VPS 5	Parallel and Distributed Software Systems	ST 16, Exercise 3

Deadline: 30th of April, 2016 08:00

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Points _____ **Effort in hours** 8

1. Dish of the Day: "Almondbreads" (4 + 8 + 8 + 4 Points)

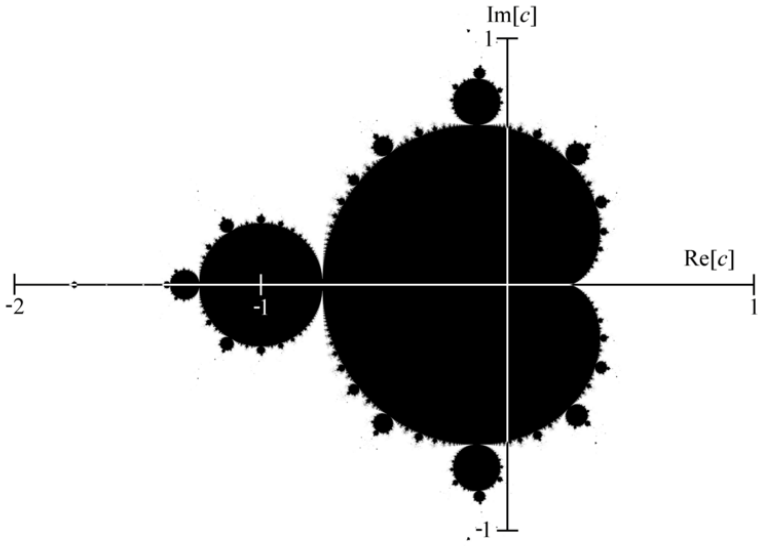
In this exercise we would like to take a look at a very special form of bread: the "Almondbread" or in other words the *Mandelbrot*. However, the Mandelbrot is not a common form of bread. It is very special (and delicious) and as a consequence, to bake a Mandelbrot we cannot just use normal grains. Instead we need special or complex grains. The recipe is the following:

The Mandelbrot set is the set of complex numbers c, for which the following (recursive) sequence of complex numbers z_n

$$z_0 = 0$$
$$z_{n+1} = z_n^2 + c$$

doesn't diverge towards infinity. If you are not so familiar with complex numbers (anymore), a short introduction can be found at the end of this exercise sheet.

If you mark these points of the Mandelbrot set in the complex plane, you get the very characteristic picture of the set (also called "Apfelmännchen" in German). The set occupies approximately the area from -2-*i* to 1+*i*:



To get even more interesting and artistic pictures the points outside the Mandelbrot set can be colored differently depending on how fast the sequence diverges towards infinity. Therefore just define an upper limit for the absolute value of z_n (usually 4). If z_n grows larger than this upper limit, it can be assumed that z_n will keep growing and will finally diverge. On the other hand if this upper limit is not exceeded in a predefined number of iterations (usually 10.000), it can be assumed that the sequence will not diverge and that the starting point c consequently is element of the Mandelbrot set. Depending on how fast z_n goes beyond the limit (number of iterations) the starting point c can be colored.

a) Write a simple generator in C# using the .NET Windows Forms framework that calculates and displays the Mandelbrot set. Additionally, the generator should have the feature to zoom into the set. Therefore, the user should be able to draw a selection rectangle into the current picture of the set which marks the new section that should be displayed. By clicking on the right mouse button, the original picture (-2-*i* to 1+*i*) should be generated again.

