

R406: Applied Economic Modelling with Python

Lecture 14: First-order Difference Equations

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Introduction

Discrete Time

- Differential equations describe economic dynamics in continuous time
- Derivatives measuring instantaneous rates of change, accelerations, decelerations, etc., are used in them
- Here we consider the case of discrete time: t takes only integer values:

$$t = \dots, -3, -2, -1, 0, 1, 2, 3, \dots$$

- Changes of variables are no longer instantaneous, so derivatives are not adequate in the description of dynamics
- The notion of differences is much more appropriate, therefore the term *difference equations*

A Word on Notation

- The integer values that the time variable takes serve to index economic variables
- Each different value indexes a separate period for which information on the respective economic variable is recorded
- We make a slight change of notation from differential equations so that we take into account the above
- Instead of writing:

$$\dot{y}(t)$$

to describe the (instantaneous) change of x , here we write:

$$\Delta y_t \quad (= y_t - y_{t-1})$$

to describe the change of x between two consecutive periods (or, the per-unit-of-time change)

A Word on Notation (2)

- Analogies to higher-order derivatives are easily made
- For example, the second derivative of x (in the continuous case), $\ddot{x}(t)$, is matched by:

$$\Delta^2 y_t = \Delta y_t - \Delta y_{t-1}$$

- The latter is also interpreted as acceleration
- The same line of reasoning is then further extended to third differences, fourth differences, etc.

What Are Difference Equations?

- By analogy to differential equations (where derivatives are included), difference equations are equations in which differences of variables are included
- The order of differences defines the order of equations
- Examples:

$$\Delta y_t = 8,$$

$$\Delta y_t = 0.4y_t + 2t + 3$$

are first-order difference equations, while

$$\Delta^2 y_t = 0.5y_t - 11y_{t-1}$$

is a second-order difference equation

What Are Difference Equations? (2)

- Take, for example, the equation:

$$\Delta y_{t+1} = 0.6y_t - 21$$

and recall the definition of differences (through deltas)

- If we leave on the left-hand side the variable with the largest index, and move all the rest to the right-hand side, we have:

$$y_{t+1} = 1.6y_t - 21$$

- This shows that the value at time $(t + 1)$ can be thought of as a function of the value at time t (and possibly some other stuff, such as time independently, or another variable)

What Are Difference Equations? (3)

- This leads to the idea that in general the difference equation can be stated as a function relating the variable to its own past values
- Formally written,

$$y_{t+1} = f(y_t, y_{t-1}, \dots)$$

- We call this a *recursive relationship*
- Every next value is obtained from this relationship; for example, in the relationship $y_{t+1} = f(y_t)$:

$$y_{t+2} = f(y_{t+1}) = f(f(y_t)) = f^2(y_t)$$

- From this follows:

$$y_{t+k} = f^k(y_t)$$

Note: k is not interpreted as a power!

Linear vs. Non-linear Equations

- Recursive relationships can be either **linear** or **non-linear**
- Therefore linear and non-linear difference equations
- (Note again that time and/or other variables could also appear as function arguments)
- We will stick most of the time to linear equations
- Linearity will be directly assumed, while non-linearity will be explicitly indicated when necessary

Constant-coefficients vs. Variable-coefficients Equations

- Take the equation:

$$y_{t+3} = ay_{t+2} + by_{t+1} + cy_t + d$$

where a, b, c, d are constants

This is a **constant-coefficients difference equation**

- Compare this to:

$$y_{t+3} = a_{t+2}y_{t+2} + b_{t+1}y_{t+1} + c_t y_t + d_t$$

This is a **variable-coefficients difference equation**

Autonomous vs. Non-autonomous Difference Equations

- **Autonomous** (or time-invariant) equations: time does not enter independently as an argument of $f(\cdot)$; example:

$$y_t = 0.4y_{t-1} + 2$$

- **Non-autonomous** (or time-variant) equations: time enters independently as an argument:

$$y_t = 0.4y_{t-1} + 3t + 2$$

- The latter are much more difficult to study, and we will only occasionally mention them

Homogeneous vs. Non-homogeneous Equations

- Take the following equation where all instances of the y variable are on the left-hand side, and 'all the rest' is summarized on the right-hand side in $g(t)$:

$$y_{t+2} + ay_{t+1} + by_t = g(t)$$

- (A second-order equation in this case, but order here does not matter)
- If $g(t) = 0$, the equation is **homogeneous**¹
- If $g(t) \neq 0$, the equation is **non-homogeneous**

¹For such equations, if y_t is a solution, so is αy_t .

