Advanced Macroeconomics II

Handout 6 - The Endogenous Grid Method

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Short recap

Prototypical DP problem:

$$V(z,k) = \max_{\{c,k'\}} u(c) + \beta E\left[V\left(z',k'\right)|z\right]$$
$$\text{s.t.} c + k' = f(z,k)$$
$$z' = h(z,\eta)\,;\eta \text{ stochastic}$$

- We are looking for functions $\mathbf{V}, \mathbf{g^c}, \mathbf{g^k}$: We cannot solve this.

We need to solve an approximate problem:

- Approximate continuous function: **Interpolation**
  - Requires "exact" solution of maximization problem: **Optimization**
  - Requires computing expectations: **Integration**

Why is VFI so costly?

$$V(z,k) = \max_{\{c,k'\}} u(c) + \beta E\left[V\left(z',k'\right)|z\right]$$

- Combination of maximization and expectations is lethal
- Optimizing requires *a lot* of function evaluations
  - Each function evaluation requires expectations, interpolations and often derivatives

Key idea:

- Can we bypass the maximization step?
- Focus on the Euler equation

Carroll (2006)

Maximization requires satisfying FOC:

$$u'(c) = \beta E\left[V_k\left(z', k'\right)|z\right] \qquad c + k' = f(z,k)$$

Usual approach:

- Fix (z, k) and solve for $\left(k', c\right)$
- Consumption is immediately given k': $c = f(z,k) - k'$
- Problem is to try a bunch of k' to solve

$$u'\left(f(z,k) - k'\right) = \beta E\left[V_k\left(z', k'\right)|z\right]$$

Carroll (2006)

Maximization requires satisfying FOC:

$$u^{'}(c) = \beta E\left[V_k\left(z^{'}, k^{'}\right)|z\right] \qquad c + k^{'} = f(z,k)$$

Carroll's approach:

- Fix $\left(k^{'}, z\right)$ and solve for k! Hence the endogenous grid name
- Problem is to solve:

$$f(z,k) = \underbrace{(u')^{-1}\left(\beta E\left[V_k\left(z^{'}, k^{'}\right)|z\right]\right) + k^{'}}_{\text{Known given } \left(k',z\right)}$$

- This is a nonlinear equation, but a simple one to solve

Key: Expectation and derivatives only taken once! No interpolations!

Standard algorithm

Algorithm 1: EGM: Standard Method

Function `EGM(`V,$\vec{k}$,$\vec{z}$,*parameters*`)`:

- **for** *i=1:*n_z **do**
  - **for** *j=1:*n_k **do**
    - $\mathrm{F(x)} = f(\vec{z}_i, x) - \vec{k}_j - (u')^{-1}\left(\beta E\left[V_k\left(z', \vec{k}_j\right)|\vec{z}_i\right]\right)$
    - # Find [k_min,k_max], check corners, further bracket zero
    - k_endo[j] = Roots(F,k_min,k_max)
    - V_endo[j] $= u(f(\vec{z}_i, k\_endo[j]) - \vec{k}_j) + \beta E\left[V\left(z', \vec{k}_j\right)|\vec{z}_i\right]$
  - # Interpolate value function to exogenous grid
  - V_new(i,:) = Interpolation(k_endo,V_endo,$\vec{k}$)
- return V_new

Change of variable - Know your states

- A change of variable makes things easier
- Define Y as total income, or cash on hand: $Y = f(z, k)$
- We can change the state in our problem

$$V(z, Y) = \max_{\{k'\}} u\left(Y - k^{'}\right) + \beta E\left[V\left(z^{'}, Y^{'}\right) | z\right]$$

$$\text{s.t.}\, Y^{'} = f\left(z^{'}, k^{'}\right)$$

$$z^{'} = h(z, \eta);\, \eta \text{ stochastic}$$

- Control variable $k^{'}$ (partially) determines future state
- We still need to hang onto z as a state, why?

