

Econ 704 Macroeconomic Theory Spring 2020*

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1 Introduction

A model is an artificial economy used to understand economic phenomena. The description of a model's environment includes specifying agents' preferences and endowments, technology available, information structure as well as property rights. One such example is the Neoclassical Growth Model. It is one of the workhorse frameworks of modern macroeconomics because it delivers some fundamental properties that are characteristics of industrialized economies. Kaldor (1957) summarizes these six stylized facts (the seventh was added later on):

1. Output per capita (Y/L) has grown at a roughly constant rate (of 2%).
2. The capital-output ratio (K/Y , where capital is measured using the perpetual inventory method) has remained roughly constant (despite output per capita growth).
3. The capital-labor ratio (K/L) has grown at a roughly constant rate equal to the growth rate of output.
4. Labor income as a share of output (WL/Y) has remained roughly constant (0.66).
5. The wage rate has grown at a roughly constant rate equal to the growth rate of output.
6. The real interest rate has been stationary and, during long periods, roughly constant.
7. Hours worked per capita have been roughly constant.

A model is not complete without the notion of an equilibrium concept. Equilibrium can be defined as a prediction of what will happen in the economy, i.e. a mapping from environments to outcomes (allocations, prices, etc.). One equilibrium concept that we will deal with during the course is the Competitive Equilibrium (CE). Characterizing the equilibrium usually involves finding solutions to a system of an infinite number of equations.¹ There are generally two ways of getting around this challenge. The first is to invoke the first welfare theorem to solve for the allocation and then find the equilibrium prices associated with it. However, this may sometimes not work due to, say, the presence of

¹ As in Arrow-Debreu or Valuation Equilibrium.

externalities. The second way is to resort to dynamic programming and study a Recursive Competitive Equilibrium (RCE), in which equilibrium objects are functions instead of sequences. We briefly review the first in the next section and then move on to recursive competitive equilibria.

2 Review: Neoclassical Growth Model

We review briefly the basic neoclassical growth model.

2.1 The Neoclassical Growth Model (Without Uncertainty)

The commodity space is

$$\mathcal{L} = \{(l_1, l_2, l_3) : l_i = (l_{it})_{t=0}^{\infty} \text{ s.th. } l_{it} \in \mathbb{R}, \sup_t |l_{it}| < \infty, i = 1, 2, 3\}.$$

The consumption possibility set is

$$X(\bar{k}_0) = \{x \in \mathcal{L} : \exists (c_t, k_{t+1})_{t=0}^{\infty} \text{ s.th. } \forall t = 0, 1, \dots \\ c_t, k_{t+1} \geq 0, x_{1t} + (1 - \delta)k_t = c_t + k_{t+1}, -k_t \leq x_{2t} \leq 0, -1 \leq x_{3t} \leq 0, k_0 = \bar{k}_0\}.$$

The production possibility set is $Y = \prod_t Y_t$, where

$$Y_t = \{(y_{1t}, y_{2t}, y_{3t}) \in \mathbb{R}^3 : 0 \leq y_{1t} \leq F(-y_{2t}, -y_{3t})\}.$$

Definition 1 *An Arrow-Debreu equilibrium is $(x^*, y^*) \in X \times Y$, and a continuous linear functional ν^* such that*

1. $x^* \in \arg \max_{x \in X, \nu^*(x) \leq 0} \sum_{t=0}^{\infty} \beta^t u(c_t(x), -x_{3t})$,
2. $y^* \in \arg \max_{y \in Y} \nu^*(y)$,

3. and $x^* = y^*$.

Note that in this definition we have added leisure. Now, let's look at the Social Planner's Problem of the one-sector growth model:

$$\begin{aligned}
 & \max \sum_{t=0}^{\infty} \beta^t u(c_t, -x_{3t}) \quad (SPP) \\
 \text{s.t.} \quad & c_t + k_{t+1} - (1 - \delta)k_t = x_{1t} \\
 & -k_t \leq x_{2t} \leq 0 \\
 & -1 \leq x_{3t} \leq 0 \\
 & 0 \leq y_{1t} \leq F(-y_{2t}, -y_{3t}) \\
 & x = y \\
 & k_0 \text{ given.}
 \end{aligned}$$

Suppose we know that a solution in sequence space exists for (SPP) and it is unique.

Exercise 1 Clearly stating sufficient assumptions on utility and production function, show that (SPP) has a unique solution.

Two important theorems show the relationship between CE allocations and Pareto optimal allocations:

Theorem 1 (FWT) Suppose that for all $x \in X$ there exists a sequence $(x_k)_{k=0}^{\infty}$ such that for all $k \geq 0$, $x_k \in X$ and $U(x_k) > U(x)$. If (x^*, y^*, ν^*) is an Arrow-Debreu equilibrium, then (x^*, y^*) is a Pareto efficient allocation.

Theorem 2 (SWT) If X is convex, preferences are convex, U is continuous, Y is convex and has an interior point, then for any Pareto efficient allocation (x^*, y^*) there exists a continuous linear functional ν such that (x^*, y^*, ν) is a quasiequilibrium, that is:

- (i) for all $x \in X$ such that $U(x) \geq U(x^*)$ it implies $\nu(x) \geq \nu(x^*)$;
- (ii) for all $y \in Y$, $\nu(y) \leq \nu(y^*)$.

Note that at the very basis of the CE definition and welfare theorems there is an implicit assumption of perfect commitment and perfect enforcement. Note also that the FWT implicitly assumes there is no externality or public goods (it achieves this implicit assumption by defining a consumer's utility function only on his own consumption set but no other points in the commodity space). The Greenwald-Stiglitz (1986) theorem establishes the Pareto inefficiency of market economies with imperfect information and incomplete markets.

From the FWT, we know that if a Competitive Equilibrium exists, it is Pareto Optimal. Moreover, if the assumptions of the SWT are satisfied and if the (SPP) has a unique solution, then the competitive equilibrium allocation is unique and is the same as the Pareto Optimal allocation. Prices can then be constructed using this allocation and first-order conditions.

Exercise 2 *Show that*

$$\frac{v_{2t}}{v_{1t}} = F_k(k_t, l_t) \text{ and } \frac{v_{3t}}{v_{1t}} = F_l(k_t, l_t).$$

One shortcoming of the Arrow-Debreu Equilibrium (ADE) is that all trade occurs at the beginning of time. This assumption is unrealistic. Modern economics is based on sequential markets. Therefore, we define another equilibrium concept, the Sequential Markets Equilibrium (SME). We can easily show that SME is equivalent to ADE by introducing Arrow-Debreu securities. All of our results still hold and SME is therefore the right problem to solve.

Exercise 3 *Define a Sequential Markets Equilibrium (SME) for the economy above. Prove that the objects we get from the AD equilibrium satisfy SME conditions and that the converse is also true. We should first show that a CE exists and therefore coincides with the unique solution of (SPP).*

Note that the (SPP) is hard to solve since we are dealing with an infinite number of choice variables. Instead, we can establish that this SPP problem is equivalent to the following dynamic problem (removing

leisure from now on), which is easier to solve:

$$\begin{aligned} v(k) &= \max_{c, k'} u(c) + \beta v(k') && (RSPP) \\ \text{s.t.} & \quad c + k' = f(k). \end{aligned}$$

2.2 A Comment on the Welfare Theorems

Situations in which the welfare theorems would not hold include externalities, public goods, situations in which agents are not price-takers (e.g. monopolies), some legal systems, when markets are missing, which could rule out certain contracts that appear to be complete, or search frictions. What happens in such situations? The solutions to the Social Planner problem and the CE do not coincide, and so we cannot use the welfare theorems we have developed for dynamic programming. As we will see in this course, we can work with Recursive Competitive Equilibria. In general, we can prove that the solution to the RCE coincides with the one derived from the SME, but not the other way around (for example when we have multiple equilibria). However, in all the models we will see in this course, this equivalence will hold.

3 Recursive Competitive Equilibrium

3.1 A Simple Example

We have so far established the equivalence between the allocation of the SP problem, which gives the unique Pareto optimal allocation, and the allocations of the AD equilibrium and the SME. We can now solve for the very complicated equilibrium allocation by solving the relatively easier Dynamic Programming problem of the social planner. One handicap of this approach is that in many environments the equilibrium is not Pareto Optimal and hence not a solution of a social planner's problem (e.g. when taxes are distortionary or when externalities are present). Therefore, the recursive formulation of the

problem (RSPP) would not be the right problem to solve. In some of these situations we can still write the problem in sequence form. However, we would lose the powerful computational techniques of dynamic programming. In order to resolve this issue we will define the Recursive Competitive Equilibrium equivalent to SME that we can always solve for.

We start with the household's problem. In order to write it recursively, we need to use equilibrium conditions that tells the household what prices are, in particular as functions of economy-wide aggregate state variables. Let aggregate capital be K and aggregate labor $N = 1$. Then from solving the firm's problem, factor prices are given by $w(K) = F_n(K, 1)$ and $R(K) = F_k(K, 1)$. Therefore, since households take prices as given, they need to know aggregate capital in order to make their decisions. A household who is choosing how much to consume and how much to work has to know the whole sequence of future prices in order to make her decision. That means that she needs to know the path of aggregate capital. Therefore, if she believes that aggregate capital changes according to the mapping G , such that $K' = G(K)$, then knowing aggregate capital today enables her to project the path of aggregate capital into the future and thus the path for prices. So, we can write the household's recursive problem given function $G(\cdot)$ as follows:

$$\begin{aligned}
 V(K, a; G) &= \max_{c, a'} u(c) + \beta V(K', a'; G) && (RCE) \\
 \text{s.t. } c + a' &= w(K) + R(K)a \\
 K' &= G(K), \\
 c &\geq 0
 \end{aligned}$$

The dynamic programming problem above is for a household that sees K in the economy, has a belief G about its evolution, and carries a units of assets from the past. The price functions $w(K), R(K)$ are obtained from the firm's FOCs. The solution of this problem yields policy functions $c(K, a; G)$ for consumption and $g(K, a; G)$ for next period asset holdings, as well as a value function $V(K, a; G)$,

which must satisfy

$$\begin{aligned} u_c(c(K, a; G)) &= \beta V_{a'}(G(K), g(K, a; G); G) \\ V_a(K, a; G) &= R(K) u_c(c(K, a; G)) \end{aligned}$$

Now we can define the Recursive Competitive Equilibrium.

Definition 2 *A Recursive Competitive Equilibrium with arbitrary expectations G is a set of functions $V, g : \mathcal{K} \times \mathcal{A} \rightarrow \mathbb{R}$, and $R, w, G : \mathcal{K} \rightarrow \mathbb{R}_+$ such that:*²

1. Given G, w, R, V and g solve the household's problem in (RCE),
2. $K' = G(K) = g(K, K; G)$ (representative agent condition),
3. $w(K) = F_n(K, 1)$, and
4. $R(K) = F_k(K, 1)$.

Note that G represents some arbitrary expectations and do not have to necessarily be rational. Next, we define another notion of equilibrium in which the expectations of the household are consistent with what happens in the economy:

Definition 3 *A Rational Expectations Recursive Competitive Equilibrium (REE) is a set of functions V, g, R, w, G^* , such that:*

1. Given $w, R, V(K, a; G^*)$ and $g(K, a; G^*)$ solve the household's problem in (RCE),
2. $K' = G^*(K) = g(K, K; G^*)$,
3. $w(K) = F_n(K, 1)$, and
4. $R(K) = F_k(K, 1)$.

² Note that we could add the policy function for consumption $c(K, a; G)$.