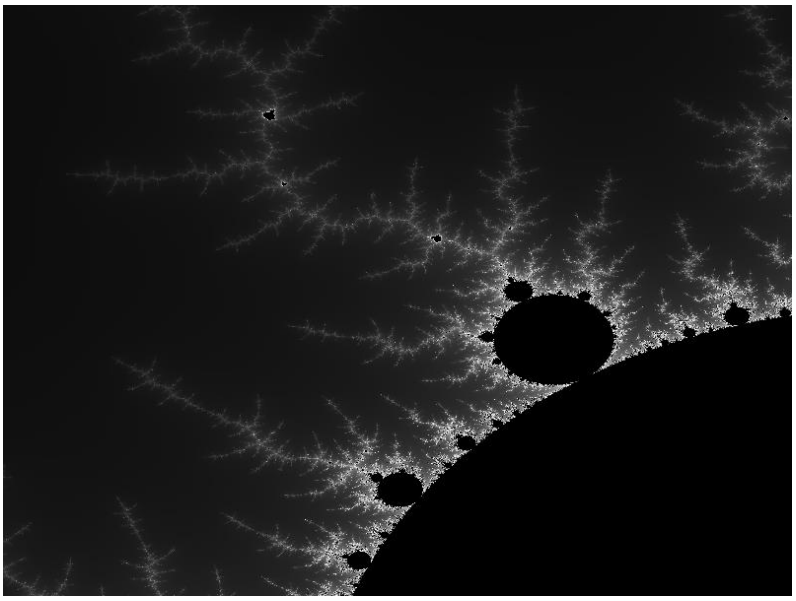
b) Take care that the calculation of the points is computationally expensive. Consequently, it is reasonable to use a separate (worker) thread, so that the user interface stays reactive during the generation of a new picture. However, it can be the case that the user selects a new section before the generation of a previous selection is finished. Furthermore, the time needed for the generation of a picture is variable depending on how many points of the Mandelbrot set are included in the current selection. So, it can also happen that the calculation of a latter selected part is finished before an earlier selected one. Therefore, synchronization is necessary to coordinate the different worker threads.

   Implement at least two different ways to create and manage your worker threads (for example you can use BackgroundWorker, threads from the thread pool, plain old thread objects, asynchronous delegates, etc.). Explain how synchronization and management of the worker threads is done in each case.

c) Think about what's the best way to partition the work and to spread it among the workers. Based on these considerations implement a parallel version of the Mandelbrot generator in C# without using the Task Parallel Library (or Parallel.For).

d) Measure the runtime of the sequential and parallel version needed to display the section -1,4-0,1*i* to -1,32-0,02*i* with a resolution of 800 times 600 pixels. Execute 10 independent runs and document also the mean runtimes and the standard deviations.

   For self-control, the generated picture could look like this:



Appendix: Calculations with Complex Numbers

As you all know, it is quite difficult to calculate the square root of negative numbers. However, many applications (electrical engineering, e.g.) require roots of negative numbers leading to the extension of real to complex numbers. So it is necessary to introduce a new number, the imaginary number *i*, which is defined as the square root of -1. A complex number *c* is of the form

$$c = a + b \cdot i$$

where *a* is called the real and *b* the imaginary part. *a* and *b* themselves are normal real numbers.

As a consequence of this special form calculations with complex numbers are a little bit more tricky than in the case of real numbers. The basic arithmetical operations are defined as follows:

$$\begin{aligned}
(a + b \cdot i) + (c + d \cdot i) &= (a + c) + (b + d) \cdot i \\
(a + b \cdot i) - (c + d \cdot i) &= (a - c) + (b - d) \cdot i \\
(a + b \cdot i) \cdot (c + d \cdot i) &= (ac - bd) + (bc + ad) \cdot i \\
\frac{a + b \cdot i}{c + d \cdot i} &= \frac{ac + bd}{c^2 + d^2} + \frac{bc - ad}{c^2 + d^2} \cdot i
\end{aligned}$$

Furthermore we also need the absolute value (distance to 0+0i) of complex numbers which can be calculated easily using the theorem of Pythagoras:

$$\mathrm{Abs}(a + b \cdot i) = \sqrt{a^2 + b^2}$$

1 Dish of the Day: Almondbreads

1a. Generator

Der Generator wurde bereits in der Übung programmiert und baut auf vorhandenem Code auf.

```
using System;
using System.Diagnostics;
using System.Drawing;

namespace MandelbrotGenerator
{
    /// <summary>
    /// Image generate on sync implementation
    /// </summary>
    public class SyncImageGenerator : IImageGenerator
    {
        /// <summary>
        /// Flag used for cancellation
        /// </summary>
        protected bool cancel;

        protected Bitmap GenerateBitmap(Area area)
        {
            int maxIterations;
            double zBorder;
            double cReal, cImg, zReal, zImg, zNewReal, zNewImg;

            maxIterations = Settings.DefaultSettings.MaxIterations;
            zBorder = Settings.DefaultSettings.ZBorder*Settings.DefaultSettings.ZBorder;

            Bitmap bitmap = new Bitmap(area.Width, area.Height);

            for (int i = 0; i < area.Width; i++)
            {
                for (int j = 0; j < area.Height; j++)
                {
                    cReal = area.MinReal + i*area.PixelWidth;
                    cImg = area.MinImg + j*area.PixelHeight;
                    zReal = 0;
                    zImg = 0;

                    int k = 0;
                    while ((zReal*zReal + zImg + zImg < zBorder)
                           && (k < maxIterations))
                    {
                        //check canecllation
                        if (cancel) return null;

