PHD21 Computational methods: Assignments

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Contents

1 Assignment 1

Questions 1 through 4

Question:

1. *Label and interpret the model ingredients properly.*
2. *Characterise the individual labor supply curve.*
3. *Characterise the aggregate labor supply curve.*
4. *Characterise the aggregate labor demand curve*

Step 1A: Working households → intensive margin labour supply. Start with the working household's problem.

$$W(a,z) = \max_{c,n,a'} \left\{ \log(c) - \eta \frac{1}{1+\frac{1}{\chi}} n^{1+\frac{1}{\chi}} + \beta v(a') \right\} \quad (1.1)$$
$$\text{s.t. } c + a' = zw(1-\tau)n + a(1+r(1-\tau)) + T$$

Construct the Lagrangian, assuming that $v(a') = \log(a')$:

$$\mathcal{L} = \log(c) - \eta \frac{1}{1+\frac{1}{\chi}} n^{1+\frac{1}{\chi}} + \beta \log(a') + \lambda \left[zw(1-\tau)n + a(1+r(1-\tau)) + T - c - a' \right]. \quad (1.2)$$

The first-order conditions are as follows:

$$\mathcal{L}_c = \frac{1}{c} + \lambda = 0 \implies \lambda = \frac{1}{c}, \quad (1.3a)$$

$$\mathcal{L}_n = -\eta n^{\frac{1}{\chi}} + \lambda zw(1-\tau) = 0 \implies \eta n^{\frac{1}{\chi}} = \frac{zw(1-\tau)}{c}, \quad (1.3b)$$

and

$$\mathcal{L}_{a'} = \frac{\beta}{a'} - \lambda = 0 \implies a' = \beta c. \quad (1.3c)$$

Combine the results of Equations (1.3b) and (1.3c) with the budget contraint to arrive at the Euler equation:

$$\underbrace{c + a'}_{\text{Use (1.3c)}} = \underbrace{zw(1-\tau)n}_{\text{Use (1.3b)}} + a(1+r(1-\tau)) + T, \quad (1.4a)$$

$$\boxed{c(1+\beta) = zw(1-\tau)\left(\frac{zw(1-\tau)}{\eta c}\right)^{\chi} + a(1+r(1-\tau)) + T.} \quad \text{(WH-ILS)}$$

Equation (WH-ILS) governs the **intensive labour supply of a working household**, $c_w^\star(a,z)$ is their consumption level.

Further, notice that $c_w^\star(a,z)$ increases in z:

$$\frac{\partial c_w^\star(a,z)}{\partial z}(1+\beta) = \underbrace{\left[w(1-\tau)\eta^{-1}\right]^{1+\chi}}_{\equiv \theta > 0} \times \frac{(1+\chi)z^\chi c_w^\star(a,z) - z^\chi \frac{\partial c_w^\star(a,z)}{\partial z}}{c_w^\star(a,z)^2} \implies \quad (1.5a)$$

$$\frac{\partial c_w^\star(a,z)}{\partial z}\left(1+\beta+\theta\frac{z^\chi}{c_w^\star(a,z)^2}\right) = \frac{\theta(1+\chi)z^\chi}{c_w^\star(a,z)} \implies \quad (1.5b)$$

$$\frac{\partial c_w^\star(a,z)}{\partial z} = \frac{\frac{\theta(1+\chi)z^\chi}{c_w^\star(a,z)}}{1+\beta+\theta\frac{z^\chi}{c_w^\star(a,z)^2}} > 0. \quad (1.5c)$$

Also, differentiate Equation (1.3b):

$$\eta\chi^{-1}n^{\frac{1}{\chi}-1}\frac{\partial n^\star(a,z)}{\partial c_w^\star(a,z)} = -zw(1-\tau)c_w^\star(a,z)^{-2} \implies \tag{1.6a}$$

$$\frac{\partial n^\star(a,z)}{\partial c_w^\star(a,z)} = \frac{-\chi zw(1-\tau)}{\eta n^{\frac{1}{\chi}-1}c_w^\star(a,z)^2}. \tag{1.6b}$$

Using the combination of the Envelope Theorem and chain rule, this implies that, at the optimal consumption-hours bundle, the household sees:

$$\frac{\partial W(a,z)}{\partial z} = \frac{1}{c_w^\star(a,z)}\frac{\partial c_w^\star(a,z)}{\partial z} - \eta n^{\frac{1}{\chi}}\frac{\partial n^\star(a,z)}{\partial z} \implies \tag{1.7a}$$

$$\frac{\partial W(a,z)}{\partial z} = \frac{1}{c_w^\star(a,z)}\frac{\partial c_w^\star(a,z)}{\partial z} - \eta n^{\frac{1}{\chi}}\frac{\partial n^\star(a,z)}{\partial c_w^\star(a,z)}\frac{\partial c_w^\star(a,z)}{\partial z} \implies \tag{1.7b}$$

$$\boxed{\frac{\partial W(a,z)}{\partial z} > 0.} \tag{1.7c}$$

Equation (1.7c) effectvely means that **$W(a,z)$ monotonically increases in z**.