What this means is that in a REE households optimize given what they believe is going to happen in the future and what happens in the aggregate is consistent with the households' decision. The proof that every REE can be used to construct a SME is left as an exercise. The reverse turns out not to be true. Notice that in a REE, function G^* projects next period's aggregate capital. If there is a multiplicity of SME, this would imply that we cannot construct such function G^* , since one value of capital today could imply more than one value of capital tomorrow, i.e. G^* is not a correspondence. From now on, we will focus on REE unless otherwise stated because it helps us select an equilibrium in case more than one exists.

Remark 1 *Note that unless otherwise stated, we will assume that the capital depreciation rate δ is 1, with the firm's profits given by $F(K, 1) - (r(K) + \delta)K - w(K)$. $R(K)$ is the gross rate of return on capital, which is given by $R(K) = F_k(K, 1) + 1 - \delta$. The net rate of return on capital is $r(K) = F_k(K, 1) - \delta$.*

3.2 The Envelope Theorem and the Functional Euler equation

To solve for the RCE and, in particular, to derive the household's optimality conditions we use envelope theorem. This method is valid because of time consistency of consumption choice.

Take the household's problem given by

$$\begin{aligned} V(K, a) &= \max_{c, a'} u(c) + \beta V(K', a') \\ \text{s.t. } c + a' &= w(K) + R(K)a \\ K' &= G(K) \\ c &\geq 0 \end{aligned}$$

with decision rules for consumption and next period asset holdings given by $c = c(K, a)$ and $a' = g(K, a)$.

By taking the first-order conditions (assuming an interior solution since u is well behaved), we get:

$$-u_c(c) + \beta V_{a'}(K', a') = 0,$$

which evaluated at the optimum is

$$-u_c(w(K) + R(K)a - g(K, a)) + \beta V_{a'}(G(K), g(K, a)) = 0 \quad (1)$$

The problem with solving the functional Euler equation is that $V_{a'}$ is not known. However, we can write the value function as a function of current states and differentiate both sides with respect to a .³ Since the Euler equation holds for all (a, K) , we have

$$V(K, a) = u(w(K) + R(K)a - g(K, a)) + \beta V(G(K), g(K, a)) \quad (2)$$

and using the implicit function theorem we can get its derivative with respect to a :

$$V_a(K, a) = u_c(w(K) + R(K)a - g(K, a))R(K) + \frac{\partial g(K, a)}{\partial a} [-u_c(w(K) + R(K)a - g(K, a)) + \beta V_{a'}(G(K), g(K, a))] \quad (3)$$

The term in square brackets in the right hand side is the first-order condition (1) and hence it is zero. So equation (3) simplifies to $V_a(K, a) = u_c(w(K) + R(K)a - g(K, a))R(K)$. Note, however, that we need $V_{a'}(G(K), g(K, a))$ to find the optimal asset holdings allocation. We would need to follow the same procedure for $V(G(K), g(K, a))$, but since equation 1 holds for all (a, K) next period's Euler equation is $u_{c'}(w(G(K)) + R(G(K))g(K, a) - g(G(k), g(K, a))) = \beta V_{a''} [G(G(K)), g(G(K), g(K, a))]$. This in turn implies that $V_{a'}(G(K), g(K, a)) = u_{c'}(w(G(K)) + R(G(K))g(K, a) - g(G(k), g(K, a))) R(G(K))$.

³ Under some assumptions, V is differentiable. See p. 121 of Prof. Krueger's notes for details.

Finally, we can replace that in equation (1) and get the functional Euler equation

$$u_c(w(K) + R(K)a - g(K, a)) - \beta u_c'(w(G(K)) + R(G(K))g(K, a) - g(G(k), g(K, a))) R(G(K)) = 0 \quad (4)$$

To illustrate this point, consider an individual who wants to loose weight and decides whether to start diet or not. However, he would rather postpone diet for tomorrow and prefer to eat well today. Let 1 denotes that he obeys the diet restrictions and 0 otherwise. Let his preference ordering be given by:

1. (0, 1, 1, 1...)
2. (1, 1, 1, 1...)
3. (0, 0, 0, 0, ...)

Even though he promises himself that he will start diet tomorrow and chooses to eat well today, tomorrow he will face the same problem. So he will choose the same option again tomorrow. He will thus never start diet and will end up with his least preferred option: (0, 0, 0, 0, ...).

However, in our model that is not what happens. Agents' preferences are time consistent, so what an individual promises today has to be optimal for her tomorrow as well. And that is why we can use the envelope theorem.

3.3 Economies with Fiscal Policy

3.3.1 Lump-Sum Tax

The government levies each period T units of goods in a lump sum fashion and spends it in a public good, say, medals. Assume however that consumers do not care about medals. The household's

problem is

$$\begin{aligned}
 V(K, a) &= \max_{c, a'} u(c) + \beta V(K', a') \\
 \text{s.t. } c + a' &= w(K) + R(K)a - T \\
 K' &= G(K) \\
 c &\geq 0
 \end{aligned}$$

Let the solution of this problem be given by policy function $g_a(K, a; M, T)$ and value function $V(K, a; M, T)$. The equilibrium can be characterized by $G^*(K; M, T) = g_a(K, K; G^*, M, T)$ and $M^* = T$ (the government budget constraint is balanced period by period). We will write a complete definition of equilibrium for a version with government debt (below).

Exercise 4 Define the aggregate resource constraint as $C + K' + M = f(K, 1)$ for the planner. Show that the equilibrium is optimal when consumers do not care about medals.

Note that if households cared about medals, then the equilibrium would not necessarily be optimal. The social planner would equate the marginal utility of consumption and of medals, while the agent would not.

3.3.2 Labor Income Tax

We have an economy in which the government levies a tax on labor income in order to purchase medals. Medals are goods that provide utility to the consumers.

$$\begin{aligned}
 V(K, a) &= \max_{c, a'} u(c, M) + \beta V(K', a') \\
 \text{s.t. } c + a' &= (1 - \tau(K))w(K) + R(K)a \\
 K' &= G(K) \\
 c &\geq 0
 \end{aligned}$$

with $M = \tau(K)w(K)$ being the government budget constraint. Since leisure is not valued, the labor decision is trivial and there is not distortion from the introduction of taxes.

Exercise 5 *Suppose medals do not provide utility to agents but leisure does. Is the CE optimal? What if medals also provide utility?*

3.3.3 Capital Income Tax

Now let us look at an economy in which the government levies tax on capital in order to purchase medals. Medals provide utility to the consumers.

$$\begin{aligned}
 V(K, a) &= \max_{c, a'} u(c, M) + \beta V(K', a') \\
 \text{s.t.} \quad c + a' &= w(K) + a [1 + r(K) (1 - \tau(K))] \\
 K' &= G(K) \\
 c &\geq 0
 \end{aligned}$$

with $M = \tau(K)r(K)K$ and $R(K) = 1 + r(K)$. Now, the First Welfare Theorem is no longer applicable and the CE will therefore not be Pareto optimal anymore (if $\tau(K) > 0$ there will be a wedge, and the efficiency conditions will not be satisfied).

Exercise 6 *Derive the first order conditions in the above problem to see the wedge introduced by taxes.*

3.3.4 Taxes and Debt

Assume that the government can now issue debt and use taxes to finance its expenditures. Also assume that agents derive utility from these government expenditures.

A government policy consists of capital taxes, spending (medals) as well as bond issuance. When the

aggregate states are K and B , as you will see why, then a government policy (in a recursive world) is

$$\tau(K, B), M(K, B) \text{ and } B'(K, B).$$

For now, we shall assume these values are chosen so that the equilibrium exists. In this environment, debt issued is relevant for the household because it permits him to correctly infer the amount of taxes. Therefore the household needs to form expectations about the future level of debt from the government.

The government budget constraint now satisfies (with taxes on labor income):

$$B + M(K, B) = \tau(K, B)R(K)K + q(K, B)B'(K, B)$$

Notice that the household does not care about the composition of his portfolio as long as assets have the same rate of return, which is true because of the no arbitrage condition.

The problem of a household with assets a is given by:

$$\begin{aligned} V(K, B, a) &= \max_{c, a'} u(c, M(K, B)) + \beta V(K', B', a') \\ \text{s.t. } c + a' &= w(K) + aR(K)(1 - \tau(K, B)) \\ K' &= G(K, B) \\ B' &= H(K, B) \\ c &\geq 0 \end{aligned}$$

Let $g(K, B, a)$ be the policy function associated with this problem. Then, we can define a RCE as follows.

Definition 4 A Rational Expectations Recursive Competitive Equilibrium, given policies $M(K, B)$ and $\tau(K, B)$, is a set of functions V, g, G, H, w, q , and R , such that

1. Given w and R , V and g solve the household's problem,

2. Factor prices are paid their marginal productivities

$$w(K) = F_2(K, 1) \text{ and } R(K) = F_1(K, 1),$$

3. Household wealth = Aggregate wealth

$$g(K, B, K + q(K^-, B^-)B) = G(K, B) + q(K, B)H(K, B),$$

4. No arbitrage condition

$$\frac{1}{q(K, B)} = [1 - \tau(G(K, B), H(K, B))] R(G(K)),$$

5. Government's budget constraint holds

$$B + M(K, B) = \tau(K, B)R(K)K + q(K, B)H(K, B),$$

6. Government debt is bounded; i.e. \exists some \bar{B} , such that for all $K \in [0, \tilde{k})$ and $B \leq \bar{B}$, $H(K, B) \leq \bar{B}$.

4 Some Other Examples

4.1 A Few Popular Utility Functions

Consider the following three utility forms:

1. $u(c, c^-)$: this function is called *habit formation* utility function. The utility is increasing in consumption today, but decreasing in the deviations from past consumption (e.g. $u(c, c^-) = v(c) - (c - c^-)^2$). Under habit persistence, an increase in current consumption lowers the

marginal utility of consumption in the current period ($u''_{1,1} < 0$) and increases it in the next period ($u''_{1,2} > 0$). Intuitively, the more the agent eats today, the hungrier she will be tomorrow. The aggregate state in this setup is K , while the individual states are a and c^- .

Definition 5 *A Recursive Competitive Equilibrium is a set of functions V , g , G , w , and R , such that*

(a) *Given w and R , V and g solve the household's problem,*

(b) *Factor prices are paid their marginal productivities*

$$w(K) = F_2(K, 1) \text{ and } R(K) = F_1(K, 1),$$

(c) *Household wealth = Aggregate wealth*

$$g(K, K, F(G^{-1}(K), 1) - K) = G(K).$$

Exercise 7 *Is the equilibrium optimum in this case?*

2. $u(c, C^-)$: this form is called *catching up with Jones*. There is an externality from aggregate consumption to the agent's payoff. Intuitively, agents care about what their neighbors consume. The aggregate states in this case are K and C^- , while c^- is no longer an individual state.

Exercise 8 *How does the agent know C ?*

Exercise 9 *Is the equilibrium optimum in this case?*

3. $u(c, C)$: this form is called *keeping up with Jones*. The aggregate state is K and C is no longer a predetermined variable.

Exercise 10 *How does the agent know C ?*

Exercise 11 *Is the equilibrium optimum in this case?*

4.2 An Economy with Capital and Land

Consider an economy with capital and land but without labor. A firm in this economy buys and installs capital, and owns one unit of land that is used in production, according to the technology $F(K, L)$. In other words, a firm is a “chunk of land of area one” (e.g. farmland), in which it installs its own capital (e.g. tractors). The firm’s shares are traded in a stock market, which are bought by households.

A household’s problem in this economy is given by:

$$\begin{aligned} V(K, a) &= \max_{c, a'} u(c) + \beta V(K', a') \\ \text{s.t. } c + P(K)a' &= a [D(K) + P(K)] \\ K' &= G(K) \end{aligned}$$

where a are shares held by the household, $P(K)$ is their price, and $D(K)$ are dividends per share.