The Initial-value Problem

The Initial-value Problem

- Take the equation:

$$y_t = f(y_{t-1}, y_{t-2}, \dots, y_{t-p})$$

- In order to be able to solve for y_t , p starting values will be needed
- Otherwise it would be impossible to find the solution
- In the case of the first-order equation, one such value is needed

Equilibrium and Stability Conditions

Equilibrium

- We begin with the autonomous first-order-equation case so that the idea is grasped more easily
- We will consider stability conditions again when we get to higher-order equations
- Start from the definition of a function's fixed point:

Definition 1

Let $K \subset \mathbb{R}^n$ and let f be a function that maps $x \in K$ into another point $f(x) \in K$ (i.e. the function maps K into itself). If the point x^* is such that $f(x^*) = x^*$, then x^* is called a **fixed (or equilibrium) point**.

Equilibrium (2)

- In the current context K consists of all y_t 's
- For example, in the difference equation $y_{t+1} = f(y_t)$, f maps y_t into y_{t+1}
- The definition then implies that y^* is an equilibrium point if and only if (iff):

$$y^* = f(y^*)$$

- Graphically, this means that equilibrium points always lie on the 45° line
- **Example:** Find the equilibrium points of $f(x) = x^3$; make a graphical sketch of your solution

Stability of Equilibrium

Let y^* be an equilibrium point of f . Some definitions follow.

Definition 2

The point y^* is **stable** if for any $\varepsilon > 0 \exists \delta > 0$:

$$|y_0 - y^*| < \varepsilon \Rightarrow |f^n(y_0) - f(y^*)| < \delta, \forall n > 0.$$

Otherwise, y^* is **unstable**.

Definition 3

The point y^* is **repelling** if $\exists \varepsilon > 0$:

$$0 < |y_0 - y^*| < \varepsilon \Rightarrow |f(y_0) - f(y^*)| > |y_0 - y^*|.$$

Stability of Equilibrium (2)

Definition 4

The point y^* is **attracting (asymptotically stable)** if:

- 1 It is stable
- 2 $\exists \eta > 0$:

$$|y_0 - y^*| < \eta \Rightarrow \lim_{t \rightarrow \infty} y_t = y^*.$$

If $\eta = \infty$, then y^* is **globally asymptotically stable**.

Stability of Equilibrium (3)

Theorem 1

Let y^* be a fixed point of $y_{t+1} = f(y_t)$, and let f be continuously differentiable at y^* . Then:

- ① If $|f'(y^*)| < 1$, then y^* is an attractor
- ② If $|f'(y^*)| > 1$, then y^* is a repeller
- ③ If $|f'(y^*)| = 1$ and:
 - ① if $f''(y^*) \neq 0$, then y^* is unstable
 - ② if $f''(y^*) = 0$ and if $f'''(y^*) > 0$, then y^* is unstable
 - ③ if $f''(y^*) = 0$ and if $f'''(y^*) < 0$, then y^* is an attractor
- ④ If $f'(y^*) = -1$ and:
 - ① if $-2f'''(y^*) - 3[f''(y^*)]^2 < 0$, then y^* is an attractor
 - ② if $-2f'''(y^*) - 3[f''(y^*)]^2 > 0$, then y^* is unstable

Note: Theorems are provided just for usage and reference, no proofs are given or required!

Stability of Equilibrium (4)

- There exist fixed points which are neither attractors not repellers
- Take for example:

$$y_{t+1} = -y_t + k$$

- If y_0 is the initial value, then

$$y_0 = y_2 = y_4 = \dots$$

$$y_1 = y_3 = y_5 = \dots$$

- Although there is a fixed point $y^* = \frac{k}{2}$, if $y_0 \neq y^*$, the system cycles between y_0 and $-y_0 + k$ without getting nearer or farther from the fixed point over time

Stability of Equilibrium (5)

- A solution y_n is periodic if

$$y_{n+m} = y_n$$

for some fixed integer m and all n . The smallest integer m is called the **the period of the solution**.

