COMPUTER SESSION II:
One-parameter bifurcation analysis of equilibria with MATCONT

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This session is devoted to the numerical continuation of equilibria in systems of autonomous ODEs depending on one parameter
\[ \dot{u} = f(u, \alpha), \quad u \in \mathbb{R}^n, \alpha \in \mathbb{R}, \]
and detection of their bifurcations.

1 An ecological model with multiple equilibria and limit points

Consider the following system appearing in mathematical ecology:

\[
\begin{align*}
\dot{x} &= rx(1-x) - \frac{xy}{x+a}, \\
\dot{y} &= -cy + \frac{xy}{x+a} - \frac{dy^2}{y^2 + b^2}.
\end{align*}
\] (1)

Fix
\[ r = 2, \quad a = 0.6, \quad b = c = 0.25, \]
and consider \( d \) as a bifurcation parameter with initial value \( d = 0.1 \). The aim is to locate equilibria of (1) and study their dependence on \( d \).

1.1 System specification

![Figure 1: The ecological model.](image)
Start matcont, choose Select|Systems|New, and input a new ODE system – say EcoMod – into matcont as shown in Figure 1.

1.2 Locate an equilibrium by numerical integration

Select Type|Initial point|Point and check that the default Type|Curve|Orbit is selected.

In the appearing integrator window, increase the integration Interval to 200 and set Rel.Tolerance to 1e-7 and Abs.Tolerance to 1e-10 (to assure smaller integration steps).

Via the Starter window, input the initial point

<table>
<thead>
<tr>
<th>X</th>
<th>1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>1</td>
</tr>
</tbody>
</table>

and the initial values of the parameters, namely

<table>
<thead>
<tr>
<th>RR</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>0.6</td>
</tr>
<tr>
<td>BB</td>
<td>0.25</td>
</tr>
<tr>
<td>CC</td>
<td>0.25</td>
</tr>
<tr>
<td>DD</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Open a 2Dplot window with Window|Plot|2Dplot. Select X and Y as variables along the corresponding axes and input – after clicking Attributes|Plotting region – the following visibility limits

| X-axis: | 0  | 1.2 |
|         |    |     |
| Y-axis: | 0  | 2.0 |

Start Compute|Forward. You will get an orbit converging to an equilibrium, see Figure 2

Figure 2: Phase orbits approaching a stable equilibrium for $d = 0.1$
To see how the coordinates vary along the orbit, select Window|Numeric which opens a numeric window. Then input another initial point:

\[
\begin{align*}
X &= 1.0 \\
Y &= 0.001
\end{align*}
\]

and Compute|Forward. You get the second orbit from Figure 2 tending to the same equilibrium, whose (approximate) coordinates can be seen in the numeric window shown in Figure 3. Close the numeric window.

1.3 Equilibrium curve

We can continue the equilibrium found by integration with respect to the parameter \(d\) (i.e. \(D\)).

Figure 3: The coordinates of the stable equilibrium.

For this, open with Select|Initial point the Select point window and select the last point of the orbit \(P_0(1)\) (click to highlight and then press Select button, see Figure 4). To tell matcont to continue an equilibrium curve, we have to specify the initial point type and and the curve type. Selecting Type|Initial point|Equilibrium we set the point type \(EQ\) and the same (default) curve type, so that we prepare to compute the \(EQ\) equilibrium curve, as indicated in the main matcont window. Two new windows appear: Starter and continuer.

Figure 4: Select point window.
Figure 5: 

**Starter window for the equilibrium continuation:** Parameter DD is activated.

Figure 6: 

**Continuation parameters in the continuer window.**
Figure 7: Equilibrium manifold in the \((d,y)\)-plane: LP’s denote limit points, H is a Hopf point.

The initial values of the parameters and the equilibrium coordinates are visible in the Starter window. Press the radio-button next to parameter \(DD\), indicating that it will be a bifurcation parameter (i.e. activate parameter \(d\)). The resulting Starter window is shown in Figure 5. There you can also see which singularities will be monitored, and whether the equilibrium eigenvalues will be computed.

In the continuer window, several default numerical parameters related to the continuation are listed. Change only

- MaxStepsize 0.02
- MaxNumPoints 100

(see Figure 6).

Change the drawing attributes of the 2Dplot window to plot the parameter \(DD\) as abscissa and the coordinate \(Y\) along as ordinate, with the visibility limits

- X-axis: 0 0.5
- Y-axis: 0 1.5

Now Compute|Forward and Compute|Backward to get a sigmoidal curve as in Figure 7. Along the forward branch, MATCONT stops at two limit points labeled LP. You can resume the computation at these points in the small control window. Along the backward branch, MATCONT stops at a Hopf point labeled H. Terminate the computation by pressing stop there.