The firm’s problem is given by

$$\begin{aligned} \Omega(K, k) &= \max_{d, k'} d + q(K')\Omega(K', k') \\ \text{s.t. } f(k', 1) &= d + k' \\ K' &= G(K) \end{aligned}$$

Ω here is the *value of the firm*, measured in units of output today. The value of the firm tomorrow must be discounted into units of output today, which is done by the discount factor $q(K')$. Note that the firm needs to know K' , using the aggregate law of motion G to do so.

Definition 6 A Recursive Competitive Equilibrium consists of functions, V , Ω , h , g , d , q , D , P , and G so that:

1. Given prices, V and h solve the household’s problem,
2. Ω , g , and d solve the firm’s problem,

3. Representative household holds all shares of the firm

$$g(K, 1) = 1,$$

4. The capital of the firm when it is representative must equal the aggregate stock of capital

$$h(K, K) = G(K),$$

5. Value of a representative firm must equal its price and dividends

$$\Omega(K, K) = D(K) + P(K),$$

6. The dividends of the representative firm must equal aggregate dividends

$$d(K, K) = D(K)$$

Exercise 12 One condition is missing in the definition of the RCE above. Find it! [Hint: it relates the discount factor of the firm $q(G(K))$ with the price and dividends households receive ($P(K), P(G(K))$, and $D(G(K))$).]

Exercise 13 Define the RCE if a were savings paying $R(K)$ as opposed to shares of the firm.

5 Adding Heterogeneity

In the previous section we looked at situations in which recursive competitive equilibria (RCE) were useful. In particular these were situations in which the welfare theorems failed and so we could not use the standard dynamic programming techniques learned earlier. In this section we look at another way in which RCE are helpful, in particular in models with heterogeneous agents.

5.1 Heterogeneity in Wealth

First, let us consider a model in which we have two types of households that differ only in the amount of wealth they own. Say there are two types of agents, labeled type R (for rich) and P (for poor), of measure μ and $1 - \mu$ respectively. Agents are identical other than their initial wealth position and there is no uncertainty in the model. The problem of an agent with wealth a is given by

$$\begin{aligned} V(K^R, K^P, a) &= \max_{c, a'} u(c) + \beta V(K^{R'}, K^{P'}, a') \\ \text{s.t. } c + a' &= w(\mu K^R + (1 - \mu)K^P) + aR(\mu K^R + (1 - \mu)K^P) \\ K^{i'} &= G^i(K^R, K^P) \quad \text{for } i = R, P. \end{aligned}$$

Remark 2 Note that (in general) the decision rules of the two types of agents are not linear (even though they might be almost linear); therefore, we cannot add the two states, K^1 and K^2 , to write the problem with one aggregate state, in the recursive form.

Definition 7 A Recursive Competitive Equilibrium is a set of functions V , g , w , R , G^1 , and G^2 such that that:

1. Given prices, V solves the household's functional equation, with g as the associated policy function,
2. w and R are the marginal products of labor and capital, respectively (watch out for arguments!),
3. Consistency: representative agent conditions are satisfied, i.e.

$$g(K^R, K^P, K^R) = G^R(K^R, K^P),$$

and

$$g(K^R, K^P, K^P) = G^P(K^R, K^P).$$

Remark 3 Note that $G^R(K^R, K^P) = G^P(K^P, K^R)$ (look at the arguments carefully). Why? (How

are rich and poor different?)

Remark 4 *This is a variation of the simple neoclassical growth model. What does the neoclassical growth model say about inequality? In the steady state, the Euler equations for the two different types simplify to*

$$u'(c^{R*}) = \beta R u'(c^{R*}), \text{ and } u'(c^{P*}) = \beta R u'(c^{P*}).$$

and we thus have $\beta R = 1$, where

$$R = F_K(\mu K^{R*} + (1 - \mu)K^{P*}, 1).$$

Finally, by the household's budget constraint, we must have:

$$c^i + a^i = w + a^i R \quad \text{for } i = R, P$$

where $a^i = K^i$ by the representative agent's condition. Therefore, we have three equations (budget constraints and Euler equation) and four unknowns (a^{i*} and c^{i*} for $i = R, P$). This implies that this theory is silent about the distribution of wealth in the steady state!

This is an important implication of the aggregation property. In fact, in the neoclassical growth model with n agents that only differ in their initial endowments, with homothetic preferences, there is a continuum with dimension $n - 1$ of steady state wealth distributions.

As we will see throughout the course, heterogeneity will matter in various situations. In the setup we have discussed above, however, wealth heterogeneity did not matter. This aggregation property applied to our macroeconomic context (see Gorman's aggregation theorem for further details) states that if agents' individual savings decision is linear in their individual state (i.e. $g(K, a) = \mu^i(K) + \lambda(K)a$, with $\lambda(K)$ being the marginal propensity to save common to all agents) provided that they all have the same preferences, then aggregate capital can be expressed as the choice of a representative agent (with savings decision given by $g(K, K) = \bar{\mu}(K) + \lambda(K)K$).

Remark 5 Does this property hold when discount factors or coefficients of relative risk aversion are heterogeneous?

5.2 Heterogeneity in Skills

Now, consider a slightly different economy in which type i has labor skill ϵ_i . Measures of agents' types, μ^1 and μ^2 , satisfy $\mu^1\epsilon_1 + \mu^2\epsilon_2 = 1$ (below we will consider the case in which $\mu^1 = \mu^2 = 1/2$).

The question we have to ask ourselves is: would the value functions of the two types remain the same, as in the previous subsection? The answer turns out to be no!

The problem of the household $i \in \{1, 2\}$ can be written as follows:

$$\begin{aligned} V^i(K^1, K^2, a) &= \max_{c, a'} u(c) + \beta V^i(K^{1'}, K^{2'}, a') \\ \text{s.t. } c + a' &= w \left(\frac{K^1 + K^2}{2} \right) \epsilon_i + aR \left(\frac{K^1 + K^2}{2} \right) \\ K^{i'} &= G^i(K^1, K^2) \quad \text{for } i = 1, 2. \end{aligned}$$

Notice that we have indexed the value function by the agent's type and thus the policy function is also indexed by i . The reason is that the marginal product of the labor supplied by each of these types is different (think of $w^i \left(\frac{K^1 + K^2}{2} \right) = w \left(\frac{K^1 + K^2}{2} \right) \epsilon_i$).

Exercise 14 Define the RCE.

Remark 6 *We can also rewrite this problem as*

$$\begin{aligned}
 V^i(K, \lambda, a) &= \max_{c, a'} \{u(c) + \beta V^i(K', \lambda', a')\} \\
 \text{s.t. } c + a' &= R(K)a + W(K)\epsilon_i \\
 K &= G(K, \lambda) \\
 \lambda' &= H(K, \lambda),
 \end{aligned}$$

where K is the total capital in this economy, and λ is the share of one type in total wealth (e.g. type 1).

Then, if g^i is the policy function of type i , then the consistency conditions of the RCE must be:

$$G(K, \lambda) = \frac{1}{2} [g^1(K, \lambda, 2\lambda K) + g^2(K, \lambda, 2(1 - \lambda)K)],$$

and

$$H(K, \lambda) = \frac{g^1(K, \lambda, 2\lambda K)}{2G(K, \lambda)}.$$

5.3 An International Economy Model

In an international economy model the definition of country is an important one. We can introduce the idea of different locations or geography, countries can be victims of different policies, trade across countries maybe more difficult due to different restrictions.

Here we will focus on a model with two countries, 1 and 2, where labor is not mobile between the countries, but capital markets perfect and thus investment can flow freely across countries. However, in order to use it in production, it must have been installed in advanced. Traded goods flow within the period.

The aggregate resource constraint is:

$$C^1 + C^2 + K^{1'} + K^{2'} = F(K^1, 1) + F(K^2, 1)$$

Suppose that there is a mutual fund that owns the firms in each country and chooses labor in each country and capital to be installed. Its shares are traded in the market and thus, as in the economy with capital and land, individuals own shares of this mutual fund.

The first question to ask, as usual, is *what are the appropriate states in this world?* As it is apparent from the resource constraint and production functions, we need the capital in each country. Moreover, we need to know total wealth in each country. Therefore, we need an additional variable as the aggregate state: the shares owned by country 1 is a sufficient statistic.

We can then write the country i 's household problem as:

$$\begin{aligned} V^i(K^1, K^2, A, a) &= \max_{c, a'(z)} u(c) + \beta V^i(K^{1'}, K^{2'}, A', a') \\ \text{s.t. } c + Q(K^1, K^2, A)a' &= w^i(K^i) + a\Phi(K^1, K^2, A) \\ K^{i'} &= G^i(K^1, K^2, A), \quad \text{for } i = 1, 2 \\ A' &= H(K^1, K^2, A) \end{aligned}$$

where A is the total amount of shares in the mutual fund that individuals in country 1 own and a is the amount of shares that an individual owns in country i .

Since labor is immobile and capital is installed in advanced, the wage is country-specific and is simply given by the marginal product of labor: $w^i(K^i) = F_N^i(K^i, 1)$.

Now let's look at the problem of the mutual fund:

$$\begin{aligned} \Phi(K^1, K^2, A, k^1, k^2) &= \max_{k^{1'}, k^{2'}, n^1, n^2} \sum_i \left[F^i(k^i, n^i) - n^i w^i(K_i) - k^{i'} \right] + \\ &\quad \frac{1}{R(K^{1'}, K^{2'}, A)} \Phi(K^{1'}, K^{2'}, A', k^{1'}, k^{2'}) \\ \text{s.t.} \quad K^{i'} &= G^i(K^1, K^2, A), \quad \text{for } i = 1, 2 \\ A' &= H(K^1, K^2, A) \end{aligned}$$

Definition 8 A Recursive Competitive Equilibrium for the (world's) economy is a list of functions, $\{V^i, h^i, g^i, n^i, w^i, G^i\}_{i=1,2}$, Φ , H , Q , and R , such that the following conditions hold:

1. Given prices and aggregate laws of motion, V^i and h^i solve the household's problem in country i (for $i \in \{1, 2\}$),
2. Given prices and aggregate laws of motion, Φ , $\{g^i, n^i\}_{i=1,2}$ solve the mutual fund problem,
3. Labor markets clear

$$n^i(K^1, K^2, A, K^1, K^2) = 1 \quad \text{for } i = 1, 2,$$

4. Consistency (MF)

$$g^i(K^1, K^2, A, K^1, K^2) = G^i(K^1, K^2, A) \quad \text{for } i = 1, 2,$$

5. Consistency (Households)

$$h^1(K^1, K^2, A, A) = H(K^1, K^2, A)$$

and

$$h^1(K^1, K^2, A, A) + h^2(K^1, K^2, A, 1 - A) = 1$$

6. No arbitrage

$$Q(K^1, K^2, A) = \frac{1}{R(K^{1'}, K^{2'}, A')} \Phi(K^{1'}, K^{2'}, A', K^{1'}, K^{2'})$$

Exercise 15 Solve for the mutual fund's decision rules. Is next period capital in each country chosen by the mutual fund priced differently? What about labor?

6 Stochastic Economies

6.1 A Review

6.1.1 Markov Processes

From now on, we will focus on stochastic economies, in which productivity shocks affects the economy. The stochastic process for productivity that we assume is a first-order Markov Process that takes on a finite number of values in the set $Z = \{z^1 < \dots < z^{n_z}\}$. A first order Markov process implies

$$\Pr(z_{t+1} = z^j | h_t) = \Gamma_{ij}, \quad z_t(h_t) = z^i$$

where h_t is the history of previous shocks. Γ is a Markov chain with the property that the elements of each rows sum to 1.