Step 1B: Non-working households. The problem is similar here, apart from the labour first order condition. Skipping the Lagrangian setup, I arrive at the following first-order conditions:

$$\mathcal{L}_c = \frac{1}{c} + \lambda = 0 \implies \lambda = \frac{1}{c} \tag{1.8a}$$

and

$$\mathcal{L}_{a'} = \frac{\beta}{a'} - \lambda = 0 \implies a' = \beta c, \tag{1.8b}$$

both of which are identical to what we see for the working household. Combining it with the budget constraint, we obtain the consumption function for the non-working household:

$$\boxed{c_{nw}^\star(a) = \frac{b + a(1+r(1-\tau)) + T}{1+\beta}.} \tag{1.9}$$

This effectively implies that:

$$\boxed{\frac{\partial N(a,z)}{\partial z} = 0.} \tag{1.10}$$

Step 2: Extensive margin labour supply decision. Household (a,z) enters the labour market when:

$$\mathbf{I}_n(a,z) = \begin{cases} 1 & \text{if} \quad W(a,z) \geq N(a,z) \\ 0 & \text{if} \quad W(a,z) < N(a,z), \end{cases} \tag{1.11}$$

where $W(\cdot,\cdot)$ and $N(\cdot,\cdot)$ are the value functions of working and not working, respectively.

Even abstracting from the Unique Point Theorem, we can see that if there exists $z^\star$ such that:

$$W\left(a, z^\star\right) = N\left(a, z^\star\right) \tag{1.12}$$

then for $z > z^\star$, we have:

$$\mathbf{I}_n(a, z) = 1. \tag{1.13}$$

This will come handy while numerically solving the model.

Step 3: Aggregate labour supply. Assuming that $\Phi(a, z)$ is the joint distribution of ex-ante wealth and productivity, the **aggregate labour supply** is:

$$L^S = \int \mathbf{I}_n(a, z) h(a, z) \, \mathrm{d}\Phi(a, z) \tag{1.14}$$

Step 4A: Aggregate labour demand. We abstract from the capital markets, which makes the representative firm's problem near-trivial:

$$Y = \max_L \left\{ AK^\alpha L^{1-\alpha} - wL - rK \right\} \implies \tag{1.15a}$$

$$w = A(1-\alpha) \left(\frac{L^D}{K} \right)^{-\alpha}, \tag{1.15b}$$

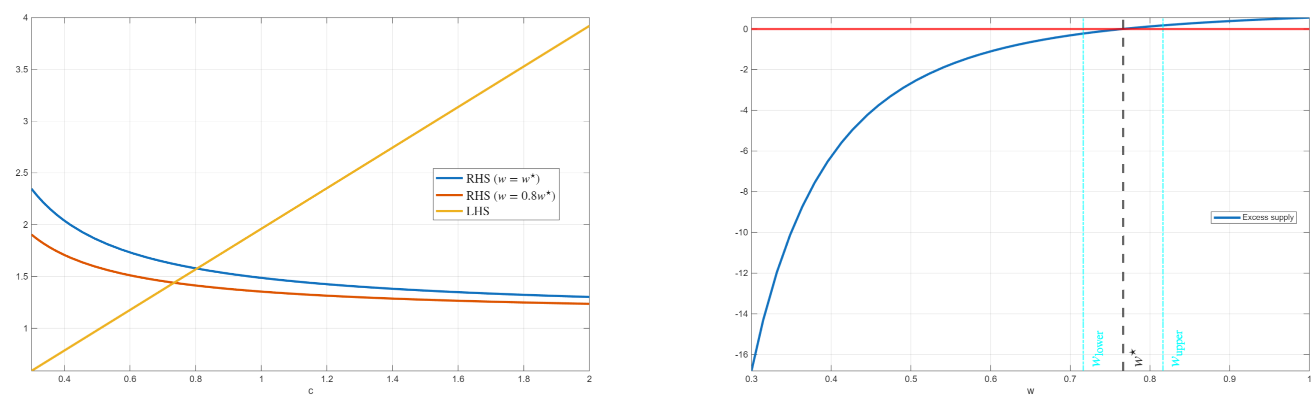
or, putting L^D on the LHS:

$$\boxed{L^D = \left(\frac{(1-\alpha)A}{w} \right)^{\frac{1}{\alpha}} K.} \tag{1.15c}$$

Figure 1.1: Household block of the model.

(a) Euler equation & consumption decision.

(b) Excess labour supply on the aggregate level.



Question 5

Question: *Suppose the following parameter levels:*

$$a = 1, \quad \alpha = 0.3, \quad \tau = 0.15, \quad \bar{z} = 1, \quad A = 1, \quad r = 0.04, \quad \beta = 0.96$$

Define and characterize the stationary recursive competitive equilibrium.