Change of variable - Know your states

Note that $Y^{'}$ is a function of $k^{'}$ and $z^{'}$ so we can write

$$\mathbb{V}\left(z,k^{'}\right)=\beta E\left[V\left(Y^{'}\left(z^{'},k^{'}\right),z^{'}\right)|z\right]$$

$$\mathbb{V}_k\left(z,k^{'}\right)=\beta E\left[V_Y\left(Y^{'}\left(z^{'},k^{'}\right),z^{'}\right)\frac{\partial Y\left(z^{'},k^{'}\right)}{\partial k}|z\right]$$

Now the problem is:

$$V\left(z,Y\right)=\max_{\{k^{\prime}\}} u\left(Y-k^{'}\right)+\mathbb{V}\left(z,k^{'}\right)$$

$$\text{s.t.}\, Y^{'}=f\left(z^{'},k^{'}\right)$$

$$z^{'}=h\left(z,\eta\right);\eta \text{ stochastic}$$

Modified EGM

Algorithm 2: EGM: Change of State Method

Function `EGM(`V,$\vec{k}$,$\vec{z}$,*parameters*`)`**:**

Note: You already know Y() for any (), let $Y_{ij} = Y(\vec{z}_i, \vec{k}_j)$

for *i=1:*n_z **do**

  for *j=1:*n_k **do**

    $\mathbb{V}_j = \beta E\left[V\left(Y(z', \vec{k}_j), z'\right) | \vec{z}_i\right]$

  $\vec{c}$_endo = $(u')^{-1}.(\mathbb{V}_k)$ (Note: Evaluating whole vector)

  $\vec{Y}$_endo = c_endo + $\vec{k}$

  $\vec{V}$_endo = $u(\vec{c}\_endo) + \mathbb{V}$

  # Interpolate value function to exogenous grid

  V_new[i,:] = Interpolation($\vec{Y}$_endo, $\vec{V}$_endo, $\vec{Y}[i,:]$)

Change variable back to k. Note: $V_{ji} = V(Y(\vec{z}_i, \vec{k}_j), z_i) = V(\vec{z}_i, \vec{k}_j)$

Some comments

The method still has some flexibility

1. How to compute derivatives (you can get it from interpolation step)
2. How to compute expectations (no interpolation if z is discrete)
3. How to judge convergence (standard practice is actually to pass $\mathbb{V}$ along and judge convergence with it)
4. How to map to capital after convergence
    4.1 Interpolation of $V\left(Y_{endo}\right)$ to $V\left(Y_{exo}\right)$: Y_{exo} maps to k by construction
    4.2 Keep Y_{endo}. Solve for $\vec{k}\left(z\right)$ s.t. $Y_{endo}\left(z\right) = f\left(z, \vec{k}\left(z\right)\right)$

Labor Supply

Labor supply adds an equation

$$V(z,k) = \max_{\{c,k'\}} u(c,\ell) + \beta E\left[V\left(z',k'\right)|z\right]$$
$$\text{s.t.}\, c + k' = f(z,k,\ell)$$
$$z' = h(z,\eta)\,;\eta \text{ stochastic}$$

FOC:

$$u_c(c,\ell) = \beta E\left[V_k\left(z',k'\right)|z\right] \qquad -u_\ell(c,\ell) = f_\ell(z,k,\ell) \qquad c+k' = f(z,k,\ell)$$

Attempting EGM - Problems

Change of variable:

$$Y(z,k) = f(z,k,\ell(z,k)) = zk^{\alpha}\ell(z,k)^{1-\alpha} + (1-\delta)k$$

- Cannot define exogenous grid for Y. Grid depends on policy function.

Euler equation:

$$u_c(c,\ell(z,k)) = \beta E\left[V_k\left(z^{'},k^{'}\right)|z\right]$$

- In general, cannot invert this equation for c.
  - Special case for additively separable preferences: $u_c(c,\ell) = u_c(c)$

If only we knew $\ell(z,k)$ we could almost use EGM!

Barillas & Fernandez-Villaverde (2007)

Idea: Mix EGM and VFI in the spirit of Howard's policy function iteration

1. Fix a policy function for labor $\ell_0(z,k)$ (a good guess is $\ell_0(z,k) = \ell_{ss}$)
2. Conduct N steps of EGM given $\ell_0(z,k)$ (say $N = 10$)
   - EGM has to be modified to include labor.
   - We need to
3. Conduct M steps of VFI (say $M = 1$) on the exogenous capital grid.
4. Replace $\ell(z,k)$ with the output of step 3 and conduct step 2.

