

# Perturbation Methods

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Juan F. Rubio-Ramírez

Emory University

We want to solve functional equations of the form

$$F(d(x)) = 0.$$

where the unknown is  $d(x)$ . Perturbation solves the problem by using Taylor's theorem and specifying an  $n$ th-order approximation

$$d_n(x, \Phi) = \sum_{i=0}^n \Phi_i (x - x_0)^i.$$

We need to find the coefficients  $\{\Phi_i\}_i$ . How?

- Many complicated mathematical problems have either
  1. a particular case, or
  2. a related problem,that is easy to solve.
- Often, we can use the solution of the simpler problem as a building block of the general solution.
- This approach has been very successful in physics.

- Judd and Guu (1993) showed how to apply perturbation methods to economic problems.
- Recently, these methods have gained popularity; second-order approximations are easy to compute and markedly improve accuracy.
- Perturbation theory generalizes the well-known linearization strategy.
- Sometimes referred to as *asymptotic methods*.

## A Baby Example: A Basic RBC

$$\max_{\{c_t, k_{t+1}\}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \log c_t$$

$$c_t + k_{t+1} = e^{z_t} k_t^{\alpha},$$

$$z_{t+1} = \rho z_t + \sigma \varepsilon_{t+1}, \quad \varepsilon_t \sim \mathcal{N}(0, 1).$$

$$\frac{1}{c_t} = \beta \mathbb{E}_t \left[ \frac{1}{c_{t+1}} \alpha e^{z_{t+1}} k_{t+1}^{\alpha-1} \right]$$

$$c_t + k_{t+1} = e^{z_t} k_t^\alpha,$$

$$z_{t+1} = \rho z_t + \sigma \varepsilon_{t+1}, \quad \varepsilon_t \sim \mathcal{N}(0, 1).$$

- Transform the problem by introducing a small perturbation parameter.
- Solve the transformed problem for a particular choice (typically setting the parameter to zero).
- Use that solution to approximate the solution of the original problem.

# A Perturbation Approach

- Choose the standard deviation  $\sigma$  as the perturbation parameter.
- Set  $\sigma = 0 \Rightarrow$  deterministic model:  $z_t = 0$  and  $e^{z_t} = 1$ .
- The deterministic steady state is straightforward to compute.



# A Re-parametrized Policy Function

We search for policy functions

$$c_t = c(k_t, z_t; \sigma).$$

$$k_{t+1} = k(k_t, z_t; \sigma).$$

$$z_{t+1} = \rho z_t + \sigma \varepsilon_{t+1}.$$

- Note the appearance of the parameter  $\sigma$ .
- We build a local approximation around  $\sigma = 0$ .

## Taylor's Theorem (assume $\delta = 1$ )

Equilibrium conditions:

$$0 = \mathbb{E}_t \left[ \frac{1}{c(k_t, z_t; \sigma)} - \beta \frac{\alpha e^{\rho z_t + \sigma \varepsilon_{t+1}} k(k_t, z_t; \sigma)^{\alpha-1}}{c(k(k_t, z_t; \sigma), \rho z_t + \sigma \varepsilon_{t+1}; \sigma)} \right],$$

$$0 = c(k_t, z_t; \sigma) + k(k_t, z_t; \sigma) - e^{z_t} k_t^\alpha$$

$$0 = z_{t+1} - \rho z_t - \sigma \varepsilon_{t+1}.$$

We will take derivatives w.r.t.  $k_t$ ,  $z_t$ , and  $\sigma$  and apply Taylor's theorem around the deterministic steady state. (How to proceed in logs?)

## Important Question

Is  $c(k, 0; 0)$  different from  $c(k, 0; \sigma)$ ?

Let  $k$  be the steady state capital in the deterministic model. Then

$$\begin{aligned} c_t = & c(k, 0; 0) + c_k(k, 0; 0)(k_t - k) + c_z(k, 0; 0)z_t + c_\sigma(k, 0; 0)\sigma \\ & + \frac{1}{2}c_{kk}(k_t - k)^2 + \frac{1}{2}c_{kz}(k_t - k)z_t + \frac{1}{2}c_{k\sigma}(k_t - k)\sigma \\ & + \frac{1}{2}c_{zk}z_t(k_t - k) + \frac{1}{2}c_{zz}z_t^2 + \frac{1}{2}c_{z\sigma}z_t\sigma \\ & + \frac{1}{2}c_{\sigma k}\sigma(k_t - k) + \frac{1}{2}c_{\sigma z}\sigma z_t + \frac{1}{2}c_{\sigma\sigma}\sigma^2 + \dots \end{aligned}$$

$$\begin{aligned} k_{t+1} = & k(k, 0; 0) + k_k(k, 0; 0)(k_t - k) + k_z(k, 0; 0)z_t + k_\sigma(k, 0; 0)\sigma \\ & + \frac{1}{2}k_{kk}(k_t - k)^2 + \frac{1}{2}k_{kz}(k_t - k)z_t + \frac{1}{2}k_{k\sigma}(k_t - k)\sigma \\ & + \frac{1}{2}k_{zk}z_t(k_t - k) + \frac{1}{2}k_{zz}z_t^2 + \frac{1}{2}k_{z\sigma}z_t\sigma \\ & + \frac{1}{2}k_{\sigma k}\sigma(k_t - k) + \frac{1}{2}k_{\sigma z}\sigma z_t + \frac{1}{2}k_{\sigma\sigma}\sigma^2 + \dots \end{aligned}$$