Step 1: Parameters left. $\mathbf{\Xi}$ represents the original vector of parameters:

$$\mathbf{\Xi} = (a, \eta, \xi, \tau, b, \beta, \sigma_z, A, \alpha, r)^T. \tag{1.16}$$

Given the pre-specified parameters, the unknown ones are:

$$\hat{\boldsymbol{\Xi}} = (\eta, b, \sigma_z, \chi)^T . \tag{1.17}$$

In my further work, I already use the calibrated parameters (see question 8).

Step 2: Equilibrium. Given the distribution of labour productivity, Φ, a set of functions $\{n, c, a', z^\star, L, w, T\}$ is a **stationary competitive equilibrium** if

1. $(n, c, a', z^\star)$ solves the household's problem.
2. (K, L) solves the production sector's problem.
3. The labour and capital markets clear.

Step 3: Equilibrium algorithm. I set out the **algorithm used to compute the equilibrium** given a set of parameters.

1. Guess (w_0, T_0).
2. Compute individual decisions.
   - `fnIntensiveLabourSupply` computes the **intensive labour supply for a working household**. The following equations flesh out the approach leveraging concavity of Equation (WH-ILS). Start at the initial consumption guess, c_0. The code follows the logic fleshed out by the equations below:

     $$RHS\,(c) \equiv zw(1-\tau)\left(\frac{zw(1-\tau)}{\eta c}\right)^{\chi} + a(1 + r(1-\tau)) + T \tag{1.18a}$$

     $$LHS\,(c) \equiv (1+\beta)c \implies \tag{1.18b}$$

     $$c_1 = \frac{RHS\,(c_0)}{1+\beta} \tag{1.18c}$$

     and

     $$\epsilon_n \equiv c_n - c_{n-1} \implies \tag{1.18d}$$

     $$\epsilon_1 = c_1 - c_0. \tag{1.18e}$$

     If it's above the tolerance level, then repeat until it works:

     $$c_n = \frac{RHS\,(c_{n-1})}{1+\beta} \implies \tag{1.18f}$$

     $$\epsilon_n = c_n - c_{n-1}. \tag{1.18g}$$

     This approach computes the indiviually optimal values of consumption and labour market participation, (c_w, n_w), provided the household chooses to work.

   - `fnExtensiveLabourSupply` determines if household (a, z) chooses to work based on Equation (1.11).
3. Aggregate all labour supply decisions (`fnAggregateLabourSupply`) and compare them with the aggregate labour demand. `fnSolvePrices` iterates w and T until both clear the labour market.
   - One way of doing that is following the same method as for `fnIntensiveLabourSupply`, with Equations (1.14) and (1.15c) used to compute labour supply and demand, respectively.
   - Another method is to use bisection, in `fnSolvePricesBisection`. As illustrated in Figure 1.1b, the method is based on creating a grid for different wage values, finding the negative value closest to 0, w_{lower}, and taking the weighted average of w_{lower} and w_{upper} (the next value in the grid). **Note**: I use the "naive" approach in my code, as bisection seems to produce a
4. If the error is too large, update (w_n, T_n) and iterate until convergence.

Question 6

Question: *Visualize the aggregate supply and demand curves in the labor market.*

Question 7

Question: *Visualize the comparative statics of the wage with respect to the change in A.*

Question 8

Question: *Estimate parameters $(\eta, b, \chi, \sigma_z)$ to match the following hypothetical moments in general equilibrium:*

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2 Assignment 2

Questions 1 through 3

Question:

1. *Label and interpret the model ingredients properly.*
2. *Discretise the idiosyncratic productivity process by the Tauchen method using 2 grid points on one standard deviation range.*
3. *Characterise the individual (probabilistic) labour supply decision analytically.*

The value functions are:

$$V_t(a,h,z) = \int \max\left\{W_t(a,h,z) + \xi_{Wt}, N_t(a,h,z) + \xi_{Nt}\right\} dG\left(\xi_{st};\xi\right) \tag{2.1a}$$

and

$$S_t(a,h,z) = \int \max\left\{\varphi W_t(a,h,z) + (1-\varphi)N_t(a,h,z) - \phi + \xi_{Wt}, N_t(a,h,z) + \xi_{Nt}\right\} dG\left(\xi_{st};\xi\right) \tag{2.1b}$$

Step 1A Working household problem:

$$\begin{aligned} W_t(a,h,z) &= \max_{c,a'} \left\{\log(c) - \eta + \beta \mathbb{E} V_{t+1}\left(a',h',z'\right)\right\} \\ \text{s.t. } & c + a' = w(h,z) + (1+r)a, \quad a' \geq 0 \\ & h' = \mathbb{I}\left\{h < \bar{h}\right\}(h+1) + \mathbb{I}\left\{h \geq \bar{h}\right\} h \end{aligned} \tag{2.2}$$

The Lagrangian:

$$\mathcal{L} = \log(c) - \eta + \beta \mathbb{E}\left[V_{t+1}\left(a',h',z'\right)\right] + \lambda\left[w(h,z) + (1+r)a - a' - c\right] \tag{2.3}$$