Algorithm 3: EGM: Fixed labor supply

Function `EGM(`$V, \vec{k}, \vec{z}, \ell(z,k), k^{'}(z,k)$, *parameters*`)`**:**

- **for** $i=1{:}n_z$ **do**
  - **for** $j=1{:}n_k$ **do**
    1. Solve for $\tilde{k}_{ij}$ s.t. $k^{'}(\tilde{k}_j) = \vec{k}_j$
    2. Evaluate for labor from old policy: $\tilde{\ell}_{ij} = \ell(\vec{z}_i, \tilde{k}_{ij})$
    3. Evaluate expectd value: $\mathbb{V} = \beta E\left[V\left(z', \vec{k}_j)\right) | \vec{z}_i\right]$
    4. Recover consumption (analytical solution): $u_c\left(\tilde{c}_{ij}, \tilde{\ell}_{ij}\right) = \mathbb{V}_k$
    5. Find endogenous capital $\hat{k}_{ij}$ s.t.: $\tilde{c}_{ij} + \vec{k}_j = f\left(\vec{z}_i, \hat{\mathbf{k}}_{\mathbf{ij}}, \tilde{\ell}_{ij}\right)$
    6. Update value at endogenous grid: $V(\vec{z}_i, \hat{k}_{ij}) = u\left(\tilde{c}_{ij}, \tilde{\ell}_{ij}\right) + \mathbb{V}$
  - 7. Interpolate to exogenous grid: V_new[i,:] = Interp($\hat{k}, V, \vec{k}$)

Some comments

1. In step 1 you can get the inverse from an interpolation routine
   - One option is to use a root finder
   - If you are using your own routine (say Cubic Splines) you can code your own inverse function
2. In step 5 we can be more ambitious and also update labor.

   5'. Find endogenous capital $\hat{k}_{ij}$ s.t.: $\tilde{c}_{ij} + \vec{k}_j = f\left(\vec{z}_i, \hat{\mathbf{k}}_{\mathbf{ij}}, \ell\left(\vec{z}_i, \hat{\mathbf{k}}_{\mathbf{ij}}\right)\right)$

   - Doing this implies adding an interpolation step to the root finding
   - It also provides a better update of the value function

   6'. Update value at endogenous grid: $V(\vec{z}_i, \hat{k}_{ij}) = u\left(\tilde{c}_{ij}, \ell\left(\vec{z}_i, \hat{\mathbf{k}}_{\mathbf{ij}}\right)\right) + \mathbb{V}$
3. Step 4 can be simplified if utility is separable $u(c, \ell) = U(c) - H(\ell)$
   - In fact, all the algorithm gets easier
   - No need to carry around the policy function for labor

Algorithm 4: EGM: Endogenous labor supply with separable utility

Function `EGM`(V,$\vec{k}$, $\vec{z}$,*parameters*):

for i=$1{:}n_z$ **do**

for j=$1{:}n_k$ **do**

1. Evaluate expectd value: $\mathbb{V} = \beta E\left[V\left(z', \vec{k}_j)\right) |\vec{z}_i\right]$
2. Recover consumption (analytical solution): $\tilde{c}_{ij} = (U')^{-1}(\mathbb{V}_k)$
3. Find $(\hat{k}_{ij}, \tilde{\ell}_{ij})$ that solve FOC:
   3a. Define $\hat{k}(\ell)$ analytically from FOC: $\frac{-H'(\ell)}{U'(\tilde{c}_{ij})} = f_\ell(\vec{z}_i, \hat{\mathbf{k}}(\ell), \ell)$
   3b. Solve for $\tilde{\ell}_{ij}$ numerically s.t.: $\tilde{c}_{ij} + \vec{k}_j = f\left(\vec{z}_i, \hat{\mathbf{k}}(\widetilde{\ell}_{\mathbf{ij}}), \tilde{\ell}_{ij}\right)$
   3c. Assign endogenous grid point $\hat{k}_{ij} = \hat{k}(\tilde{\ell}_{ij})$
4. Update value at endogenous grid: $V(\vec{z}_i, \hat{k}_{ij}) = u\left(\tilde{c}_{ij}, \tilde{\ell}_{ij}\right) + \mathbb{V}$

5. Interpolate to exogenous grid: V_new[i,:] = Interp($\hat{k}$, V, $\vec{k}$)

Envelope Condition Method

Maliar & Maliar (2013)

First order conditions:

$$u_c(c,\ell) = \beta E\left[V_k\left(z^{'},k^{'}\right)|z\right] \tag{1}$$

$$\frac{-u_\ell(c,\ell)}{u_c(c,\ell)} = f_\ell(z,k,\ell) \tag{2}$$

$$c + k^{'} = f(z,k,\ell) \tag{3}$$

Envelope condition:

$$V_k(k,a) = u_c(c,\ell)\, f_k(z,k,\ell) \tag{4}$$

Combining (1) and (4) we get a recursive equation for value derivative:

$$V_k(k,a) = \beta f_k(z,k,\ell)\, E\left[V_k\left(z^{'},k^{'}\right)|z\right] \tag{5}$$