```

```
44                          zNewReal = zReal*zReal - zImg*zImg + cReal;
45                          zNewImg = 2*zReal*zImg + cImg;
46
47                          zReal = zNewReal;
48                          zImg = zNewImg;
49
50                          k++;
51                      }
52
53                      bitmap.SetPixel(i, j, ColorSchema.GetColor(k));
54                  }
55              }
56              return bitmap;
57          }
58
59          /// <summary>
60          /// Generate the given area
61          /// </summary>
62          /// <param name="area"></param>
63          public virtual void GenerateImage(Area area)
64          {
65              Stopwatch sw = new Stopwatch();
66              sw.Start();
67              Bitmap bm = GenerateBitmap(area);
68              sw.Stop();
69
70              //bm is null on cancellation
71              if (bm != null)
72              {
73                  OnImageGenerated(area, bm, sw.Elapsed);
74              }
75
76          }
77
78          /// <summary>
79          /// Event when the generation is finished
80          /// </summary>
81          public event EventHandler<EventArgs<Tuple<Area, Bitmap, TimeSpan>>> ImageGenerated;
82
83          /// <summary>
84          /// Image generated event invoker
85          /// </summary>
86          /// <param name="area"></param>
87          /// <param name="bitmap"></param>
88          /// <param name="timespan"></param>
89
90          protected virtual void OnImageGenerated(Area area, Bitmap bitmap, TimeSpan timespan)
91          {
92              var handler = ImageGenerated;
```

```
93              handler?.Invoke(this,
94                  new EventArgs<Tuple<Area, Bitmap, TimeSpan>>(new Tuple<Area, Bitmap, TimeSpan>(ar
95          }
96      }
97  }
```

1b. Asynchrone Implementierung

Um asynchrone Implementierungen zu ermöglichen, wurde das Interface `IImageGenerator` um das Event `ImageGenerated` erweitert. Weiters muss bei der Zuweisung des Ergebnisses an die GUI der Thread gewechselt werden.

Die folgenden Implementierungen leiten vom originalen `SyncImageGenerator` ab und verlagern die Arbeit in den Hintergrund. Dabei wurde eine einfache Möglichkeit zum Abbrechen der Berechnung implementiert. Hierzu wurde die Implementierung um ein simples Stop-Flag erweitert. (Code siehe 1.a)

Implementierung 1: `AsyncImageGenerator`

Bei dieser Implementierung wurden `Threads` verwendet, um die Arbeit in den Hintergrund zu verlagern. Die Prüfung ob bereits eine Berechnung läuft, wird über die Abfrage des Thread-Status `IsAlive` durchgeführt. Ist noch eine Berechnung aktiv, wird das Stop-Flag gesetzt und dann auf die Beendigung des Threads gewartet. *Anmerkung:* Auf die Beendigung wird am GUI-Thread gewartet, da der Hintergrundthread bei jedem Schleifendurchgang prüft, ob das Stop-Flag gesetzt ist. Diese Zeitspanne ist sehr kurz und verursacht somit kein Einfrieren der Oberfläche.

```
1  using System.Threading;
2
3  namespace MandelbrotGenerator
4  {
5      /// <summary>
6      /// Async version using threads
7      /// </summary>
8      public class AsyncImageGenerator:SyncImageGenerator
9      {
10         private Thread workerThread;
11
12         public override void GenerateImage(Area area)
13         {
14             //Check if calculation is running and cancel it
15             if (workerThread != null && workerThread.IsAlive)
16             {
17                 cancel = true;
18                 workerThread.Join();
19             }
20             cancel = false;
21             workerThread = new Thread(Run);
22             workerThread.Start(area);
23         }
```

```
24
25          private void Run(object o)
26          {
27              Area area = o as Area;
28              //call base logic
29              base.GenerateImage(area);
30          }
31      }
32  }
```