The FOCs:

$$\mathcal{L}_c = \frac{1}{c} - \lambda = 0 \implies \lambda = \frac{1}{c} \tag{2.4a}$$

$$\mathcal{L}_{a'} = \beta \frac{\partial \mathbb{E}\left[V_{t+1}\left(a',h',z'\right)\right]}{\partial a'} - \lambda = 0 \implies \lambda = \beta \frac{\partial \mathbb{E}\left[V_{t+1}\left(a',h',z'\right)\right]}{\partial a'}. \tag{2.4b}$$

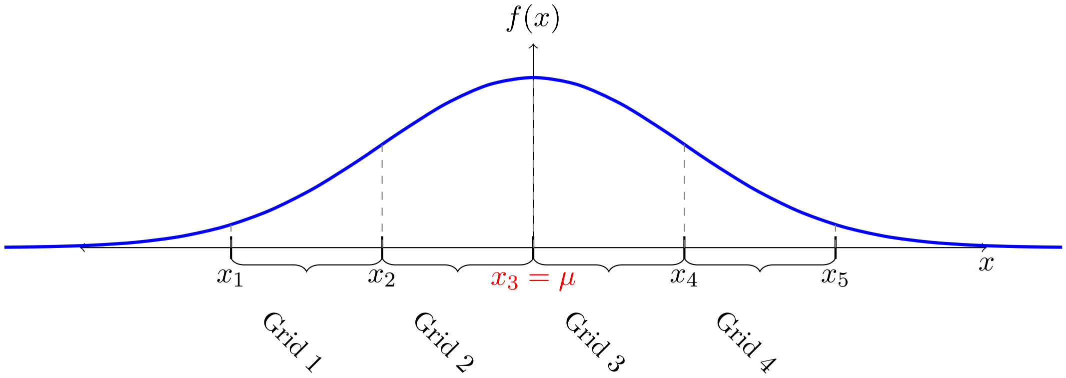


Figure 2.1: Tauchen discretisation.

Then, the optimality is given by:

$$\boxed{\frac{1}{c} = \beta \frac{\partial \mathbb{E}\left[V_{t+1}\left(a', h', z'\right)\right]}{\partial a'}.} \tag{2.5}$$

Further, assuming that $V_{T+1} = \log\left(a'\right)$, the terminal asset choice is:

$$\frac{1}{c} = \frac{\beta}{a'} \implies \tag{2.6a}$$

$$a' = \beta c \implies \tag{2.6b}$$

$$\left(1 + \frac{1}{\beta}\right) a' = w(h, z) + (1 + r)a \implies \tag{2.6c}$$

$$\boxed{a' = \frac{1+\beta}{\beta}\left[w(h, z) + (1 + r)a\right].} \tag{2.6d}$$

This can be used to recover the solution and final V_t, which can later be used to solve the problem.

Step 1B Working household problem: The non-working household faces the following problem:

$$\begin{aligned} N_t(a, h, z) &= \max_{c, a'} \log(c) + \beta \mathbb{E} S_{t+1}\left(a', h', z'\right) \\ \text{s.t. } & c + a' = b + (1 + r)a, \quad a' \geq 0 \\ & h' = h \end{aligned} \tag{2.7}$$

Following the same steps, we arrive at the optimality condition:

$$\boxed{\frac{1}{c} = \beta \frac{\partial \mathbb{E}\left[S_{t+1}\left(a', h', z'\right)\right]}{\partial a'}.} \tag{2.8}$$

The terminal asset choice becomes:

$$\boxed{a' = \frac{1+\beta}{\beta}\left[b + (1 + r)a\right].} \tag{2.9}$$

Step 2 Tauchen discretisation: `fnTauchenLogNormal` allows for conducting a quick Tauchen discretisation under the assumption that z follows $\log \mathcal{N}\left(0, \sigma_z\right)$, as visualised on Figure 2.1.

Step 3 Probabilistic labour supply decision: Given the presence of the Gumbel "shock" in the participation decision, the conditional decisions to participate, d_v and d_s, are governed by the following binary probabilities:

$$\mathbb{P}\left(d_v = 1\right) = \frac{\exp\left(\frac{W}{\zeta}\right)}{\exp\left(\frac{W}{\zeta}\right) + \exp\left(\frac{N}{\zeta}\right)} \tag{2.10a}$$

and

$$\mathbb{P}\left(d_s = 1\right) = \frac{\exp\left(\frac{\varphi W + (1-\varphi)N - \phi}{\zeta}\right)}{\exp\left(\frac{\varphi W + (1-\varphi)N - \phi}{\zeta}\right) + \exp\left(\frac{N}{\zeta}\right)}. \tag{2.10b}$$