Key: EGM works by solving (1), (2) and (3). ECM solves (4), (2) and (3). Equation (5) lets us update V_k directly without computing V

ECM - Algorithm - Inelastic labor supply

Algorithm 5: ECM: Inelastic labor supply

Function ECM($V_k, \vec{k}, \vec{z}$,*parameters*)**:**

for i=1:n_z **do**

for j=1:n_k **do**

1. Get consumption analytically: $c_{ij} = (u')^{-1}\left(\frac{V_k(\vec{z}_i,\vec{k}_j)}{f_k\left(\vec{z}_i,\vec{k}_j\right)}\right)$

   Note: We are using present k, not future k.

2. Get k': $k'_{ij} = f\left(\vec{z}_i, \vec{k}_j\right) - c_{ij}$

3. Update V_k: $V_k^{new}\left(\vec{z}_i, \vec{k}_j\right) = \beta f_k\left(\vec{z}_i, \vec{k}_j\right) E\left[V_k\left(z', k'_{ij}\right)|\vec{z}_i\right]$

   Note: This step requires interpolation inside expectation

return V_k^{new};

Some comments

1. No optimization or root finding in any step!
2. Careful when updating derivatives directly
   - You lose the power of the contraction mapping theorem
   - Particularly you lose uniqueness ($V_k = 0$ is a fixed point)
   - Remember that your function is monotone, so $V_k > 0$!
3. Alternative is to update with V as we do always:
   0'. Get derivative of V at grid nodes $V_k\left(\vec{z}_i, \vec{k}_j\right)$
   3'. Update value function: $V^{new}(z,k) = u(c_{ij}) + \beta E\left[V\left(z', k'_{ij}\right)|z\right]$
      - Note that you still need to do the interpolation inside the expectation
4. Authors say they get better results with V_k
   - They reference another paper (Maliar & Maliar, 2012) that solves problems with 16 states using variants of the ECM

ECM - Labor supply

Algorithm 6: ECM: Endogenous labor supply, Separable utility

Function ECM($V_k, \vec{k}, \vec{z}$, *parameters*):

for i=1:n_z **do**

for j=1:n_k **do**

1. Get labor ℓ_{ij} numerically: $V_k(\vec{z}_i, \vec{k}_j) = \frac{H'\left(\ell_{ij}\right)}{f_\ell\left(\vec{z}_i, \vec{k}_j, \ell_{ij}\right)} f_k\left(\vec{z}_i, \vec{k}_j, \ell_{ij}\right)$

   Note: No interpolation or expectation

2. Get consumption analytically: $c_{ij} = (U')^{-1}\left(\frac{H'\left(\ell_{ij}\right)}{f_\ell\left(\vec{z}_i, \vec{k}_j, \ell_{ij}\right)}\right)$

3. Get k': $k'_{ij} = f\left(\vec{z}_i, \vec{k}_j, \ell_{ij}\right) - c_{ij}$

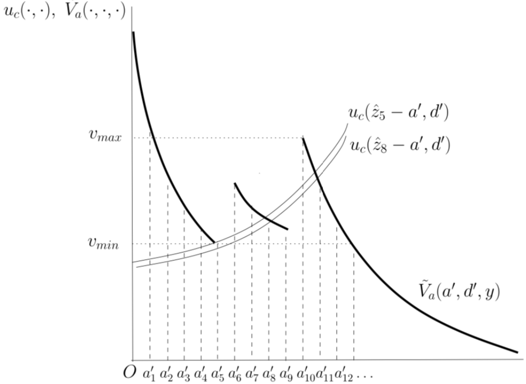
3. Update V_k: $V_k^{new}\left(\vec{z}_i, \vec{k}_j\right) = \beta f_k\left(\vec{z}_i, \vec{k}_j, \ell_{ij}\right) E\left[V_k\left(z', k'_{ij}\right) | \vec{z}_i\right]$

return V_k^{new};

Extensions

Non-Convex, Non-Smooth Problems - Fella (2014)

- Extend EGM to a problem with discrete state variable and continuous choices
- Discreteness is a problem because it generates kinks in the function
- Idea: EGM works away from the kinks!
- This is worth checking!



2 States+Borrowing Const. - Hintermaier & Koeniger (2010)

- Method for model with occasionally binding collateral constraints and non-separable utility in durable and non-durable consumption
- Good for applications with uninsurable income risk
- Idea: Solve the problem with a new state variable
  - x : Cash on hand or beginning of period wealth