Definition 5

If the sequence $\{y_t\}$ has q repeating values, then y_1, y_2, \dots, y_q are called **period points**, and the set $\{y_1, y_2, \dots, y_q\}$ is called a **periodic orbit**.

- For example, if the equation is $y_{t+1} = f(y_t)$, a k -periodic point is the y -coordinate of the intersection point of $f^k(y)$ and the 45° -line $y_{t+1} = y_t$

Stability of Equilibrium (6)

Theorem 2

Let b be a k -period point of f . Then b is:

- ① *Stable if it is a stable fixed point of f^k*
- ② *Asymptotically stable if it is an attracting point of f^k*
- ③ *Repelling if it is a repelling fixed point of f^k*

First-order Difference Equations

First-order Difference Equations: Problem Setup

- A first-order difference equation is one in which the recursive relationship extends only to one period in the past, i.e.:

$$y_{t+1} = f(y_t)$$

- Initial-value problem:

$$\left| \begin{array}{l} y_{t+1} = f(y_t) \\ y(0) = y_0 \end{array} \right.$$

where y_0 is given initially

- It is easy to see that $y_1 = f(y_0)$, $y_2 = f(y_1)$, $y_3 = f(y_2)$, etc.
- In other words, it implies the following sequence of values:

$$y_0, f(y_0), f(f(y_0)), f(f(f(y_0))), \dots$$

- As already noted, sometimes this is denoted more conveniently as follows:

$$y_0, f(y_0), f^2(y_0), f^3(y_0), \dots$$

Solution

- Start with the non-homogeneous, constant-coefficients case:

$$\left| \begin{array}{l} y_{t+1} = ay_t + b \\ y(0) = y_0 \end{array} \right.$$

- Beginning with y_0 , the next values are obtained through iteration:

$$y_0$$

$$y_1 = ay_0 + b$$

$$y_2 = ay_1 + b = a^2y_0 + ab + b$$

$$\dots$$

$$y_t = a^t y_0 + b(a^{t-1} + a^{t-2} + \dots + a + 1)$$

Solution (2)

- We have the sum of a geometric series in the parentheses
- Using the standard formula, this sum equals:

$$\begin{cases} \frac{1 - a^t}{1 - a}, & a \neq 1 \\ t, & a = 1 \end{cases}$$

- Let $a \neq 1$. Then the solution to the equation is:

$$y_t = a^t \left(y_0 - \frac{b}{1 - a} \right) + \frac{b}{1 - a}$$

- In the other case ($a = 1$), the solution is:

$$y_t = y_0 + tb$$

Solution (3)

- To find the equilibrium (fixed) point of this equation, we seek for a solution y^* such that $y_t = y^*, \forall t$ (i.e. if we start at this point, we stay there at all times)
- This means that it should satisfy in particular the following: $y_{t+1} = y_t = y^*$
- Plug this into the equation:

$$y^* = ay^* + b$$

- It follows that the fixed point is:

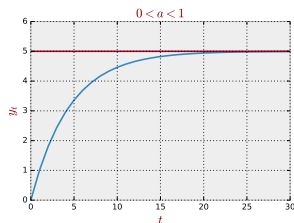
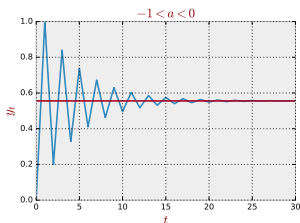
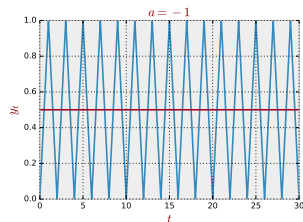
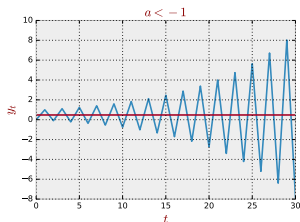
$$y^* = \frac{b}{1-a}, a \neq 1$$