Let μ be a probability distribution over initial states, i.e.

$$\sum_i \mu_i = 1$$

and $\mu_i \geq 0 \forall i = 1, \dots, n_z$.

For next periods the probability distribution can be found by $\mu' = \Gamma^T \mu$.

If Γ is "nice" then \exists a unique μ^* s.t. $\mu^* = \Gamma^T \mu^*$ and $\mu^* = \lim_{m \rightarrow \infty} (\Gamma^T)^m \mu_0, \forall \mu_0 \in \Delta^i$.

Γ induces the following probability distribution conditional on the initial draw z_0 on $h_t = \{z^0, z^1, \dots, z^t\}$:

$$\Pi(\{z^0, z_1\}) = \Gamma_{i,\cdot} \quad \text{for } z^0 = z_i.$$

$$\Pi(\{z^0, z_1, z_2\}) = \Gamma^T \Gamma_{i,\cdot} \quad \text{for } z^0 = z_i.$$

Then, $\Pi(h_t)$ is the probability of history h_t conditional on z^0 . The expected value of z' is $\sum_{z'} \Gamma_{zz'} z'$ and $\sum_{z'} \Gamma_{zz'} = 1$.

6.1.2 Problem of the Social Planner

Let productivity affect the production function in a multiplicative fashion; i.e. technology is $zF(K, N)$, where z is a shock that follows a Markov chain on a finite state-space. Recall that the problem of the social planner problem (SPP) in sequence form is

$$\begin{aligned} \max_{\{c_t(z^t), k_{t+1}(z^t)\} \in X(z^t)} & \sum_{t=0}^{\infty} \sum_{z^t} \beta^t \pi(z^t) u(c_t(z^t)) \\ \text{s.t.} & c_t(z^t) + k_{t+1}(z^t) = z_t F(k_t(z^{t-1}), 1), \end{aligned}$$

where z_t is the realization of the shock in period t , and z^t is the history of shocks up to (and including) time t . $X(z^t)$ is similar to the consumption possibility set defined earlier but this is after history z^t has occurred and is for consumption and next period capital.

We can then formulate the stochastic SPP in a recursive fashion as

$$\begin{aligned} V(z_i, K) = \max_{c, K'} & \left\{ u(c) + \beta \sum_j \Gamma_{ij} V(z_j, K') \right\} \\ \text{s.t.} & c + K' = z_i F(K, 1), \end{aligned}$$

where Γ is the Markov transition matrix. The solution to this problem gives us a policy function of the form $K' = G(z, K)$.

In a decentralized economy, the Arrow-Debreu equilibrium can be defined by:

$$\begin{aligned} & \max_{\{c_t(z^t), k_{t+1}(z^t), x_{1t}(z^t), x_{2t}(z^t), x_{3t}(z^t)\} \in X(z^t)} \sum_{t=0}^{\infty} \sum_{z^t} \beta^t \pi(z^t) u(c_t(z^t)) \\ & \text{s.t.} \quad \sum_{t=0}^{\infty} \sum_{z^t} p_t(z^t) \cdot x_t(z^t) \leq 0, \end{aligned}$$

where $X(z^t)$ is again a variant of the consumption possibility set after history z^t has occurred. Ignore the overloading of notation. Note that we are assuming the markets are dynamically complete; i.e. there is a complete set of securities for every possible history.

By the same procedure as before, the SME can be written in the following way:

$$\begin{aligned} & \max_{\{c_t(z^t), b_{t+1}(z^t, z_{t+1}), k_{t+1}(z^t)\}} \sum_{t=0}^{\infty} \sum_{z^t} \beta^t \pi(z^t) u(c_t(z^t)) \\ & \text{s.t.} \quad c_t(z^t) + k_{t+1}(z^t) + \sum_{z_{t+1}} q_t(z^t, z_{t+1}) b_{t+1}(z^t, z_{t+1}) \\ & \quad \quad \quad = k_t(z^{t-1}) R_t(z^t) + w_t(z^t) + b_t(z^{t-1}, z_t) \\ & \quad \quad \quad b_{t+1}(z^t, z_{t+1}) \geq -B. \end{aligned}$$

To replicate the AD equilibrium, we have introduced Arrow securities to allow agents to trade with each other against possible future shocks.

Note that when there is no heterogeneity, there will be no trade in equilibrium, i.e. $b_{t+1}(z^t, z_{t+1}) = 0$ for any z^t, z_{t+1} . Moreover, we have two ways of delivering the goods specified in an Arrow security contract: *after production* and *before production*. In an after production setting, the goods will be delivered after production takes place and can only be consumed or saved for the next period. This is the above setting. It is also possible to allow the consumer to rent the Arrow security income as capital to firms, which will correspond to the before production setting.

An important condition that must hold true in the *before production setting* is the no-arbitrage condi-

tion:

$$\sum_{z_{t+1}} q_t(z^t, z_{t+1}) = 1$$

Exercise 16 Every equilibrium achieved in AD settings can also be achieved in a SM setting, by the relation where

$$q_t(z^t, z_{t+1}) = \frac{p_{1t+1}(z^t, z_{t+1})}{p_{1t}(z^t)},$$

$$R_t(z^t) = \frac{p_{2t}(z^t)}{p_{1t}(z^t)},$$

and

$$w_t(z^t) = \frac{p_{3t}(z^t)}{p_{1t}(z^t)}.$$

Check from the FOC's that the we get the same allocations in the two settings.

Exercise 17 The problem above assumes state contingent goods are delivered in terms of consumption goods. Instead of this assume they are delivered in terms of capital goods. Show that the same allocation would be achieved in both settings.

6.1.3 Recursive Competitive Equilibrium

Assume that households can trade state contingent assets, as in the sequential markets case above. Then, we can write a household's problem in recursive form as:

$$\begin{aligned}
 V(K, z, a) &= \max_{c, k', b'(z')} u(c) + \beta \sum_{z'} \Gamma_{zz'} V(K', z', a'(z')) \\
 \text{s.t.} \quad &c + k' + \sum_{z'} q(K, z; z') b'(z') = w(K, z) + aR(K, z) \\
 &K' = G(K, z) \\
 &a'(z') = k' + b'(z').
 \end{aligned}$$

Exercise 18 Write the FOC's for this problem, given prices and the law of motion for aggregate capital.

Definition 9 A Recursive Competitive Equilibrium is a collection of functions V , g^k , g^b , w , R , $q_{z'}$, and G so that

1. Given G , w , and R , V solves the household's functional equation, with g^k and g^b as the associated policy function,
2. $g^b(K, z, K; z') = 0$, for all z' ,
3. $g^k(K, z, K) = G(K, z)$,
4. $w(K, z) = zF_n(K, 1)$ and $R(K, z) = zF_k(K, 1)$,
5. and $\sum_{z'} q(K, z; z') = 1$.

The last condition is known as the no-arbitrage condition (recall that we had this equation in the case of sequential markets as well). To see why this is a necessary equation in the equilibrium, note that an agent can either save in the form of capital or through Arrow securities. However, these two choices must cost the same, which implies Condition 5 above.

Remark 7 Note that in the SME version of the household problem, in order for households not to achieve infinite consumption, we need a no-Ponzi condition. Such condition is

$$\lim_{t \rightarrow \infty} \frac{a_t}{\prod_{s=0}^t R_s} < \infty.$$

This is the weakest condition that imposes no restrictions on the first order conditions of the household's problem. It is harder to come up with its analogue for the recursive case. One possibility is to assume that a' lies in a compact set \mathcal{A} , or a set that is bounded from below.⁴

6.2 A Stochastic International Economy Model

We revisit the international economy model studied before and we now add country-specific shocks. Let z_1 and z_2 represent productivity shocks in country 1 and 2, respectively. The aggregate state variables are now the productivity shocks, the aggregate stocks of capital in each country, and the amount of shares owned by country 1 in the mutual fund.

The problem of a household in country i is:

$$\begin{aligned} V^i(\vec{z}, \vec{K}, A, a) &= \max_{c, a'(\vec{z}')} u(c) + \beta \sum_{\vec{z}'} \Gamma_{\vec{z}\vec{z}'} V^i(\vec{z}', \vec{K}', A'(\vec{z}'), a'(\vec{z}')) \\ \text{s.t.} \quad c + \sum_{\vec{z}'} q(\vec{z}, \vec{K}, A; \vec{z}') a'(\vec{z}') &= w^i(z_i, K_i) + a\Phi(\vec{z}, \vec{K}, A) \\ K'_i &= G_i(\vec{z}, \vec{K}, A), \quad \text{for } i = 1, 2 \\ A'(\vec{z}') &= H(\vec{z}, \vec{K}, A; \vec{z}') \quad \forall \vec{z}' \end{aligned}$$

Let decision rule for next period asset holdings be $a'(\vec{z}') = h(\vec{z}, \vec{K}, A, a; \vec{z}') \quad \forall \vec{z}'$. Note the financial market structure assumed here. The agent is fully insured against all possible states of the world. As before, labor is immobile and thus wages are country-specific and given by $w^i(z_i, K_i) = z_i F_N(K_i, 1)$.

⁴ We must specify \mathcal{A} such that the borrowing constraint implicit in \mathcal{A} is never binding.

Exercise 19 Write this economy with state-contingent claims in own country only.

Exercise 20 Write this economy where individuals can move freely in advance, but with incomplete markets.

Now let's look at the net present value of the mutual fund in equilibrium:

$$\Phi(\vec{z}, \vec{K}, A) = \sum_{z_i} [z_i F(K_i, 1) - w^i(z_i, K_i)] - \sum_i G_i(\vec{z}, \vec{K}, A) + \sum_{\vec{z}'} \Gamma_{\vec{z}\vec{z}'} Q(\vec{z}', G(\vec{z}, \vec{K}, A), H(\vec{z}, \vec{K}, A; \vec{z}')) \Phi(\vec{z}', G(\vec{z}, \vec{K}, A), H(\vec{z}, \vec{K}, A; \vec{z}')) \quad (5)$$

where Q (or $\frac{1}{R}$) represents intertemporal prices, which in equilibrium should satisfy $\forall \vec{z}'$:

$$q(\vec{z}, \vec{K}, A; \vec{z}') = \Gamma_{\vec{z}\vec{z}'} Q(\vec{z}', G(\vec{z}, \vec{K}, A), H(\vec{z}, \vec{K}, A; \vec{z}')) \Phi(\vec{z}', G(\vec{z}, \vec{K}, A), H(\vec{z}, \vec{K}, A; \vec{z}'))$$

Exercise 21 There is one more condition for G_i that equates expected return in each country. What is it?

Definition 10 A Recursive Competitive Equilibrium for the (world's) economy is a set of functions V^i , $h_{\vec{z}}^i$, Φ , w^i , Q , $q_{\vec{z}}$, G_i , and H , for $i \in \{1, 2\}$, such that the following conditions hold:

1. Given prices and laws of motion, V^i and h^i solve the household's problem in country i for $i \in \{1, 2\}$,
2. The mutual fund's value Φ satisfies equation 5
3. $w^i(z_i, K_i)$ is equated to the marginal products of labor in each country i for $i \in \{1, 2\}$
4. The expected rates of return on capital is equalized across countries
5. The market for shares in the mutual fund clears

$$h^1(\vec{z}, \vec{K}, A, A; \vec{z}') + h^2(\vec{z}, \vec{K}, A, 1 - A; \vec{z}') = 1 \quad \forall \vec{z}'$$

6. The representative agent condition must hold

$$h^1(\vec{z}, \vec{K}, A, A; \vec{z}') = H(\vec{z}, \vec{K}, A, A; \vec{z}') \quad \forall \vec{z}'$$

7. No arbitrage

$$q(\vec{z}, \vec{K}, A; \vec{z}') = \Gamma_{\vec{z}\vec{z}'} Q(\vec{z}', G(\vec{z}, \vec{K}, A), H(\vec{z}, \vec{K}, A; \vec{z}')) \Phi(\vec{z}', G(\vec{z}, \vec{K}, A), H(\vec{z}, \vec{K}, A; \vec{z}')) \quad \forall \vec{z}'$$

8. The aggregate resource constraint must hold:

$$\sum_i \left[z_i F(K_i, 1) - G_i(\vec{z}, \vec{K}, A) - \left(w^i(z_i, K_i) + A_i \Phi(\vec{z}, \vec{K}, A) - \sum_{\vec{z}'} q(\vec{z}, \vec{K}, A; \vec{z}') h^i(\vec{z}, \vec{K}, A, A_i; \vec{z}') \right) \right] = 0$$

where $A_1 = A$ and $A_2 = 1 - A$.