Gumbel probabilities trick: Estimating Equations (2.10a) and (2.10b) in MATLAB is tricky. In each case, both numerators and denominators get very large (small), with the programme doing a bad job at computing $\frac{0}{0}$ or $\frac{\infty}{\infty}$. The method I leverage in `fnGumbelTrickProbabilities` is based on the proprtis of the logistic sigmoid function. For notational parsimony, set, $A \equiv \frac{W}{\zeta}$ and $B \equiv \frac{N}{\zeta}$, $X \equiv \max(A, B)$, and focus on Equation (2.10a):

$$\mathbb{P}\left(d_v = 1\right) = \frac{\exp A}{\exp A + \exp B} \implies \tag{2.11a}$$

$$\log \mathbb{P}\left(d_v = 1\right) = A - \log\left(\exp A + \exp B\right) \underbrace{-X + \log(\exp X)}_{=0} \implies \tag{2.11b}$$

$$\log \mathbb{P}\left(d_v = 1\right) = A - X - \log\left[\exp(A - X) + \exp(B - X)\right] \implies \tag{2.11c}$$

$$\boxed{\mathbb{P}\left(d_v = 1\right) = \exp\left\{\underbrace{A - X}_{\leq 0} - \log\left[\underbrace{\exp(\overbrace{A - X}^{\leq 0}) + \exp\overbrace{(B - X)}^{\leq 0}}_{\leq 1}\right]\right\}}. \tag{2.11d}$$

By restating the problem as in Equation (2.11d) I ensure that MATLAB doesn't have to deal with excessively large numbers.

Questions 4 through 6

Question:

- *Suppose the following parameter levels:*

$$\zeta = 0.01, \varphi = 0.80, \phi = 0.5, \eta = 2, b = 0.2, \bar{h} = 10, r = 0.04, \beta = 0.96$$
$$\sigma_z = 0.05, \rho = 0.90, \gamma_h = 0.1, \gamma_z = 0.1, \gamma_0 = 0.2$$

- *Simulate 20,000 households (same cohort) and simulate them for the life time.*
- *Visualize the life-time wealth and consumption patterns.*

Step 1 The algorithm: The model's solution is structured according to the following algorithm.

1. `LoadParameters.m` loads parameters and sets the wealth, skill, productivity, and age grids. For the skill grid, I use a standard Tauchen method from `fnTauchenLogNormal.m`.

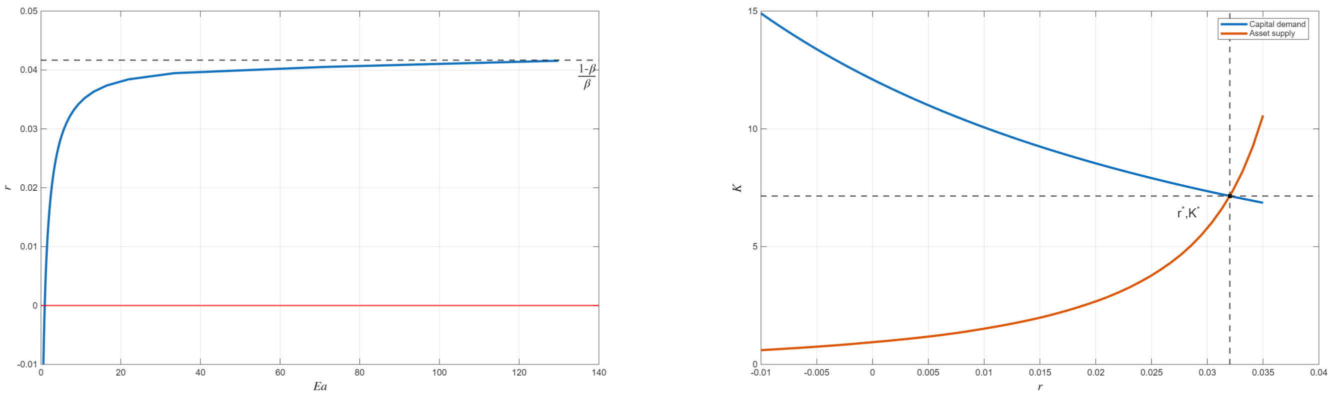
2. In `fnValueFunctionMatrices.m`, the algorithm computes the value function for worker (a, h, z, t, a').

    (a) For $t = 50$, I compute $\mathbb{E}V\left(a', h', z'\right) = \mathbb{E}S\left(a', h', z'\right) = \log a'$.

Figure 3.1: Reproduced figures from Aiyagari (1994).

(a) Mean assets vs. interest rate.

(b) Asset supply and demand.



(b) For $t < 50$, I compute:

$$W\left(a, h, z, t, a'\right) = \log c - \eta + \beta \mathbb{E}_t V_{\max}\left(a', z, t, h\right) \tag{2.12a}$$

$$N\left(a, h, z, t, a'\right) = \log c + \beta \mathbb{E}_t S_{\max}\left(a', z, t, h\right) \tag{2.12b}$$

$$V\left(a, h, z, t, a'\right) = \zeta \left\{ \delta_E + \log\left[\exp\left(\frac{W}{\zeta}\right) + \exp\left(\frac{N}{\zeta}\right)\right]\right\} \tag{2.12c}$$

$$S\left(a, h, z, t, a'\right) = \zeta \left\{ \delta_E + \log\left[\exp\left(\frac{\varphi W + (1-\varphi)N - \phi}{\zeta}\right) + \exp\left(\frac{N}{\zeta}\right)\right]\right\} \tag{2.12d}$$

3 Assignment 3

Questions (a) through (d)

Question:

- *Why does a household need to understand the aggregate state Φ*
- *In the long run, will the economy reach a stationary state or not? Why?*
- *Given the problem, define the stationary recursive competitive equilibrium (SRCE).*
- *How large is the labor supply in each period?*

Questions (e) and (f)

Question: *Solve the general equilibrium model using the interpolated search and the histogram methods. Replicate Figures IIa and IIb from Aiyagari (1994).*

Part 1 The algorithm: To be added later.