- It is directly obvious that in the homogeneous case $y^* = 0$

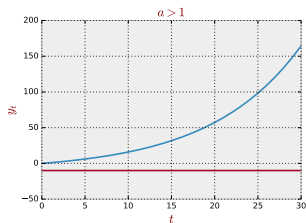
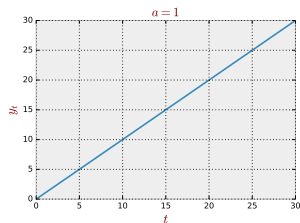
Fixed-point Stability

- Using Theorem 1 and Theorem 2, we can obtain the stability conditions very easily
- The first derivative of f with respect to y_t equals a ; the higher-order derivatives are all zero
- Therefore:
 - ① If $|a| < 1$, the equilibrium is stable
 - ② If $|a| > 1$, the equilibrium is unstable
 - ③ If $a = 1$, the fixed point is undefined
 - ④ If $a = -1$, the fixed point equals $\frac{b}{2}$ but it is neither stable nor unstable; the solution is periodic and the system cycles between y_0 and $-y_0 + b$

Fixed-point Stability (2)



Fixed-point Stability (3)



Time-varying b

- Let b_t be an arbitrary but known function of t (i.e. the values of b_t are given beforehand)
- The equation becomes:

$$y_{t+1} = ay_t + b_t, \quad t = 0, 1, 2, \dots$$

- Starting from a given y_0 , recursive substitutions leads eventually to:

$$y_t = a^t y_0 + \sum_{k=0}^{t-1} a^{t-k-1} b_k, \quad t = 0, 1, 2, \dots$$

- Fixed points and stability conditions are much harder to specify
- However, equations of this kind are successfully used to describe special types of time series data (we'll get to this next semester)
- Stability conditions are derived after plausible assumptions on b_t are made

Time-varying a

- If, in addition to b , the coefficient a also changes over time, then the equation becomes:

$$y_{t+1} = a_t y_t + b_t, \quad t = 0, 1, 2, \dots$$

- The same line of reasoning as before can be applied finally leading to:

$$y_t = \left(\prod_{k=0}^{t-1} a_k \right) y_0 + \sum_{i=0}^{t-1} \left(\prod_{k=i+1}^{t-1} a_k \right) b_i$$

where all terms $\prod_{k=t}^{t-1} a_k$ are set to equal 1.

Example 1: Mortgage Repayment

- An amount equal to K is borrowed at time 0 to finance a mortgage at the fixed monthly interest rate r
- The mortgage is repaid monthly at amounts equal to a , and the number of monthly payments until full repayment equals T
- In each period the outstanding principal b_t satisfies the following relationship:

$$b_{t+1} = (1 + r)b_t - a$$

- Additionally, it is obvious from the problem that $b_0 = K$ and $b_T = 0$

Example 1: Mortgage Repayment (2)

- Assuming that $r > 0$, the fixed point is:

$$b^* = -\frac{a}{1 - (1 + r)} = \frac{a}{r}$$

- Therefore, the solution is:

$$b_t = (1 + r)^t \left(b_0 - \frac{a}{r} \right) + \frac{a}{r}$$

or:

$$b_t = (1 + r)^t \left(K - \frac{a}{r} \right) + \frac{a}{r}$$

Example 1: Mortgage Repayment (3)

- For $t = T$, the solution is:

$$0 = (1 + r)^T \left(K - \frac{a}{r} \right) + \frac{a}{r}$$

- If we solve the latter for K , we get:

$$K = \frac{a}{r} \left(1 - \frac{1}{(1 + r)^T} \right) = a \sum_{t=1}^T \frac{1}{(1 + r)^t}$$

i.e. the borrowed amount equals the sum of PDVs of all monthly payments until full repayment

Example 1: Mortgage Repayment (4)

- We could also solve for a :

$$a = \frac{rK}{1 - (1 + r)^{-T}} = \frac{rK(1 + r)^T}{(1 + r)^T - 1}$$

or, in other words, this result allows to calculate the monthly mortgage payment given the borrowed amount and the interest rate