Implementierung 2: `AsyncWorkerImageGenerator`

Die `AsyncWorkerImageGenerator` Implementierung verwendet einen .NET `BackgroundWorker`, um die Arbeit in den Hintergrund zu verlagern. Die Ergebnisweiergabe wird über das Event `RunWorkerCompleted` und die Eigenschaft `Result` abgewickelt. Die Synchronisierung der Berechnungen wird über die Eigenschaft `IsBusy` der Klasse `BackgroundWorker` gelöst.

```
1  using System;
2  using System.ComponentModel;
3  using System.Diagnostics;
4  using System.Drawing;
5
6  namespace MandelbrotGenerator
7  {
8      /// <summary>
9      /// Async background worker implementation
10     /// </summary>
11     public class AsyncWorkerImageGenerator:SyncImageGenerator
12     {
13         private BackgroundWorker worker;
14
15         /// <summary>
16         /// Generate the given area
17         /// </summary>
18         /// <param name="area"></param>
19         public override void GenerateImage(Area area)
20         {
21             if (worker != null && worker.IsBusy)
22             {
23                 cancel = true;
24             }
25
26             worker = new BackgroundWorker();
27             worker.DoWork += DoWork;
28             worker.RunWorkerCompleted += OnWorkCompleted;
29             cancel = false;
30             worker.RunWorkerAsync(area);
31         }
```

```
32
33          private void OnWorkCompleted(object sender, RunWorkerCompletedEventArgs e)
34          {
35              (sender as BackgroundWorker).RunWorkerCompleted -= OnWorkCompleted;
36
37              Tuple<Area, Bitmap, TimeSpan> res = e.Result as Tuple<Area, Bitmap, TimeSpan>;
38              if (res == null)
39              {
40                  throw new InvalidOperationException("Result is null");
41              }
42              //bitmap is null on cancellation
43              if (res.Item2 != null)
44              {
45                  OnImageGenerated(res.Item1, res.Item2, res.Item3);
46              }
47
48          }
49
50          private void DoWork(object sender, DoWorkEventArgs e)
51          {
52              Area area = e.Argument as Area;
53              if (area == null)
54                  throw new InvalidOperationException("First argument area cannot be null");
55
56              Stopwatch sw = new Stopwatch();
57              sw.Start();
58              Bitmap bm = GenerateBitmap(area);
59              sw.Stop();
60              e.Result = new Tuple<Area, Bitmap, TimeSpan>(area,bm,sw.Elapsed);
61          }
62
63      }
64  }
```

1c. Parallele Version

Die Aufteilung der Arbeit auf die Worker kann zeilenweise erfolgen. Dabei wird die benötigte Anzahl an Worker-Threads erzeugt, wobei jeder dieser Threads immer eine Zeile berechnet. Sobald alle Zeilen berechnet sind, werden die Threads beendet. Diese Aufteilung hat den Vorteil, dass die Threads ungefähr gleich ausgelastet sind, da zwei benachbarte Zeilen ungefähr den selben Rechnaufwand verursachen.