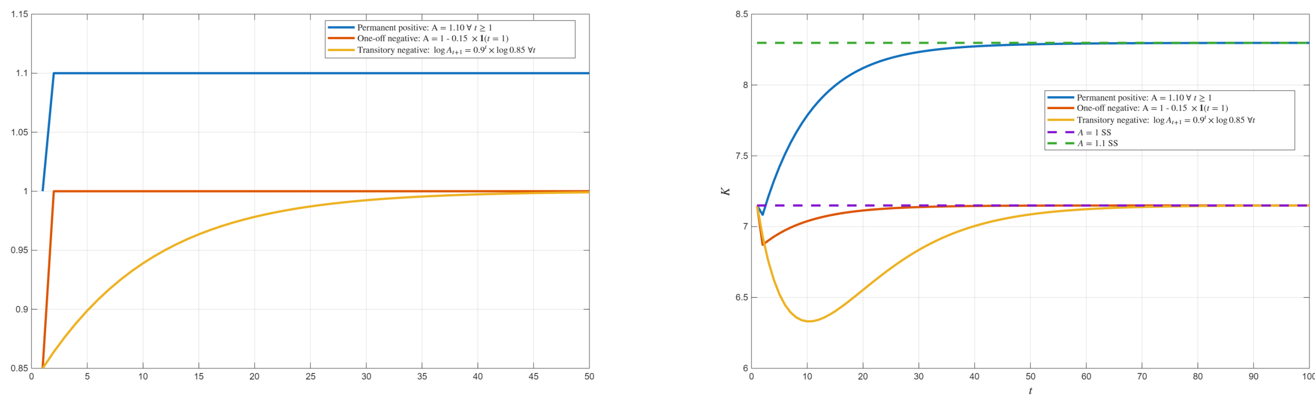
Part 2 Plots: Figures 3.1a and 3.1b reproduce Figures IIa and IIb from Aiyagari (1994).

Questions (g) through (i)

Question: *Solve the general equilibrium model using the interpolated search and the histogram methods. Replicate Figures IIa and IIb from Aiyagari (1994).*

Figure 4.1: Transition dynamics.

(a) Shock types. (b) Capital dynamics.



4 Assignment 4

Questions (a) through (e)

Question:

- *Solve the stationary competitive equilibrium for $A = 1$ and $A = 1.1$.*
- *Define the transitional competitive equilibrium for the jump in A.*
- *Compute the transitional competitive equilibrium.*
- *How long does it take for an economy to converge to the new stationary competitive equilibrium?*

Part 1 Equilibrium definition: Let $\mathbf{\Theta_0}$ be the original SRCE distribution, for $A = 1$, and v_{T+1} be the new SRCE value function, for $A = 1.1$.

Definition 4.1 *(Transitional competitive equilibrium) Given $\mathbf{\Theta_0}$ and v_{T+1}, $(g_{a,t}, g_{c,t}, v_t, G_t, r_t, w_t, \boldsymbol{\Theta_t})_{t=1}^{T}$ and $(g_K, g_{a,L})$ are* ***transitional compettive equilibrium*** *if:*

1. *$(g_{a,t}, g_{c,t}, v_t)_{t=1}^{T}$ solves the household's problem given $(\boldsymbol{\Theta_t})_{t=1}^{T}$.*
2. *$(g_K, g_{a,L})$ solves a representative firm's problem given $(\boldsymbol{\Theta_t})_{t=1}^{T}$.*
3. *$(r_t, w_t)_{t=1}^{T}$ clears the capital and labour markets $\forall t$:*

$$[K]: \quad g_K(\boldsymbol{\Theta_t}) = \int a \, \mathrm{d}\boldsymbol{\Theta_t} \tag{4.1a}$$

$$[L]: \quad g_{a,L}(\boldsymbol{\Theta_t}) = \iint \boldsymbol{\Theta_t}(a, z) z \, \mathrm{d}a \mathrm{d}z. \tag{4.1b}$$

4. *The aggregate resource constraint holds:*

$$\iint g_{c,t}(a, z) + g_{a,t}(a, z) \, \mathrm{d}\boldsymbol{\Theta_t} = F(g_K, g_{a,L}) + (1 - \delta) g_K. \tag{4.2}$$

Questions (g)

Question: *Calculate the Gini coefficient for each period on the transition path.*