Define the vector of equilibrium conditions as

$$F(k_t, z_t; \sigma) = \mathbb{E}_t \begin{bmatrix} \frac{1}{c(k_t, z_t; \sigma)} - \beta \frac{\alpha e^{\rho z_t + \sigma \varepsilon_{t+1}} k(k_t, z_t; \sigma)^{\alpha-1}}{c(k_t, z_t; \sigma) + k(k_t, z_t; \sigma) - e^{z_t} k_t^\alpha} \\ z_{t+1} - \rho z_t - \sigma \varepsilon_{t+1} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}.$$

Equivalently, write  $F(k_t, z_t; \sigma) = \mathbb{E}_t H(c_t, c_{t+1}, k_t, k_{t+1}, z_t, z_{t+1})$ , and let subscripts  $H_i$  denote derivatives w.r.t. the  $i$ th argument (evaluated at steady state when used below).

# Zero-Order Approximation

Evaluate at  $(k_t, z_t, \sigma) = (k, 0, 0)$ :

$$F(k, 0; 0) = 0.$$

Steady state (for  $\delta = 1$ ):

$$\frac{1}{c} = \beta \alpha (k)^{\alpha-1} \quad \Leftrightarrow \quad 1 = \alpha \beta (k)^{\alpha-1}.$$

Thus

$$k = (\alpha \beta)^{\frac{1}{1-\alpha}}, \quad c = (\alpha \beta)^{\frac{\alpha}{1-\alpha}} - (\alpha \beta)^{\frac{1}{1-\alpha}}. \quad (\text{or using the resource constraint})$$

How good is this approximation?

# First-Order Approximation

Take derivatives of  $F(k_t, z_t; \sigma)$  and evaluate at  $(k, 0, 0)$ :

$$F_k(k, 0; 0) = 0, \quad F_z(k, 0; 0) = 0, \quad F_\sigma(k, 0; 0) = 0.$$



Recall

$$F(k_t, z_t; \sigma) = \mathbb{E}_t H(c(k_t, z_t; \sigma), c(k(k_t, z_t; \sigma), \rho z_t + \sigma \varepsilon_{t+1}), k_t, k(k_t, z_t; \sigma), z_t, \rho z_t + \sigma \varepsilon_{t+1}) = 0.$$

Since  $F$  is identically zero, its derivatives of any order are also zero. Therefore (at the steady state):

$$F_k = H_1 c_k + H_2(c_k k_k) + H_3 + H_4 k_k = 0,$$

$$F_z = H_1 c_z + H_2(c_k k_z + c_z \rho) + H_4 k_z + H_5 + H_6 \rho = 0,$$

$$F_\sigma = H_1 c_\sigma + H_2(c_k k_\sigma + c_z \mathbb{E} \varepsilon_{t+1} + c_\sigma) + H_4 k_\sigma + H_6 \mathbb{E} \varepsilon_{t+1} = 0.$$

## Solving the System II

Where

$$H_1 = \begin{bmatrix} -1 \\ \overline{c_{ss}^2} \\ 1 \\ 0 \end{bmatrix}, H_2 = \begin{bmatrix} 1 \\ \overline{c_{ss}^2} \\ 0 \\ 0 \end{bmatrix}, H_3 = \begin{bmatrix} 0 \\ -\alpha k_{ss}^{\alpha-1} \\ 0 \end{bmatrix}, H_4 = \begin{bmatrix} \frac{\alpha-1}{k_{ss} c_{ss}} \\ 1 \\ 0 \end{bmatrix}, H_5 = \begin{bmatrix} 0 \\ -k_{ss}^{\alpha} \\ -\rho \end{bmatrix}, H_6 = \begin{bmatrix} \frac{1}{c_{ss}} \\ 0 \\ 1 \end{bmatrix}$$

Unknowns at first order:  $c_k, c_z, k_k, k_z, c_\sigma, k_\sigma$ . We have a system to determine them.

How to solve it efficiently?

Note that the pair

$$F_k = 0, \quad F_z = 0$$

constitutes a quadratic system in the four unknowns  $(c_k, c_z, k_k, k_z)$  and does not depend on  $(c_\sigma, k_\sigma)$ . Procedures to solve such systems: Blanchard and Kahn (1980), Uhlig (1999), Sims (2000), Klein (2000) — all equivalent. Why quadratic? Stable vs. unstable manifolds.