To determine stability of the equilibria and read the bifurcation parameter values, open Window|Numeric and select Window|Layout in the numeric window. Click eigenvalues turning them into EIGENVALUES, see Figure 8. This makes the eigenvalues of the equilibrium visible in the numeric window (upon resizing it).
Figure 8: Show eigenvalues in the numeric window.

Figure 9: Numeric windows at the first and second limit point.

Figure 10: Pause at each computed point.
Clear the **2Dplot** window with **Plot|Clear** and repeat **Compute|Forward**. In the **numeric** window you can read the LP parameter:

\[ d_1 = 0.176927 \ldots, \quad d_2 = 0.256805 \ldots \]

(see Figure 9). One eigenvalue (close to) zero is also present in each case. The existence of three equilibria for \( d \in (d_1, d_2) \) is evident from the figure.

In the MATLAB Command Window, the value of the *fold normal form* coefficient \( a \) is shown at each limit point:

```
label = LP, x = ( 0.619532 0.927986 0.256805 )
a=-5.311546e-01
```

```
label = LP, x = ( 0.911266 0.268200 0.176927 )
a=5.681504e-01
```

Finally, clear the **2Dplot** window once more and recompute the equilibrium curve forward with **Options|Pause** mode selected as shown in Figure 10. Resume computations after each computed point and monitor the eigenvalues in the **numeric** window. You should see that, indeed, the upper and lower branches correspond to linearly stable equilibria (with all \( \text{Re} \lambda_i < 0 \)), while the middle branch correspond to a linear saddle (with \( \lambda_1 < 0 < \lambda_2 \)). Since \( a \neq 0 \) to within numerical accuracy, the equilibrium curve is approximately a (scaled) parabola near each of them.

Restore the original pause option (At special points) via **Option|Pause** and close the **numeric** window.

![Figure 11: Two stable equilibria (a focus and a node) and a saddle in the ecological model at \( d = 0.2 \). The stable manifold of the saddle separates the domain of attraction of the focus from that of the node.](image-url)
1.4 Phase portrait
To verify our conclusions, compute several orbits to get a phase portrait of the system at \( d = 0.2 \) as in Figure 11. Start always at \( x = 1.2 \) but with different \( y \)'s.

2 Limit and branching points in a discretization of Bratu-Gelfand PDE
Consider the following evolution problem for \( u = u(x, t) \) with \( x \in [0, 1], t \geq 0 \):

\[
    u_t = u_{xx} + \lambda e^u, \quad u(0) = u(1) = 0, \tag{2}
\]

where \( \lambda \) is a parameter. It is called the Bratu-Gelfand problem. In this section we study the behaviour of the stationary solution to (2) as function of \( \lambda \) using finite-difference approximation over the equidistant mesh. One such time-independent solution is obvious: \( u \equiv 0 \) for \( \lambda = 0 \).

2.1 Discretization
Characterize a solution to (2) at time \( t \) by its values \( u_i(t) = u(x_i, t) \) at the uniformly distributed mesh points

\[
    x_i = ih, \quad h = \frac{1}{N + 1}, \quad i = 0, 1, \ldots, N, N + 1,
\]

for some \( N > 1 \). Then approximate the spatial derivative in (2) by finite differences at the inner points

\[
    \dot{u}_i(t) = \frac{u_{i-1}(t) - 2u_i(t) + u_{i+1}(t)}{h^2} + \lambda \exp(u_i) = 0, \quad i = 0, 1, 2, \ldots, N, \tag{3}
\]

and add the boundary conditions in the form

\[
    \begin{cases}
    u_0(t) = 0, \\
    u_{N+1}(t) = 0.
    \end{cases} \tag{4}
\]

After elimination \( u_0(t) \) and \( u_{N+1}(t) \), the equations (3) and (4) take the form of the ODE-system

\[
    \dot{U} = F(U, \lambda), \tag{5}
\]

where \( U = (u_1, u_2, \ldots, u_N) \) and \( F : \mathbb{R}^{N+1} \times \mathbb{R} \to \mathbb{R}^{N+1} \) is given by (3). An equilibrium of this system approximates a stationary solution to (2) with the \( O(h^2) \)-accuracy.