To compute the Gini coefficient, I adapt the following formula:

$$G = \frac{1}{2\mu} \iint p(x)p(x) \left| x - y \right| \, \mathrm{d}x\mathrm{d}y, \tag{4.3}$$

where μ is the average asset position of the households. In my Matlab code, $p(\cdot)$ comes from `iMarginalDist` in each iteration:

$$p(x) = \texttt{iMarginalDist} = \begin{pmatrix} \varphi_1 \\ \varphi_2 \\ \cdots \\ \varphi_N \end{pmatrix} \implies \tag{4.4a}$$

$$\iint p(x)p(y) \, \mathrm{d}x\mathrm{d}y = \iint \boldsymbol{\iota}^T \begin{pmatrix} \varphi_1 \\ \varphi_2 \\ \cdots \\ \varphi_N \end{pmatrix} \times \begin{pmatrix} \varphi_1 & \varphi_2 & \cdots & \varphi_N \end{pmatrix} \boldsymbol{\iota} \, \mathrm{d}x\mathrm{d}y \implies \tag{4.4b}$$

$$\iint p(x)p(y) \, \mathrm{d}x\mathrm{d}y = \texttt{sum(sum(iMDist * iMDist'))} \tag{4.4c}$$

which can be combined with the fact that:

$$\iint \left| x - y \right| \, \mathrm{d}x\mathrm{d}y = \iint \left| \boldsymbol{\iota}^T \begin{pmatrix} a_1 \\ a_2 \\ \cdots \\ a_N \end{pmatrix} - \begin{pmatrix} a_1 & a_2 & \cdots & a_N \end{pmatrix} \boldsymbol{\iota} \right| \, \mathrm{d}x\mathrm{d}y \implies \tag{4.4d}$$

$$\iint \left| x - y \right| \, \mathrm{d}x\mathrm{d}y = \texttt{abs(repmat(vGridA2',pNA2,1)-repmat(vGridA2,1,pNA2))}. \tag{4.4e}$$

This gives:

$$G = \texttt{sum((iMDist*iMDist').*abs(repmat(vGridA2',pNA2,1)-repmat(vGridA2,1,pNA2)),'all')}. \tag{4.4f}$$

5 Assignment 5

Part 1: Re-writing the problem. Consider the problem without plugging all the functions. To solve the policy function iteration, we effectively need to "get rid off" the value function.

$$\begin{aligned} V(k) &= \max_{n,k',c} \left\{ u(c) + u(n) + \beta V\left(k'\right) \right\} \\ &\text{s.t.} c + k' + \Psi\left(k, k'\right) = (1+r)k + wn \end{aligned} \tag{5.1}$$

The problem's Lagrangian is:

$$\mathcal{L} = u(c) + u(n) + \beta V\left(k'\right) + \lambda \left[(1+r)k + wn - c - k' - \Psi\left(k, k'\right) \right], \tag{5.2}$$

with the associated optimality conditions:

$$\mathcal{L}_c = u_c(c) - \lambda = 0 \implies \lambda = u_c(c) \tag{5.3a}$$

$$\mathcal{L}_n = u_n(n) + \lambda n = 0 \implies u_n(n) = -u_c(c)w \tag{5.3b}$$

$$\mathcal{L}_{k'} = \beta V_{k'}\left(k'\right) - \lambda \left[1 + \Psi_{k'}\left(k, k'\right) \right] = 0 \implies \beta V_{k'}\left(k'\right) = u_c(c) \left[1 + \Psi_{k'}\left(k, k'\right) \right]. \tag{5.3c}$$

We want to find an expression for the first derivative of the value fuction, which can be simplified using the first-order conditions:

$$V_k(k) = u_c(c)\frac{\partial c}{\partial k} + u_n(n)\frac{\partial n}{\partial k} + \beta V_{k'}(k')\frac{\partial k'}{\partial k} \implies \tag{5.4a}$$

$$V_k(k) = u_c(c)\frac{\partial c}{\partial k} - u_c(c)w\frac{\partial n}{\partial k} + u_c(c)\left[1 + \Psi_{k'}(k,k')\right]\frac{\partial k'}{\partial k} \implies \tag{5.4b}$$

$$V_k(k) = u_c(c)\left\{\frac{\partial c}{\partial k} - w\frac{\partial n}{\partial k} + \left[1 + \Psi_{k'}(k,k')\right]\frac{\partial k'}{\partial k}\right\}. \tag{5.4c}$$

The unpleasant terms from the "curly" bracket can be obtained from the budget constraint's derivative w.r.t. k:

$$\frac{\partial c}{\partial k} + \frac{\partial k'}{\partial k} + \Psi_k(k,k') + \Psi_{k'}(k,k')\frac{\partial k'}{\partial k} = (1+r) + w\frac{\partial n}{\partial k} \implies \tag{5.5a}$$

$$\frac{\partial c}{\partial k} - w\frac{\partial n}{\partial k} + \left[1 + \Psi_{k'}(k,k')\right]\frac{\partial k'}{\partial k} = 1 + r - \Psi_k(k,k'). \tag{5.5b}$$

This implies that:

$$\boxed{V_k(k) = u_c(c)\left[1 + r - \Psi_k(k,k')\right],} \tag{5.6}$$

which is the key element of the policy function iteration.