6.3 Heterogeneity in Wealth and Skills with Complete Markets

Now, let us consider a model in which we have two types of households, with equal measure $\mu_i = 1/2$, that care about leisure, but differ in the amount of wealth they own as well as their labor skill. There is also uncertainty and Arrow securities like we have seen before.

Let A^1 and A^2 be the aggregate asset holdings of the two types of agents. These will now be state variables for the same reason K^1 and K^2 were state variables earlier. The problem of an agent $i \in \{1, 2\}$

with wealth a is given by

$$\begin{aligned}
V^i(z, A^1, A^2, a) &= \max_{c, n, a'(z')} u(c, n) + \beta \sum_{z'} \Gamma_{zz'} V^i(z', A^1(z'), A^2(z'), a'(z')) \\
\text{s.t.} \quad c + \sum_{z'} q(z, A^1, A^2, z') a'(z') &= R(z, K, N) a + W(z, K, N) \epsilon_i n \\
A^i(z') &= G^i(z, A^1, A^2, z'), \quad \text{for } i = 1, 2, \forall z' \\
N &= H(z, A^1, A^2) \\
K &= \frac{A^1 + A^2}{2}.
\end{aligned}$$

Let $g^i(z, A^1, A^2, a^i)$ and $h^i(z, A^1, A^2, a^i)$ be the asset and labor policy functions be the solution of each type i to this problem. Then, we can define the RCE as below.

Definition 11 A Recursive Competitive Equilibrium with Complete Markets is a set of functions V^i , g^i , h^i , G^i for $i \in \{1, 2\}$, R , w , H , and q , such that:

1. Given prices and laws of motion, V^i , g^i and h^i solve the problem of household i for $i \in \{1, 2\}$,
2. Labor markets clear:
$$H(z, A^1, A^2) = \epsilon_1 h^1(z, A^1, A^2, A^1) + \epsilon_2 h^2(z, A^1, A^2, A^2),$$
3. The representative agent condition:
$$G^i(z, A^1, A^2, z') = g^i(z, A^1, A^2, A^i, z') \quad \text{for } i = 1, 2, \forall z'$$
4. The average price of the Arrow security must satisfy:
$$\sum_{z'} q(z, A^1, A^2, z') = 1,$$
5. $G^1(z, A^1, A^2, z') + G^2(z, A^1, A^2, z')$ is independent of z' (due to market clearing).
6. R and W are the marginal products of capital and labor.

Exercise 22 Write down the household problem and the definition of RCE with non-contingent claims instead of complete markets.

7 Asset Pricing: Lucas Tree Model

We now turn to the simplest of all models in term of allocations as they are completely exogenous, called the *Lucas tree model*. We want to characterize the properties of prices that are capable of inducing households to consume the stochastic endowment.

7.1 The Lucas Tree with Random Endowments

Consider an economy in which the only asset is a tree that gives fruit. The agent's problem is to choose consumption c and the amount of shares of the tree to hold s' according to

$$V(z, s) = \max_{c, s'} u(c) + \beta \sum_{z'} \Gamma_{zz'} V(z', s')$$
$$s.t. \quad c + p(z) s' = s [p(z) + d(z)],$$

where $p(z)$ is the price of the shares (to the tree), in state z , and $d(z)$ is the dividend associated with state z .

Definition 12 *A Rational Expectations Recursive Competitive Equilibrium is a set of functions, V , g , d , and p , such that*

1. V and g solves the household's problem given prices,
2. $d(z) = z$, and,
3. $g(z, 1) = 1$, for all z .

To explore the problem further, note that the FOC for the household's problem imply the equilibrium condition

$$u_c(c(z, 1)) = \beta \sum_{z'} \Gamma_{zz'} \left[\frac{p(z') + d(z')}{p(z)} \right] u_c(c(z', 1)).$$

where we have $u_c(z) := u_c(c(z, 1))$. Then this simplifies to

$$p(z) u_c(z) = \beta \sum_{z'} \Gamma_{zz'} u_c(z') [p(z') + z'] \quad \forall z.$$

Exercise 23 Derive the Euler equation for household's problem to show the result above.

Note that this is just a system of n_z equations with unknowns $\{p(z_i)\}_{i=1}^n$. We can use the power of matrix algebra to solve the system. To do so, let:

$$\mathbf{p} := \begin{bmatrix} p(z_1) \\ \vdots \\ p(z_n) \end{bmatrix}_{(n_z \times 1)},$$

and

$$\mathbf{u}_c := \begin{bmatrix} u_c(z_1) & & 0 \\ & \ddots & \\ 0 & & u_c(z_n) \end{bmatrix}_{(n_z \times n_z)}.$$

Then

$$\mathbf{u}_c \cdot \mathbf{p} = \begin{bmatrix} p(z_1) u_c(z_1) \\ \vdots \\ p(z_n) u_c(z_n) \end{bmatrix}_{(n_z \times 1)},$$

and

$$\mathbf{u}_c \cdot \mathbf{z} = \begin{bmatrix} z_1 u_c(z_1) \\ \vdots \\ z_n u_c(z_n) \end{bmatrix}_{(n_z \times 1)},$$

Now, rewrite the system above as

$$\mathbf{u}_c \mathbf{p} = \beta \Gamma \mathbf{u}_c \mathbf{z} + \beta \Gamma \mathbf{u}_c \mathbf{p},$$

where Γ is the transition matrix for z , as before. Hence, the price for the shares is given by

$$(\mathbf{I}_{n_z} - \beta \Gamma) \mathbf{u}_c \mathbf{p} = \beta \Gamma \mathbf{u}_c \mathbf{z},$$

or

$$\mathbf{p} = ([\mathbf{I}_{n_z} - \beta \Gamma] \mathbf{u}_c)^{-1} \beta \Gamma \mathbf{u}_c \mathbf{z},$$

where \mathbf{p} is the vector of prices that clears the market.

Exercise 24 *How are prices defined when the agent faces taste shocks?*

7.2 Asset Pricing

Consider our simple model of Lucas tree with fluctuating output. What is the definition of an asset in this economy? It is “a claim to a chunk of fruit, sometime in the future.”

If an asset, a , promises an amount of fruit equal to $a_t(z^t)$ after history $z^t = (z_0, z_1, \dots, z_t)$ of shocks, after a set of (possible) histories in H , the price of such an entitlement in date $t = 0$ is given by:

$$p(a) = \sum_t \sum_{z^t \in H} q_t^0(z^t) a_t(z^t),$$

where $q_t^0(z^t)$ is the price of one unit of fruit after history z^t in today's “dollars”; this follows from a no-arbitrage argument. If we have the date $t = 0$ prices, $\{q_t\}$, as functions of histories, we can *replicate any possible asset by a set of state-contingent claims* and use this formula to price that asset.

To see how we can find prices at date $t = 0$, consider a world in which the agent wants to solve

$$\begin{aligned} \max_{c_t(z^t)} \quad & \sum_{t=0}^{\infty} \beta^t \sum_{z^t} \pi_t(z^t) u(c_t(z^t)) \\ \text{s.t.} \quad & \sum_{t=0}^{\infty} \sum_{z^t} q_t^0(z^t) c_t(z^t) \leq \sum_{t=0}^{\infty} \sum_{h^t} q_t^0(z^t) z_t. \end{aligned}$$

This is the familiar Arrow-Debreu market structure, where the household owns a tree, and the tree yields $z \in Z$ amount of fruit in each period. The FOC for this problem imply:

$$q_t^0(z^t) = \beta^t \pi_t(z^t) \frac{u_c(z_t)}{u_c(z_0)}.$$

This enables us to price the good in each history of the world and price any asset accordingly.

Comment 1 *What happens if we add state-contingent shares b into our recursive model? Then the agent's problem becomes:*

$$\begin{aligned} V(z, s, b) = \max_{c, s', b'(z')} \quad & u(c) + \beta \sum_{z'} \Gamma_{zz'} V(z', s', b'(z')) \\ \text{s.t.} \quad & c + p(z) s' + \sum_{z'} q(z, z') b'(z') = s[p(z) + z] + b. \end{aligned}$$

A characterization of q can be obtained by the FOC, evaluated at the equilibrium, and thus written as:

$$q(z, z') u_c(z) = \beta \Gamma_{zz'} u_c(z').$$

We can thus price all types of securities using p and q in this economy.

To see how we can price an asset given today's shock is z , consider *the option to sell it tomorrow* at price P as an example. The price of such an asset today is

$$\hat{q}(z, P) = \sum_{z'} q(z, z') \max\{P - p(z'), 0\},$$

where the agent has the option not to sell it. The American option to sell at price P either tomorrow

or the day after tomorrow is priced as:

$$\tilde{q}(z, P) = \sum_{z'} q(z, z') \max \{P - p(z'), \hat{q}(z', P)\}.$$

Similarly, an European option to buy the asset at price P the day after tomorrow is priced as:

$$\bar{q}(z, P) = \sum_{z'} \sum_{z''} \max \{p(z'') - P, 0\} q(z', z'') q(z, z').$$

Note that $R(z) = [\sum_{z'} q(z, z')]^{-1}$ is the gross risk free rate, given today's shock is z . The unconditional gross risk free rate is then given by $R^f = \sum_z \mu_z^* R(z)$ where μ^* is the steady-state distribution of the shocks.

The average gross rate of return on the stock market is $\sum_z \mu_z^* \sum_{z'} \Gamma_{zz'} \left[\frac{p(z') + z'}{p(z)} \right]$ and the risk premium is the difference between this rate and the unconditional gross risk free rate (i.e. given by $\sum_z \mu_z^* \left(\sum_{z'} \Gamma_{zz'} \left[\frac{p(z') + z'}{p(z)} \right] - R(z) \right)$).

Exercise 25 Use the expressions for p and q and the properties of the utility function to show that risk premium is positive.

7.3 Taste Shocks

Consider an economy in which the only asset is a tree that gives fruits. The fruit is constant over time (normalized to 1) but the agent is subject to preference shocks for the fruit each period given by $\theta \in \Theta$. The agent's problem in this economy is

$$\begin{aligned} V(\theta, s) = \max_{c, s'} & \theta u(c) + \beta \sum_{\theta'} \Gamma_{\theta\theta'} V(\theta', s') \\ \text{s.t.} & c + p(\theta) s' = s [p(\theta) + d(\theta)]. \end{aligned}$$

The equilibrium is defined as before. The only difference is that, now, we must have $d(\theta) = 1$ since z is normalized to 1. What does it mean that the output of the economy is constant (fixed at one), but the tastes for this output change? In this setting, the function of the price is to convince agents to keep their consumption constant even in the presence of taste shocks. All the analysis follows through as before once we write the FOC's characterizing the prices of shares, $p(\theta)$, and state-contingent prices $q(\theta, \theta')$.