# How to do it?

Rewrite as

$$\begin{bmatrix} H_4 & H_6 & H_2 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ c_k & c_z \end{bmatrix} \begin{bmatrix} k_k \\ 0 \end{bmatrix} = - \begin{bmatrix} H_3 & H_5 & H_1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ c_k \end{bmatrix},$$
$$\begin{bmatrix} H_4 & H_6 & H_2 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ c_k & c_z \end{bmatrix} \begin{bmatrix} k_z \\ \rho \end{bmatrix} = - \begin{bmatrix} H_3 & H_5 & H_1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ c_z \end{bmatrix}.$$

## How to do it?

Or compactly

$$\underbrace{\begin{bmatrix} H_4 & H_6 & H_2 \end{bmatrix}}_A \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ c_k & c_z \end{bmatrix}}_M \underbrace{\begin{bmatrix} k_k & k_z \\ 0 & \rho \end{bmatrix}}_{h_x} = - \underbrace{\begin{bmatrix} H_3 & H_5 & H_1 \end{bmatrix}}_B M.$$

Let  $h_x = \begin{bmatrix} k_k & k_z \\ 0 & \rho \end{bmatrix}$  and unknown vector  $\begin{bmatrix} c_k & c_z \end{bmatrix}^\top$ .

## How to do it?

Let  $\Lambda$  and  $P$  be the eigenvalue and eigenvector matrices of  $h_x$ :

$$h_x P = P \Lambda.$$

Then

$$A M P \Lambda = -B M P.$$

# How to do it?

Define

$$Z := MP = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ c_k & c_z \end{bmatrix} P, \quad A := \begin{bmatrix} H_4 & H_6 & H_2 \end{bmatrix}, \quad B := - \begin{bmatrix} H_3 & H_5 & H_1 \end{bmatrix}.$$

Then the generalized eigenvalue problem reads

$$AZ \Lambda = BZ.$$

# Generalized Eigenvalue Problem

For given  $A$  and  $B$ , there exists a matrix  $V = [V_1 \ V_2]$  and a block-diagonal  $D = \text{diag}(D_{11}, D_{22})$  such that

$$A \begin{bmatrix} V_1 & V_2 \end{bmatrix} \begin{bmatrix} D_{11} & 0 \\ 0 & D_{22} \end{bmatrix} = B \begin{bmatrix} V_1 & V_2 \end{bmatrix}.$$

$D_{11}$  collects roots with  $|\lambda| < 1$ .



Assume the number of eigenvalues with  $|\lambda| < 1$  equals the number of states. Then set  $\Lambda = D_{11}$  and  $Z = V_1$ :

$$MP = V_1 = \begin{bmatrix} V_{11} \\ V_{21} \end{bmatrix} \Rightarrow P = V_{11}, \quad \begin{bmatrix} c_k & c_z \end{bmatrix} = V_{21}P^{-1}.$$

Finally,

$$h_x = PD_{11}P^{-1}.$$

Importantly, we know that some of the entries of  $h_x$  are related to the exogenous process.

## Solving the System III

With  $c_k, c_z, k_k, k_z$  in hand, determine  $(c_\sigma, k_\sigma)$  from the linear homogeneous system

$$F_\sigma = H_1 c_\sigma + H_2(c_k k_\sigma + c_\sigma) + H_4 k_\sigma = 0 \implies \begin{bmatrix} H_1 + H_2 & H_2 c_k + H_4 \end{bmatrix} \begin{bmatrix} c_\sigma \\ k_\sigma \end{bmatrix} = 0.$$

Hence

$$c_\sigma = k_\sigma = 0.$$

- Since  $c_\sigma = k_\sigma = 0$ , the first-order solution exhibits **certainty equivalence** — no precautionary behavior.
- Distinguish *risk aversion* (second derivative of utility) from the *precautionary motive* (third derivative of utility): Leland (1968), Kimball (1990).
- Ignoring numerical error, the *policy* functions have no approximation error at first order; the *value function* still does.

- After Kydland and Prescott (1982), LQ methods/linearization became popular to solve macro models.
- Properly implemented, linearization, LQ, and first-order perturbation are equivalent.
- Advantages of perturbation: access to higher-order terms with clear theorems.

## Second-Order Approximation

Take second derivatives at  $(k, 0, 0)$ :

$$F_{kk} = 0, \quad F_{kz} = 0, \quad F_{k\sigma} = 0, \quad F_{zz} = 0, \quad F_{z\sigma} = 0, \quad F_{\sigma\sigma} = 0.$$

(Remember Young's theorem.)

# Solving the Second-Order System

- Substitute known first-order coefficients.
- Obtain a linear system of 12 equations in 12 unknowns.
- Cross terms in  $k\sigma$  and  $z\sigma$  are zero.
- Conjecture: all terms with odd powers of  $\sigma$  vanish.

- A term in  $\sigma^2$  appears at second order.
- Captures the precautionary motive.
- Certainty equivalence no longer holds.
- Key advantage of going to second order.

- The recursion can be continued to arbitrarily high order.
- Major advantage: the procedure is *recursive*.
- Often, a few iterations suffice.
- Accuracy depends on the objective (see Fernández-Villaverde, Rubio-Ramírez, and Santos, 2006).