Part 2: Global nonlinear solution method in the sequence space (Lee, 2025). I adapt the lecture algorithm to the problem.

1. I simulate $\boldsymbol{A} \equiv (A_t)_{t=1}^{T}$ and guess $\boldsymbol{\Theta}^0 \equiv \left(K_t^0, N_t^0, C_t^0, W_t^0\right)_{t=1}^{T}$, with $T = 10,000$.
2. (**Backward solution**) For each $K_t^{(n)}$ pick up all the potential future TFPs, $\tilde{A}_{t+1}$ (apart from the realised A_{t+1}). For each of them, find the "neighbour" candidates, called `vKlow` and `vKHigh` in the code. For simplicity, denote the higher neighbour candidate as $\overline{K}_t^{(n)}$ and the lower neighbour candidate as $\underline{K}_t^{(n)}$.
   (a) Calculate standard weights for the candidates.
   (b) Compute the associated wage, labour participation, interest rate, and first derivative of the adjustment cost. For the "lower" neighbour, they are:

$$\underline{w}_t^{(n)} = \tilde{A}_t(1-\alpha)\left(\underline{K}_t^{(n)}\right)^{\alpha}\left(N_t^{(n)}\right)^{-\alpha} \tag{5.7a}$$

$$\underline{N}_t^{(n)} = \left[\frac{\left(C_t^{(n)}\right)^{-\sigma}\underline{w}_t^{(n)}}{\eta}\right]^{\chi} \tag{5.7b}$$

$$\underline{r}_t^{(n)} = \tilde{A}_t\alpha\left(\underline{K}_t^{(n)}\right)^{\alpha-1}\left(\underline{N}_t^{(n)}\right)^{1-\alpha} - \delta \tag{5.7c}$$

$$\underline{\Psi}_{k,t}^{(n)} = -\mu\left(\frac{\underline{K}_{t+1}^{(n)} - \underline{K}_t^{(n)}}{\underline{K}_t^{(n)}}\right)\frac{\underline{K}_{t+1}^{(n)}}{\underline{K}_t^{(n)}} + \frac{\mu}{2}\left(\frac{\underline{K}_{t+1}^{(n)} - \underline{K}_t^{(n)}}{\underline{K}_t^{(n)}}\right)^2 \tag{5.7d}$$

   Then, they are plugged to Equation (5.6) to find:

$$\underline{V}_{k,t}^{(n)} = \left(C_t^{(n)}\right)^{-\sigma}\left[1 + \underline{r}_t^{(n)} - \underline{\Psi}_{k,t}^{(n)}\right] \tag{5.7e}$$

   (c) Compute the interpolated derivative:

$$\mathcal{V}_{k,t}^{(n)} = \omega\underline{V}_{k,t}^{(n)} + (1-\omega)\overline{V}_{k,t}^{(n)}. \tag{5.8}$$

(d) Re-do the same computations, without the interpolation element, for the "true" realised shock, A_{t+1}. Combined together, I have:

$$\left[\begin{array}{l|l} \mathcal{V}_{k,t}^{n}\left(A_{1}\right) & \text{Counterfactual} \\ \mathcal{V}_{k,t}^{n}\left(A_{2}\right) & \text{Counterfactual} \\ \cdots & \cdots \\ V_{k,t}^{n}\left(A_{m}\right) & \text{Realised} \\ \cdots & \cdots \\ \mathcal{V}_{k,t}^{n}\left(A_{N_a}\right) & \text{Counterfactual} \end{array}\right]. \tag{5.9}$$

(e) These allow me to compute the expected value of the first derivative of the value function:

$$\mathbb{E}_t\left[V_{k,t+1}^{n}\left(K_{t+1}^{(n)}\right)\right] = \pi_{\text{Realised}} V_{k,t}^{n}\left(K_{t+1}^{(n)}\right) + \left(1-\pi_{\text{Realised}}\right)\mathbb{E}_t\left[\mathcal{V}_{k,t+1}^{n}\left(K_{t+1}^{(n)}\right) \mid \text{Counterfactual}\right]. \tag{5.10}$$

(f) This, in turn, allows me to use the envelope condition to recover the optimal consumption level:

$$\boxed{C_t^{\star(n)} = \left(\frac{1+\mu\frac{K_{t+1}^{(n)}-K_t^{(n)}}{K_t^{(n)}}}{\beta\,\mathbb{E}_t\left[V_{k,t+1}^{n}\left(K_{t+1}^{(n)}\right)\right]}\right)^{-\frac{1}{\sigma}}} \tag{5.11}$$

(g) Update the labour allocation:

$$N_t^{\star(n)} = \left[\frac{\left(C_t^{\star(n)}\right)^{-\sigma} w_t^{(n)}}{\eta}\right]^{\chi} \tag{5.12}$$

3. (**Iterate forward**) Next

References

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