This is a simple model, in the sense that the household does not have a real choice regarding consumption and savings. Due to market clearing, household consumes what nature provides her. In each period, according to the state of productivity z and taste θ , prices adjust such that household would like to consume z , which is the amount of fruit that the nature provides. In this setup, output is equal to z . If we look at the business cycle in this economy, the only source of output fluctuations is caused by nature. Everything determined by the supply side of the economy and the demand side has indeed no impact on output.

In next section, we are going to introduce search frictions to incorporate a role for the demand side into our model.

8 Endogenous Productivity in a Product Search Model

We will model the situation in which households need to find the fruit before consuming it.⁵ Assume that households have to find the tree in order to consume the fruit. Finding trees is characterized by a constant returns to scale (increasing in both arguments) matching function $M(T, D)$,⁶ where T is the *number of trees* in the economy and D is the aggregate *shopping effort* exerted by households when searching. The probability that a tree finds a shopper is given by $\frac{M(T, D)}{T}$, i.e. the total number of matches divided by the number of trees. The probability that a unit of shopping effort finds a tree is given by $\frac{M(T, D)}{D}$, i.e. the total number of matches divided by the economy's effort level.

⁵ Think of fields in *The Land of Apples*, full of apples, that are owned by firms; agents have to buy the apples. In addition, they have to search for them as well!

⁶ What does the fact that M is constant returns to scale imply?

Let's assume that $M(T, D)$ takes the form $D^\varphi T^{1-\varphi}$ and denote $\frac{1}{Q} := \frac{D}{T}$, i.e. the ratio of shoppers per trees, as capturing *the market tightness* (and thus $Q = \frac{T}{D}$). The probability of a household finding a tree is given by $\Psi^h(Q) := \frac{M(T,D)}{D} = Q^{1-\varphi}$ and thus the higher the number of people searching, the smaller the probability of a household finding a tree. The probability of a tree finding a household is then given by $\Psi^f(Q) := \frac{M(T,D)}{T} = Q^{-\varphi}$, and thus the higher the number of people searching, the higher the probability of a tree finding a shopper. Note that in this economy the number of trees is constant and equal to one.⁷

Let us assume households face a demand side shock θ and a supply side shock z . They are follow independent Markov processes with transitional probabilities $\Gamma_{\theta\theta'}$ and $\Gamma_{zz'}$, respectively. Households choose the consumption level c , the search effort exerted to get the fruit d , and the shares of the tree to hold next period s' . The household's problem can be written as

$$V(\theta, z, s) = \max_{c,d,s'} u(c, d, \theta) + \beta \sum_{\theta', z'} \Gamma_{\theta\theta'} \Gamma_{zz'} V(\theta', z', s') \quad (6)$$

$$s.t. \quad c + P(\theta, z) s' = P(\theta, z) \left[s \left(1 + \hat{R}(\theta, z) \right) \right] \quad (7)$$

$$c = d \Psi^h(Q(\theta, z)) z. \quad (8)$$

where P is the price of the tree relative to that of consumption and \hat{R} is the dividend income (in units of the tree). Note that the equation 7 is our standard budget constraint, while equation 8 corresponds to the shopping constraint.

Note some notation conventions here. $P(\theta, z)$ is in terms of consumption goods, while $\hat{R}(\theta, z)$ is in terms of shares of the tree (that's why we are using the hat). We could also write the household budget constraint in terms of the price of consumption relative to that of the tree. To do so, let's

⁷ It is easy to find the statements for Ψ^h and Ψ^f , given the Cobb-Douglas matching function:

$$\Psi^h(Q) = \frac{D^\varphi T^{1-\varphi}}{D} = \left(\frac{T}{D} \right)^{1-\varphi} = Q^{1-\varphi},$$

$$\Psi^f(Q) = \frac{D^\varphi T^{1-\varphi}}{T} = \left(\frac{T}{D} \right)^{-\varphi} = Q^{-\varphi}.$$

The question is: is Cobb-Douglas an appropriate choice for the matching function, or its choice is a matter of simplicity?

define $\hat{P}(\theta, z) = \frac{1}{P(\theta, z)}$ as the price of consumption goods in terms of the tree. Then the budget constraint can be defined as:

$$c\hat{P}(\theta, z) + s' = s \left(1 + \hat{R}(\theta, z)\right)$$

Let's maintain our notation with $P(\theta, z)$ and $\hat{R}(\theta, z)$ from now on. We can substitute the constraints into the objective and solve for d in order to get the Euler equation for the household. Using the market clearing condition in equilibrium, the problem reduces to one equation and two unknowns, $P(\theta, z)$ and $Q(\theta, z)$ (other objects, C, D and \hat{R} are known functions of P and Q , and the amount shares of the tree in equilibrium is 1 as before). We thus still need another functional equation to solve for the equilibrium of this economy, i.e. we need to specify the search protocol. We now turn to one way of doing so.

Exercise 26 *Derive the Euler equation of the household from the problem defined above.*

8.1 Competitive Search

Competitive search is a particular search protocol of what is called non-random (or directed) search. To understand this protocol, consider a world consisting of a large number of islands. Each island has a sign that displays two numbers, $P(\theta, z)$ and $Q(\theta, z)$. $P(\theta, z)$ is the price on the island and $Q(\theta, z)$ is a measure of market tightness in that island (or if the price is a wage rate W , then Q is the number of workers on the island divided by the number of job opportunities in that island). Both individuals and firms have to decide to go to one island. For instance, in an island with a higher wage, the worker might have a higher income conditional on finding a job. However, the probability of finding a job might be low on that island given the tightness of the labor market on that island. The same story holds for the job owners, who are searching to hire workers.

In our economy, both firms and workers search for specific markets indexed by price P and a market tightness Q .⁸ An island, or a pair of (P, Q) , is operational if there exists some consumer and firm

⁸ From now on, we will drop the arguments of P and Q .

choosing that market. Therefore, an agent should choose P and Q such that it gives sufficient profit to the firm, so that it wants to be in that island as opposed to doing something else, which will be determined in the equilibrium. Competitive search is magic in the sense that it does not presuppose a particular pricing protocol that other search protocols need (e.g. bargaining).

Maintaining the demand shock θ and supply side shock z we introduced before, we can then define the household problem with competitive search as follows

$$V(\theta, z, s) = \max_{c, d, s', P, Q} u(c, d, \theta) + \beta \sum_{\theta', z'} \Gamma_{\theta\theta'} \Gamma_{zz'} V(\theta', z', s') \quad (9)$$

$$s.t. \quad c + Ps' = P \left[s \left(1 + \hat{R}(\theta, z) \right) \right], \quad (10)$$

$$c = d \Psi^h(Q) z \quad (11)$$

$$\frac{z \Psi^f(Q)}{P} \geq \hat{R}(\theta, z) \quad (12)$$

Let $u(c, d, \theta) = u(\theta c, d)$ from here on. The first two constraints were defined above, while the last is the firm's participation constraint, which is the condition that states that firms would prefer this market to other markets in which they would get $\hat{R}(\theta, z)$.

To solve the problem, let's take the first order conditions. One way to do this is to first plug the first two constraints into the objective function (expressing c and s' as functions of d) and then take the derivative with respect to d (recall that $\Psi^h = Q^{1-\varphi}$) to get:

$$\begin{aligned} \theta Q^{1-\varphi} z u_c(\theta d Q^{1-\varphi} z, d) + u_d(\theta d Q^{1-\varphi} z, d) = \\ \beta \sum_{\theta', z'} \Gamma_{\theta\theta'} \Gamma_{zz'} V_3 \left(\theta', z', s(1 + \hat{R}(\theta, z)) - \frac{d Q^{1-\varphi} z}{P} \right) \frac{Q^{1-\varphi} z}{P} \quad (13) \end{aligned}$$

To find V_3 consider the original problem where constraints are not plugged into the objective function.

Using the envelope theorem we get:

$$V_3(\theta, z, s) = \left[\theta u_c(\theta d Q^{1-\varphi} z, d) + \frac{u_d(\theta d Q^{1-\varphi} z, d)}{Q^{1-\varphi} z} \right] P(1 + \hat{R}(\theta, z))$$

Combining these two gives the Euler equation:

$$\theta u_c(\theta d Q^{1-\varphi} z, d) + \frac{u_d(\theta d Q^{1-\varphi} z, d)}{Q^{1-\varphi} z} = \beta \sum_{\theta', z'} \Gamma_{\theta\theta'} \Gamma_{zz'} \frac{P'(1 + \hat{R}(\theta', z'))}{P} \left[\theta' u_c(\theta' d' Q'^{1-\varphi} z', d') + \frac{u_d(\theta' d' Q'^{1-\varphi} z', d')}{Q'^{1-\varphi} z'} \right] \quad (14)$$

Observe that this equation is the same as the Euler equation from the random search model. This gives us the optimal search and saving behavior for a given island (i.e. a market tightness $1/Q$ and price level P). To understand which market to search in, we need to look at the FOC with respect to Q and P . Let λ denote the Lagrange multiplier on the firm's participation constraint, then the FOC with respect to Q and P are respectively:

$$\theta d(1 - \varphi) Q^{-\varphi} z u_c(\theta d Q^{1-\varphi} z, d) = \beta \sum_{\theta', z'} \Gamma_{\theta\theta'} \Gamma_{zz'} V_3 \left(\theta', z', s(1 + \hat{R}(\theta, z)) - \frac{d Q^{1-\varphi} z}{P} \right) \frac{d(1 - \varphi) Q^{-\varphi} z}{P} - \lambda \frac{\varphi Q^{-\varphi-1} z}{P} \quad (15)$$

and

$$\beta \sum_{\theta', z'} \Gamma_{\theta\theta'} \Gamma_{zz'} V_3 \left(\theta', z', s(1 + \hat{R}(\theta, z)) - \frac{d Q^{1-\varphi} z}{P} \right) dQ = -\lambda \quad (16)$$

Combining these two equation gives us:

$$\theta u_c(\theta d Q^{1-\varphi} z, d) = \beta \sum_{\theta', z'} \Gamma_{\theta\theta'} \Gamma_{zz'} V_3 \left(\theta', z', s(1 + \hat{R}(\theta, z)) - \frac{d Q^{1-\varphi} z}{P} \right) \left[\frac{1}{(1 - \varphi)P} \right] \quad (17)$$

Recall that we had defined $V_3(\cdot, \cdot, \cdot)$ above and thus this Euler equation simplifies to

$$(1-\varphi)\theta u_c(\theta d Q^{1-\varphi} z, d) = \beta \sum_{\theta', z'} \Gamma_{\theta\theta'} \Gamma_{zz'} \frac{P'(1 + \hat{R}(\theta', z'))}{P} \left[\theta' u_c(\theta' d' Q'^{1-\varphi} z', d') + \frac{u_d(\theta' d' Q'^{1-\varphi} z', d')}{Q'^{1-\varphi} z'} \right] \quad (18)$$

Or by equations (14) and (18), we get:

$$\theta u_c(\theta d Q^{1-\varphi} z, d) + \frac{u_d(\theta d Q^{1-\varphi} z, d)}{Q^{1-\varphi} z} = (1 - \varphi)\theta u_c(\theta d Q^{1-\varphi} z, d) \quad (19)$$

Now we can define the equilibrium:

Definition 13 *An equilibrium with competitive search consists of functions V , c , d , s' , P , Q , and R that satisfy:*

1. Household's budget constraint, (condition 10)
2. Household's shopping constraint, (condition 11)
3. Household's Euler equation, (condition 14)
4. Market condition, (condition 18)
5. Firm's participation constraint, (condition 12), which gives us that the dividend payment is the profit of the firm, $\hat{R}(\theta, z) = \frac{zQ^{-\varphi}}{P}$,
6. Market clearing, i.e. $s' = 1$ and $Q = 1/d$.