In this section, we will study a crude spatial discretization of (2) with only two internal points (i.e. \( N = 2 \) and \( h = \frac{1}{2} \)), so that (5) becomes

\[
    \begin{cases}
    \dot{u}_1 = -2u_1 + u_2 + \alpha e^{u_1}, \\
    \dot{u}_2 = u_1 - 2u_2 + \alpha e^{u_2},
    \end{cases} \tag{6}
\]

where \( \alpha = h^2 \lambda = \frac{1}{4} \lambda \) and time is also scaled. The system (6) has a \( \mathbb{Z}_2 \)-symmetry: It is invariant under the involution \( (u_1, u_2) \mapsto (u_2, u_1) \).

We will compute the equilibrium manifold of (6) in the \((u_1, u_2, \alpha)\)-space starting from point \((0, 0, 0)\) corresponding to the trivial stationary solution of (2), namely \( u(x, t) \equiv 0 \).

2.2 System specification
Input a new ODE system into MATCONT, namely

\[
    \begin{align*}
    u1' &= -2u1+u2+alpha*exp(u1) \\
    u2' &= u1-2u2+alpha*exp(u2)
    \end{align*}
\]

and choose to generate the partial derivatives of order 1 and 2 symbolically.
Figure 12: The curve of symmetric equilibria of (6) with limit point LP, neutral saddle H, and branching point BP.

2.3 Symmetric equilibrium branch

Select Type|Initial point|Equilibrium. Two windows will appear: Starter and continuer windows corresponding to the equilibrium continuation (curve type EQ_EQ).

In the Starter window, activate the parameter alpha. Since (6) has an equilibrium \( u_1 = u_2 = 0 \) for \( \alpha = 0 \), no further changes to the Starter parameters are required.

Open a 2Dplot window and select the parameter alpha and the coordinate \( u_1 \) as abscissa and ordinate, respectively, with the visibility limits

\[
\text{X-axis: } 0 \quad 0.5 \\
\text{Y-axis: } 0 \quad 8.0
\]

To monitor stability of the equilibrium, open a numeric window and select EIGENVALUES to be visible in it via Window|Layout.

Click Compute|Forward. The first bifurcation point, namely a limit point LP, will be located at \( \alpha = 0.367879 \). In MATLAB Command Window, you can read the following message:

\[
\text{label = LP, x = ( 1.000001 1.000001 0.367879 )} \\
a=3.535537e-01
\]
that gives the critical equilibrium coordinates and the critical parameter value, as well as the quadratic normal form coefficient $a = 0.35355 \ldots$ at LP. Thus, the limit point is nondegenerate and the equilibrium manifold near LP looks like a parabola.

Further computation detects a neutral saddle $H$ at $\alpha = 0.270671 \ldots$, where the equilibrium has eigenvalues $\lambda_{1,2} = \pm 1$, so that their sum is zero. This is not a bifurcation point for the equilibrium, since it is a hyperbolic saddle.

Resume computations to get the second bifurcation point at $\alpha = 0.14936122 \ldots$, namely, a branching point BP. Extend the equilibrium curve further until you leave the window. You should get Figure 12.

Notice that along the whole computed branch we have $u_1 = u_2$, i.e. it is composed of symmetric equilibria. Check by looking at the eigenvalues in the numeric window that only the lower part of the branch is stable, while it is a saddle between LP and BP, and a repellor above it.

Rename the computed curve via Select | Curves followed by curve|rename... to symmetric.

### 2.4 Symmetry breaking

Let us compute the second branch passing through the branching point BP. For this, open with Select|Initial point the Select point window and select the BP: Branch point of the equilibrium curve symmetric. The $(u_1, u_2, \alpha)$-values corresponding to BP will be loaded.

Select Type|Curve type|Equilibrium. In the appearing Starter window, select no for all singularities to monitor as in Figure 13.

![Starter window to switch branches at BP.](image)

Change nothing in the continuer window but Compute|Forward and Compute|Backward. You will get Figure 14. Thus, the branching point BP corresponds, actually, to a pitchfork bifurcation: Two more branches of equilibria bifurcate vertically from this point. Moreover, each branch is composed of equilibria which are not symmetric, $u_1 \neq u_2$. However, one branch is mapped into another by the involution. This phenomenon is called the symmetry breaking: We got nonsymmetric equilibrium solutions in a symmetric system.

**Warning:** We have shown numerically that a discretization of the Bratu-Gelfand problem (2) has multiple stationary solutions and limit and branching points. It does not imply immediately that the original PDE problem has the same properties. To verify this, one has to repeat the continuation with smaller $h$ (i.e., bigger $N$) and eventually make some error estimates. It should be noted that the appearance of the pitchfork is due to the equidistant mesh with a small number
Figure 14: Two equilibrium branches passing through point BP.
of points. If more accurate discretizations of (2) are used, the pitchfork and associated branches disappear. The limit point remains and corresponds to a limit point on the branch of the stationary solutions of (2).