Example 2: Compound Interest and PDVs with Constant Interest Rates

- Let w_t denote a person's wealth (assets) at time t
- If y_t and c_t are respectively this person's income and consumption
- Given a constant interest rate r , we have:

$$w_{t+1} = (1 + r)w_t + y_{t+1} - c_{t+1}$$

- If initial wealth is w_0 , then the solution is:

$$w_t = (1 + r)^t w_0 + \sum_{k=0}^{t-1} (1 + r)^{t-k-1} (y_{k+1} - c_{k+1})$$

Example 2: Compound Interest and PDVs with Constant Interest Rates (2)

- Divide both sides by $(1 + r)^t$ to get:

$$(1 + r)^{-t} w_t = w_0 + \sum_{k=0}^{t-1} (1 + r)^{-k-1} (y_{k+1} - c_{k+1})$$

- The left-hand side is the PDV of w_t at time 0
- It equals the initial wealth plus the PDV of the flow of savings from time 1 to time t

Example 3: The Harrod-Domar Growth Model

- We consider the discrete-time version
- Saving is a fixed share of output/income:

$$S_t = sY_t, \quad 0 < s < 1$$

- Investment depends on output growth:

$$I_t = v(Y_t - Y_{t-1}), \quad v > 0$$

- Saving equals investment:

$$S_t = I_t$$

Example 3: The Harrod-Domar Growth Model (2)

- Substituting the first two equations into the third yields:

$$sY_t = v(Y_t - Y_{t-1}) \Rightarrow Y_t = \frac{v}{v-s} Y_{t-1}$$

- Solving the equation leads to:

$$Y_t = \left(\frac{v}{v-s} \right)^t Y_0,$$

and the only fixed point is 0

- There are several possibilities for the relationship between s and v , leading to different conclusions on the stability of the system

Example 4: Hog Cycles and Cobwebs

- Based on the fact that for various commodities output and prices exhibit cyclical behaviour
- Cycles stem from the consecutive adjustments which are manifested as movements between the supply and demand curve
- Also, from the technological perspective, there is a span of time required in order to produce a certain output (e.g. in agriculture)
- Generally speaking, the “cobweb phenomenon” stem from the presence of lagged effects on some economic variables
- Also, there is a mismatch between the time of the production decision and the time of purchase decisions by customers (demand)

Example 4: Hog Cycles and Cobwebs (2)

- Initially, the system (the market) is in equilibrium
- Each cycle begins with a demand or with a supply shock
- In this version of the model, only one-period lags matter
- Supply, demand, and equilibrium are described via the following three equations:

$$q_t^D = \alpha - \beta p_t$$

$$q_t^S = \gamma + \delta p_{t-1}$$

$$q_t^D \equiv q_t^S$$

where $\alpha > 0$, $\beta > 0$, and $\delta > 0$.

Example 4: Hog Cycles and Cobwebs (3)

- Substituting supply and demand in the equilibrium condition leads to the following difference equation:

$$p_t = \frac{\alpha - \gamma}{\beta} - \frac{\delta}{\beta} p_{t-1},$$

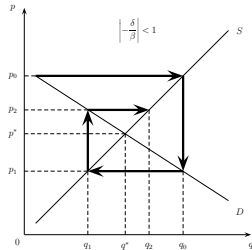
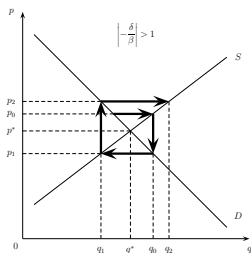
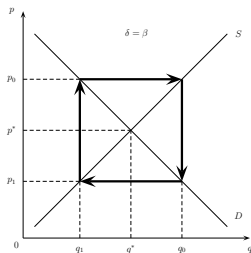
- Its solution is:

$$p_t - p^* = \left(-\frac{\delta}{\beta}\right)^t (p_0 - p^*)$$

where p^* is the equilibrium price

- There are three possible system behaviours depending on the values of δ and β

Example 4: Hog Cycles and Cobwebs (4)



References

- Sydsæter et al. (2008), ch. 11
- Chiang and Wainwright (2005), ch. 17
- Shone (2002), ch. 3