Note that if you had solved the problem by replacing c and d as functions of s' , then the Euler equations (14) and (18) would be given by:

$$\theta u_c + \frac{u_d}{Q^{1-\varphi} z} = \beta \sum_{\theta', z'} \Gamma_{\theta\theta'} \Gamma_{zz'} \frac{P'(1 + \hat{R}(\theta', z'))}{P} \left[\theta' u'_c + \frac{u'_d}{Q'^{1-\varphi} z'} \right] \quad (20)$$

and

$$\theta u_c + \frac{u_d}{Q^{1-\varphi}z} = -\frac{(1-\varphi)}{\varphi} \frac{u_d}{Q^{-1-\varphi}z} \quad (21)$$

where now $u_c = u_c \left(\theta P \left[s \left(1 + \hat{R} \right) - s' \right], \frac{P[s(1+\hat{R})-s']}{Q^{1-\varphi}z} \right)$ and $u_d = u_d \left(\theta P \left[s \left(1 + \hat{R} \right) - s' \right], \frac{P[s(1+\hat{R})-s']}{Q^{1-\varphi}z} \right)$.

Also, if the agent's budget constraint would be defined as $c + P(\theta, z)s' = s(P(\theta, z) + R(\theta, z))$, then the firm's participation constraint is given by $z\Psi^f(Q(\theta, z)) \geq R(\theta, z)$ and the equilibrium conditions are

$$\theta u_c + \frac{u_d}{Q^{1-\varphi}z} = \beta \sum_{\theta', z'} \Gamma_{\theta\theta'} \Gamma_{zz'} \frac{P' + R'}{P} \left[\theta' u'_c + \frac{u'_d}{Q'^{1-\varphi}z'} \right] \quad (22)$$

and

$$\left(\theta u_c + \frac{u_d}{Q^{1-\varphi}z} \right) \left[s \left(1 - \varphi \frac{R}{Q} \right) - s' \right] = (1-\varphi) Q^{-\varphi} \left(\frac{s[P+R] - Ps'}{z} \right) u_d \quad (23)$$

where now $u_c = u_c \left(\theta [s(P+R) - Ps'], \frac{s[P+R]-Ps'}{Q^{1-\varphi}z} \right)$ and $u_d = u_d \left(\theta [s(P+R) - Ps'], \frac{s[P+R]-Ps'}{Q^{1-\varphi}z} \right)$.

Exercise 27 Define the recursive equilibrium with competitive search for this last setup.

8.1.1 Firms' Problem

Note that in any given period a firm maximizes its returns to the tree by choosing the appropriate market, Q . Note that, by choosing a market Q , the firm is effectively choosing a price. Let the numeraire be the price of trees, then $\hat{P}(Q)$ is price of consumption.

Since there is nothing dynamic in the choice of a market (note that, we are assuming firms can choose a different market in each period), we can write the problem of a firm as:

$$\pi = \max_Q \hat{P}(Q) \Psi^f(Q) z. \quad (24)$$

The first order condition for the optimal choice of Q is

$$\hat{P}'(Q) \Psi^f(Q) + \hat{P}(Q) \Psi^{f'}(Q) = 0, \quad (25)$$

which then determines $\hat{P}(Q)$ as

$$\frac{\hat{P}'(Q)}{\hat{P}(Q)} = -\frac{\Psi^{f'}(Q)}{\Psi^f(Q)}. \quad (26)$$

9 Measure Theory

This section will be a quick review of measure theory, so that we are able to use it in the subsequent sections. In macroeconomics we encounter the problem of aggregation often and it's crucial that we do it in a reasonable way. Measure theory is a tool that tells us when and how we could do so. Let us start with some definitions on sets.

Definition 14 For a set S , \mathcal{S} is a family of subsets of S , if $B \in \mathcal{S}$ implies $B \subseteq S$ (but not the other way around).

Remark 8 Note that in this section we will assume the following convention

1. small letters (e.g. s) are for elements,
2. capital letters (e.g. S) are for sets, and
3. fancy letters (e.g. \mathcal{S}) are for a set of subsets (or families of subsets).

Definition 15 A family of subsets of S , \mathcal{S} , is called a σ -algebra in S if

1. $S, \emptyset \in \mathcal{S}$;
2. if $A \in \mathcal{S} \Rightarrow A^c \in \mathcal{S}$ (i.e. \mathcal{S} is closed with respect to complements and $A^c = S \setminus A$); and,

3. for $\{B_i\}_{i \in \mathbb{N}}$, if $B_i \in \mathcal{S}$ for all $i \Rightarrow \bigcap_{i \in \mathbb{N}} B_i \in \mathcal{S}$ (i.e. \mathcal{S} is closed with respect to countable intersections and by De Morgan's laws, \mathcal{S} is closed under countable unions).

Example 1

1. The power set of S (i.e. all the possible subsets of a set S), is a σ -algebra in S .
2. $\{\emptyset, S\}$ is a σ -algebra in S .
3. $\{\emptyset, S, S_{1/2}, S_{2/2}\}$, where $S_{1/2}$ means the lower half of S (imagine S as an closed interval in \mathbb{R}), is a σ -algebra in S .
4. If $S = [0, 1]$, then

$$\mathcal{S} = \left\{ \emptyset, \left[0, \frac{1}{2}\right), \left\{\frac{1}{2}\right\}, \left[\frac{1}{2}, 1\right], S \right\}$$

is not a σ -algebra in S . But

$$\mathcal{S} = \left\{ \emptyset, \left\{\frac{1}{2}\right\}, \left\{\left[0, \frac{1}{2}\right) \cup \left(\frac{1}{2}, 1\right]\right\}, S \right\}$$

is a σ -algebra in S .

Why do we need the σ -algebra? Because it defines which sets may be considered as "events": things that have positive probability of happening. Elements not in it may have no properly defined measure. Basically, a σ -algebra is the "patch" that lets us avoid some pathological behaviors of mathematics, namely non-measurable sets. We are now ready to define a measure.

Definition 16 Suppose \mathcal{S} is a σ -algebra in S . A measure is a real-valued function $x : \mathcal{S} \rightarrow \mathbb{R}_+$, that satisfies

1. $x(\emptyset) = 0$;
2. if $B_1, B_2 \in \mathcal{S}$ and $B_1 \cap B_2 = \emptyset \Rightarrow x(B_1 \cup B_2) = x(B_1) + x(B_2)$ (additivity); and,

3. if $\{B_i\}_{i \in \mathbb{N}} \in \mathcal{S}$ and $B_i \cap B_j = \emptyset$ for all $i \neq j \Rightarrow x(\cup_i B_i) = \sum_i x(B_i)$ (countable additivity).⁹

Put simply, a measure is just a way to assign each possible “event” a non-negative real number. A set S , a σ -algebra in it (\mathcal{S}), and a measure on \mathcal{S} (x) define a measurable space, (S, \mathcal{S}, x) .

Definition 17 A Borel σ -algebra is a σ -algebra generated by the family of all open sets \mathfrak{B} (generated by a topology). A Borel set is any set in \mathfrak{B} .

Since a Borel σ -algebra contains all the subsets generated by the intervals, you can recognize any subset of a set using a Borel σ -algebra. In other words, a Borel σ -algebra corresponds to complete information.

Definition 18 A probability measure is a measure with the property that $x(S) = 1$ and thus (S, \mathcal{S}, x) is now a probability space. The probability of an event is then given by $x(A)$, where $A \in \mathcal{S}$.

Definition 19 Given a measurable space (S, \mathcal{S}, x) , a real-valued function $f : S \rightarrow \mathbb{R}$ is measurable (with respect to the measurable space) if, for all $a \in \mathbb{R}$, we have

$$\{b \in S \mid f(b) \leq a\} \in \mathcal{S}.$$

Given two measurable spaces (S, \mathcal{S}, x) and (T, \mathcal{T}, z) , a function $f : S \rightarrow T$ is measurable if for all $A \in \mathcal{T}$, we have

$$\{b \in S \mid f(b) \in A\} \in \mathcal{S}.$$

One way to interpret a σ -algebra is that it describes the information available based on observations, i.e. a structure to organize information. Suppose that S is comprised of possible outcomes of a dice throw. If you have no information regarding the outcome of the dice, the only possible sets in your σ -algebra can be \emptyset and S . If you know that the number is even, then the smallest σ -algebra given that information is $\mathcal{S} = \{\emptyset, \{2, 4, 6\}, \{1, 3, 5\}, S\}$. Measurability has a similar interpretation. A function is

⁹ Countable additivity means that the measure of the union of countable disjoint sets is the sum of the measure of these sets.

measurable with respect to a σ -algebra \mathcal{S} , if it can be evaluated under the current measurable space (S, \mathcal{S}, x) .

Example 2 Suppose $S = \{1, 2, 3, 4, 5, 6\}$. Consider a function f that maps the element 6 to the number 1 (i.e. $f(6) = 1$) and any other elements to -100. Then f is NOT measurable with respect to $\mathcal{S} = \{\emptyset, \{1, 2, 3\}, \{4, 5, 6\}, S\}$. Why? Consider $a = 0$, then $\{b \in S \mid f(b) \leq a\} = \{1, 2, 3, 4, 5\}$. But this set is not in \mathcal{S} .

We can also generalize Markov transition matrices to any measurable space, which is what we do next.

Definition 20 Given a measurable space (S, \mathcal{S}, x) , a function $Q : S \times S \rightarrow [0, 1]$ is a transition probability if

1. $Q(s, \cdot)$ is a probability measure for all $s \in S$; and,
2. $Q(\cdot, B)$ is a measurable function for all $B \in \mathcal{S}$.

Intuitively, for $B \in \mathcal{S}$ and $s \in S$, $Q(s, B)$ gives the probability of being in set B tomorrow, given that the state is s today. Consider the following example: a *Markov chain* with transition matrix given by

$$\Gamma = \begin{bmatrix} 0.2 & 0.2 & 0.6 \\ 0.1 & 0.1 & 0.8 \\ 0.3 & 0.5 & 0.2 \end{bmatrix},$$

on the set $S = \{1, 2, 3\}$, with the σ -algebra $\mathcal{S} = P(S)$ (where $P(S)$ is the power set of S). If Γ_{ij} denotes the probability of state j happening, given the current state i , then

$$Q(3, \{1, 2\}) = \Gamma_{31} + \Gamma_{32} = 0.3 + 0.5.$$

As another example, suppose we are given a measure x on S with x_i being the fraction of type i , for any $i \in S$. Given the previous transition function, we can calculate the fraction of types that will be in

i tomorrow using the following formulas:

$$\begin{aligned}x'_1 &= x_1\Gamma_{11} + x_2\Gamma_{21} + x_3\Gamma_{31}, \\x'_2 &= x_1\Gamma_{12} + x_2\Gamma_{22} + x_3\Gamma_{32}, \\x'_3 &= x_1\Gamma_{13} + x_2\Gamma_{23} + x_3\Gamma_{33}.\end{aligned}$$

In other words

$$\mathbf{x}' = \Gamma^T \mathbf{x},$$

where $\mathbf{x}^T = (x_1, x_2, x_3)$.

To extend this idea to a general case with a general transition function, we define an *updating operator* as $T(x, Q)$, which is a measure on S with respect to the σ -algebra \mathcal{S} , such that

$$\begin{aligned}x'(B) &= T(x, Q)(B) \\ &= \int_S Q(s, B) x(ds), \quad \forall B \in \mathcal{S},\end{aligned}$$

where we integrated over all the possible current states s to get the probability of landing in set B tomorrow.