2.5 Stop at zero of a user function

Sometimes we want to stop computation at a prescribed parameter value. This can be done in MATCONT by specifying a user function. For example, let us compare two nonsymmetric equilibria at $\alpha = 0.1$.

![User function input](image.png)

Click `Select|User functions` and define a user function `stop` with the associated label $S$ by typing `res=alpha-0.1` in the edit field (see Figure 15). Then press OK button. The Starter window will change and show a user function control.

Recomputing the nonsymmetric branches with `Compute|Forward` and `Compute|Backward` will stop at two points labeled $S$, where the user-defined function `stop` vanishes. You can see the corresponding equilibrium coordinates and eigenvalues in the numeric window.

3 Additional continuation problems

- Study equilibria of the following complex ODE:

$$\dot{z} = \alpha + z^2, \quad z \in \mathbb{C},$$

where the parameter $\alpha$ and the time are real. *Hint:* Write $z = x + iy$, where $(x, y)$ are real. Then (7) takes the form

$$\begin{cases} \dot{x} &= \alpha + x^2 - y^2, \\ \dot{y} &= 2xy. \end{cases}$$

At $\alpha = -1$ this system has equilibrium $(x_0, y_0) = (1, 0)$, which can be continued.

Plot also the phase portraits in the $(x, y)$-plane of (8) for $\alpha = -0.25$, $\alpha = 0$, and $\alpha = 0.25$. 

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Consider the following chemical model
\[
\begin{align*}
\dot{x} &= 2q_1 z^2 - 2q_5 x^2 - q_3 xy, \\
\dot{y} &= q_2 z - q_6 y - q_3 xy, \\
\dot{s} &= q_4 z - K q_4 s, \\
\end{align*}
\]
where \( z = 1 - x - y - s \) and
\[
q_1 = 2.5, \quad q_2 = 1.55, \quad q_3 = 10, \quad q_4 = 0.0675, \quad q_5 = 1.0, \quad q_6 = 0.1, \quad K = 2.0.
\]

Given an equilibrium \((x, y, s) = (0.0032, 0.8838, 0.0376)\), find two more positive equilibria of the system.

Hint: Compute a curve in the \((x, y, s)\)-space defined by the first two equations:
\[
\begin{align*}
2q_1 z^2 - 2q_5 x^2 - q_3 xy &= 0, \\
q_2 z - q_6 y - q_3 xy &= 0,
\end{align*}
\]
and detect zeros of the user-defined function \( F = q_4 z - K q_4 s \) along this curve.

• Analyze effect of increasing the number of equidistant mesh points to \( N = 3 \) and \( N = 4 \) on the \( \lambda \)-values corresponding to the limit and branching points in the finite-difference approximation (3)-(4) of the Bratu-Gelfand problem (2).

Hint: Do not forget that \( \lambda = (N + 1)^2 \alpha \).

4 Examination Problem II

Find a real eigenvalue and the corresponding eigenvector of the matrix
\[
B = \begin{pmatrix}
-5 & 2 & -3 \\
-5 & 0 & -4 \\
8 & -2 & 6
\end{pmatrix}
\]
by continuation of the eigenvector \( v_1 = (0, 0, 1)^T \) of the matrix
\[
A = \begin{pmatrix}
1 & 0 & 0 \\
0 & -1 & 0 \\
0 & 0 & -2
\end{pmatrix},
\]
corresponding to its eigenvalues \( \lambda_1 = -2 \).

1. Consider a one-parameter family of matrices
\[
C(\alpha) = \alpha B + (1 - \alpha)A, \quad C(0) = A, \quad C(1) = B,
\]
and the following continuation problem in the \((v, \lambda, \alpha)\)-space:
\[
\begin{align*}
C(\alpha)v - \lambda v &= 0, \\
v^T v - 1 &= 0.
\end{align*}
\]
Explain, how it can be used to solve the formulated problem.

2. Setup an auxiliary 4D-system
\[
\begin{align*}
\dot{v} &= C(\alpha)v - \lambda v, \\
\dot{\lambda} &= v^T v - 1,
\end{align*}
\]
and continue its equilibrium manifold in the \((v, \lambda, \alpha)\)-space. Use \((v_1, \lambda_1, 0)\) as the initial point. Stop when \( \alpha = 1 \) using a user-defined function.

3. Continue other two eigenvectors of \( A \) and produce a plot tracing all three real eigenvalues in the \((\alpha, \lambda)\)-plane.