Zur Verwaltung der Berechnung wird ein zusätzlicher Management-Thread verwendet. Dieser übernimmt die Zeitmessung und das Auslösen des Events. Der Zugriff auf das Bitmap wird mit Hilfe von Locks gesichert.

```
1  using System;
2  using System.Diagnostics;
3  using System.Drawing;
```

```
4  using System.Linq;
5  using System.Threading;
6
7  namespace MandelbrotGenerator
8  {
9      /// <summary>
10     /// Paralell implementation
11     /// </summary>
12     class ParallelImageGenerator : IImageGenerator
13     {
14         private readonly object bitmapLock = new object();
15         private readonly object indexLock = new object();
16         private int currentIndex;
17         private Bitmap result;
18         private Thread[] threads;
19         private Thread managementThread;
20         private bool cancel;
21
22         /// <summary>
23         /// Generate the given area
24         /// </summary>
25         /// <param name="area"></param>
26         public void GenerateImage(Area area)
27         {
28             //check canecllation
29             if (managementThread != null && managementThread.IsAlive)
30             {
31                 cancel = true;
32                 managementThread.Join();
33             }
34
35             managementThread = new Thread(ManagementThreadMethod);
36             managementThread.Start(area);
37         }
38
39         public event EventHandler<EventArgs<Tuple<Area, Bitmap, TimeSpan>>> ImageGenerated;
40
41         protected virtual void OnImageGenerated(Area area, Bitmap bitmap, TimeSpan time)
42         {
43             ImageGenerated?.Invoke(this,
44                 new EventArgs<Tuple<Area, Bitmap, TimeSpan>>(new Tuple<Area, Bitmap, TimeSpan>(ar
45         }
46
47         public void ManagementThreadMethod(object input)
48         {
49             cancel = false;
50             Area area = input as Area;
51             Stopwatch sw = new Stopwatch();
52
```

```
53              sw.Start();
54              currentIndex = 0;
55              result = new Bitmap(area.Width, area.Height);
56              threads = new Thread[Settings.DefaultSettings.Workers];
57              //Create worker threads
58              for (int i = 0; i < threads.Length; i++)
59              {
60                  Thread t = new Thread(WorkerThreadMethod);
61                  threads[i] = t;
62                  t.Start(area);
63              }
64              //Wait for finishing
65              foreach (var thread in threads)
66              {
67                  thread.Join();
68              }
69              sw.Stop();
70              //check cancellation
71              if (!cancel)
72              {
73                  OnImageGenerated(area, result, sw.Elapsed);
74              }
75
76          }
77
78          public void WorkerThreadMethod(object input)
79          {
80              Area area = input as Area;
81
82              while (!cancel)
83              {
84                  int index;
85                  lock (indexLock)
86                  {
87                      index = currentIndex;
88                      currentIndex++;
89                  }
90
91                  //for all threads which are already finished
92                  if (index >= area.Height)
93                  {
94                      return;
95                  }
96                  GenerateBitmapLine(area, index);
97              }
98          }
99
100         /// <summary>
101         /// Generates one line of the bitmap
```

```
102         /// </summary>
103         /// <param name="area"></param>
104         /// <param name="line"></param>
105         public void GenerateBitmapLine(Area area, int line)
106         {
107             int maxIterations;
108             double zBorder;
109             double cReal, cImg, zReal, zImg, zNewReal, zNewImg;
110 
111             maxIterations = Settings.DefaultSettings.MaxIterations;
112             zBorder = Settings.DefaultSettings.ZBorder*Settings.DefaultSettings.ZBorder;
113 
114 
115             for (int i = 0; i < area.Width; i++)
116             {
117                 int j = line;
118                 cReal = area.MinReal + i*area.PixelWidth;
119                 cImg = area.MinImg + j*area.PixelHeight;
120                 zReal = 0;
121                 zImg = 0;
122 
123                 int k = 0;
124                 while ((zReal*zReal + zImg + zImg < zBorder)
125                        && (k < maxIterations))
126                 {
127                     //check canecllation
128                     if (cancel)
129                     {
130                         return;
131                     }
132 
133                     zNewReal = zReal*zReal - zImg*zImg + cReal;
134                     zNewImg = 2*zReal*zImg + cImg;
135 
136                     zReal = zNewReal;
137                     zImg = zNewImg;
138 
139                     k++;
140                 }
141                 lock (bitmapLock)
142                 {
143                     result.SetPixel(i, j, ColorSchema.GetColor(k));
144                 }
145             }
146         }
147     }
148 }
```

1d. Performance

Parameter

- Ausschnitt: -1,4-0,1i bis -1,32-0,02i
- Auflösung: 800x600
- WorkerThreads: 8 (parallele Implementierung)

Tabelle 1: Ergebnisse

Simulation		
Lauf	Sync [ms]	Parallel [ms]
1	2832	603
2	2817	595
3	2829	617
4	2822	583
5	2819	592
6	2828	612
7	2834	600
8	2822	619
9	2823	606
10	2844	599
Ø	**2827**	**599**
Std. Abw.	7,73	10,73

- SpeedUp: 4,69