these leaves have the same colour. It ends when values are found in the highest-order open leaf and the process will iterate to the root associated with this leaf.

7. Muller's method.

This is the most elaborate of all the methods that I investigated with the objective of finding the roots of high degree complex polynomials and generating polynomiographs of the results. In Muller's method we have to determine the roots of:

$$F(Z,C) = \sum_{n=0}^{n=k} C_n Z^n ; C \text{ and } Z \text{ are complex numbers; degree of polynomial is } k$$

and apply this method by defining a quadratic curve through three points on the curve defined by the complex polynomial function $F(Z)$ and intersecting this curve with the X-axis. This leads to the equation:

$$\begin{aligned} & \frac{(Z - Z_{n-2}) \cdot (Z - Z_{n-1})}{(Z_n - Z_{n-2}) \cdot (Z_n - Z_{n-1})} * F(Z_n) + \frac{(Z - Z_{n-2}) \cdot (Z - Z_n)}{(Z_{n-1} - Z_{n-2}) \cdot (Z_{n-1} - Z_n)} * F(Z_{n-1}) + \\ & + \frac{(Z - Z_{n-1}) \cdot (Z - Z_n)}{(Z_{n-2} - Z_{n-1}) \cdot (Z_{n-2} - Z_n)} * F(Z_{n-2}) = 0 \end{aligned} \quad (11)$$

The values of Z are calculated by assigning world coordinates for complex numbers to the screen coordinates (640x480) in the same way as we did in the case of the previous methods. In this way we examine all 640x480 seed values for Z_n . The values of Z_{n-1} and Z_{n-2} are derived from Z_n by making them slightly different from Z_n .

This quadratic equation results in two values for Z , which is the new seed value in the iteration process for finding one of the roots of the polynomial. We chose one of these values by comparing them to the lastly found Z and continue with the value which is closest to that lastly found value. In case we don't find all the roots we will repeat the iteration process, starting from the initially chosen seed value(s) and pick the Z value which is the result of applying the positive sign in the quadratic equation (11). We can exhaust the search for all the roots by repeating the iteration process once more and choosing the other sign of the quadratic equation.

With Muller's method we have found the roots of formula (1) with $C = -.37-.63i$, and using world coordinates between (-1.2, 1.2, 1.2, -1.2) for resp. rmin, rmax, imax, imin. As expected, the roots are similar to those found with Newton-Raphson or Regula Falsi.

The generated polynomiograph (MU-polynomiograph) is totally different from the NR-polynomiograph and RF-polynomiograph. The boundaries between the coloured areas are sharp and the picture exhibits a rather chaotic character. Many seed values did not result in finding any root (the black areas in the MU-polynomiograph with the symbolic name gmull). This may have been caused by the limit that was set in the number of allowed iteration steps. It is also possible that the used strategies where we had to make a choice in determining which value of the two values that are the result of evaluating formula (11) had to be used. A random selection of the use of the plus- or minus-sign in calculating Z in formula (11) might give different results. Due to the complication of making these choices the time necessary for generating the MU-polynomiograph is extremely long. However,

the program that calculates the roots is almost as fast as the program used in the Newton-Raphson approach, despite the more elaborate computations that are involved in Muller's method.

The MU-polynomiograph for the complex equation of formula (1) is shown below. The little black square boxes in the larger coloured patterns indicate the location of the roots.