A stationary distribution is a fixed point of T , that is x^* such that

$$x^*(B) = T(x^*, Q)(B), \quad \forall B \in \mathcal{S}.$$

We know that, if Q has nice properties (monotone, Feller property, and enough mixing),¹⁰ then a unique stationary distribution exists (for instance, we discard alternating from one state to another) and we have that

$$x^* = \lim_{n \rightarrow \infty} T^n(x_0, Q),$$

¹⁰ See Chapters 11/12 in Stockey, Lucas, and Prescott (1989) for more details.

for any x_0 in the space of probability measures on (S, \mathcal{S}) .

Exercise 28 Consider unemployment in a very simple economy (in which the transition matrix is exogenous). There are two states of the world: being employed and being unemployed. The transition matrix is given by

$$\Gamma = \begin{pmatrix} 0.95 & 0.05 \\ 0.50 & 0.50 \end{pmatrix}.$$

Compute the stationary distribution corresponding to this Markov transition matrix.

10 Industry Equilibrium

10.1 Preliminaries

Now we are going to study an equilibrium model of an industry developed by Hopenhayn (1992). We abandon the general equilibrium framework from the previous sections to study the dynamics of the distribution of firms in a partial equilibrium environment. We formally drop the household sector and assume an exogenously given demand function for the good produced in the industry.

To motivate things, let's start with the problem of a single firm that produces a good using labor n as an input according to a technology described by the production function $f(n)$. Let us assume that this function is increasing, strictly concave, and with $f(0) = 0$. A firm that hires n units of labor, at price w , is able to produce output $sf(n)$, where s is the firm's productivity, and sell it on the market at price p . Markets are assumed to be competitive and the good is homogeneous, so a firm takes prices (p and w) as given. A firm then chooses n in order to maximize its profits according to

$$\pi(s, p) = \max_{n \geq 0} \{psf(n) - wn\}. \quad (27)$$

The first order condition implies that in the optimum n^* solves

$$psf_n(n^*) = w. \quad (28)$$

Let us denote the solution to this problem as the function $n^*(s; p)$.¹¹ Given the above assumptions, n^* is an increasing function of both s (i.e. more productive firms have more workers) and p (i.e. the higher the output price, the more workers the firm will hire).

Suppose now there is a mass of firms in that industry, each characterized by a productivity parameter $s \in S \subset \mathbb{R}_+$, where $S := [\underline{s}, \bar{s}]$. Let \mathcal{S} denote a σ -algebra on S (a Borel σ -algebra, for instance). Let x be a probability measure defined over the space (S, \mathcal{S}) , which describes the cross-sectional distribution of productivity among firms. Then, for any $B \subset S$ with $B \in \mathcal{S}$, $x(B)$ is the mass of firms having productivities in S . As we will see later, the measure x will be useful to compute statistics at the industry level.

The aggregate supply of the industry corresponds to the sum of each firm's output. Since firm-level supply after choosing labor is given by $sf(n^*(s; p))$, we can write the aggregate supply Y^S as¹²

$$Y^S(p) = \int_S sf(n^*(s; p)) x(ds). \quad (29)$$

Observe that Y^S is only a function of the price p . For any price p , $Y^S(p)$ gives us the supply curve in this economy.

Suppose now that the aggregate demand for that industry's good is described by some function $Y^D(p)$. Then the industry's equilibrium price p^* is determined by the market clearing condition

$$Y^D(p^*) = Y^S(p^*). \quad (30)$$

So far, everything is too simple to be interesting. The ultimate goal here is to understand how the

¹¹ As we declared in advance, this is a partial equilibrium analysis. Hence, we ignore the dependence of the solution on w to focus on the determination of p .

¹² S in Y^S stands for supply.

object x is determined by the fundamentals of the industry. Hence, we will be adding tweaks to this basic environment in order to obtain a theory of firms' distribution in a competitive environment. Let's start by allowing firms to die.

10.2 A Simple Dynamic Environment

Consider now a dynamic environment, in which firms face the above problem in every period. Firms discount profits at rate r_t , which is exogenously given. In addition, assume that a firm faces a probability $(1 - \delta)$ of exiting the market in each period. Notice first that the firm's decision problem is still a static problem. We can easily write the value of an incumbent firm with productivity s as

$$\begin{aligned} V(s; p) &= \sum_{t=0}^{\infty} \left(\frac{\delta}{1+r} \right)^t \pi(s; p) \\ &= \left(\frac{1+r}{1+r-\delta} \right) \pi(s; p) \end{aligned}$$

Note that we are considering that p is fixed (that is why we use a semicolon and therefore we can omit it from the expressions above).

In what follows, we will focus on *stationary equilibria*, i.e. an equilibrium in which the price of the final output p , the rate of return, r , and the productivity of firm, s , stay constant through time. Note however that every period there is a positive mass of firms that die $(1 - \delta)$. Then, how can this economy be in a stationary equilibrium? To achieve that, we have to assume that there is a constant flow of firms entering the economy in each period as well, so that the mass of firms that disappears is exactly replaced by new entering firms.

As before, let x be the measure of firms within the industry. The mass of firms that die in any given period is given by $(1 - \delta)x(s)$. We will allow these firms to be replaced by new entrants. These entrants draw a productivity parameter s from a probability distribution γ over (S, \mathcal{S}) .

One might ask what keeps these firms out of the market in the first place? If $\pi(s; p) = p s f(n^*(s; p)) -$

$wn^*(s; p) > 0$, which is the case for the firms operating in the market (since $n^* > 0$), then all the (potential entering) firms with productivities in S would want to enter the market. We can fix this by assuming that there is a fixed entry cost that each firm must pay in order to operate in the market, denoted by c^E . Moreover, we will assume that the entrant has to pay this cost before learning s . Hence the value of a new entrant is given by the following

$$V^E(p) = \int_S V(s; p) \gamma(ds) - c^E. \quad (31)$$

Entrants will continue to enter if $V^E \geq 0$ and decide not to enter if $V^E < 0$ (since the option value from staying out of the market is 0). As a result, stationarity occurs when V^E is exactly equal to zero (which is the *free-entry* condition).¹³ You can think of this condition as a “*no money left on the table*” condition, which ensures additional entrants find it unprofitable to operate in the industry.

Let’s analyze how this environment shapes the distribution of firms in the market. Let x_t be the cross-sectional distribution of firms in any given period t . For any $B \subset S$, a fraction $1 - \delta$ of firms with productivity $s \in B$ will die and newcomers will enter the market (the mass of which is m). Hence, next period’s measure of firms on set B will be given by

$$x_{t+1}(B) = \delta x_t(B) + m\gamma(B), \quad (32)$$

That is, the mass m of firms would enter the market in $t + 1$, but only fraction $\gamma(B)$ of them will have productivities in the set B . As you might suspect, this relationship must hold for every $B \in \mathcal{S}$. Moreover, since we are interested in a stationary equilibrium, the previous expression tells us that the cross-sectional distribution of firms will be completely determined by γ .

Define the updating operator T be defined as

$$Tx(B) = \delta x(B) + m\gamma(B), \quad \forall B \in \mathcal{S}. \quad (33)$$

Then, a stationary distribution is the fixed point of the mapping T , i.e. x^* such that $Tx^* = x^*$, which

¹³ We are assuming that there is an infinite number (mass) of prospective firms willing to enter the industry.

implies the following stationary measure of firms on set B

$$x^*(B; m) = \frac{m}{1 - \delta} \gamma(B), \quad \forall B \in \mathcal{S}. \quad (34)$$

Note that the demand and supply condition in equation (30) takes the form

$$Y^D(p^*(m)) = \int_{\mathcal{S}} s f(n^*(s; p^*)) dx^*(s; m), \quad (35)$$

whose solution $p^*(m)$ is a continuous function under regularity conditions stated in Stockey, Lucas, and Prescott (1989).

We now have two equations, (31) and (35), and two unknowns, p and m . Thus, we can defined the equilibrium as follows

Definition 21 *A stationary equilibrium consists of functions V , π^* , n^* , p^* , x^* , and m^* such that*

1. *Given prices, V , π^* , and n^* solve the incumbent firm's problem;*
2. *Supply equals demand: $Y^D(p^*(m)) = \int_{\mathcal{S}} s f(n^*(s; p^*)) dx^*(s; m);$*
3. *Free-entry condition: $\int_{\mathcal{S}} V(s; p^*) \gamma(ds) = c^E;$ and,*
4. *Stationary distribution: $x^*(B) = \delta x^*(B) + m^* \gamma(B), \quad \forall B \in \mathcal{S}.$*

10.3 Introducing Exit Decisions

Next, we want to introduce more economic content by making the exit of firms endogenous (i.e. a decision of the firm). As a first step, we let the productivity of firms follow a Markov process governed by the transition function Γ . This changes the mapping T in Equation (33) to

$$Tx(B) = \delta \int_{\mathcal{S}} \Gamma(s, B) x(ds) + m \gamma(B), \quad \forall B \in \mathcal{S}. \quad (36)$$

This alone doesn't add much economic content to our environment; firms still don't make any (interesting) decision.

Another ingredient that we introduce in the model is to let firms face operating costs. Suppose firms now have to pay c^v each period in order to stay in the market. In this case, when s is low, the firm's profit might not cover its operating cost. The firm might therefore decide to leave the market. Note, however, that the firm has already paid (the sunk cost of) c^E from entering the market and since s follows a first-order Markov process, the prospects of future profits might deter the firm from exiting the market. Therefore, having negative profits in one period does not necessarily imply that the firm's optimal choice is to leave the market.

By adding such a minor change, the solution will feature a reservation productivity property (under some conditions to be discussed in the comment below). There will be a minimum productivity, $s^* \in S$, above which it is profitable for the firm to stay in the market (and below which the firm decides to exit).

To see this, note that the value of a firm currently operating in the market with productivity $s \in S$ is given by

$$V(s; p) = \max \left\{ 0, \pi(s; p) + \frac{1}{(1+r)} \int_S V(s'; p) \Gamma(s, ds') - c^v \right\}. \quad (37)$$

Exercise 29 Show that the firm's decision takes the form of a reservation productivity strategy, in which, for some $s^* \in S$, $s < s^*$ implies that the firm would leave the market.

Then the law of motion of the distribution of firms on S is given by

$$x'(B) = \int_{s^*}^{\bar{s}} \Gamma(s, B \cap [s^*, \bar{s}]) x(ds) + m\gamma(B \cap [s^*, \bar{s}]), \quad \forall B \in \mathcal{S}, \quad (38)$$

and a stationary distribution, x^* , is the fixed point of this equation.

Example 3 How productive does a firm have to be, to be in the top 10% largest firms in this economy

(in the stationary equilibrium)? The answer to this question is the solution to the following equation

$$\frac{\int_{\hat{s}}^{\bar{s}} x^*(ds)}{\int_{s^*}^{\bar{s}} x^*(ds)} = 0.1,$$

where \hat{s} is the productivity level above which a firm is in the top 10% largest firm. Then, the fraction of the labor force in the top 10% largest firms in this economy, is

$$\frac{\int_{\hat{s}}^{\bar{s}} n^*(s, p) x^*(ds)}{\int_{s^*}^{\bar{s}} n^*(s, p) x^*(ds)}.$$

Exercise 30 Compute the average growth rate of the smallest one third of the firms. What would be the fraction of firms in the top 10% largest firms in the economy that remain in the top 10% in next period? What is the fraction of firms younger than five years?

Comment 2 To see that the firm's decision is determined by a reservation productivity, we need to start by showing that the profit function (before the variable cost) $\pi(s; p)$ is increasing in s . Hence the productivity threshold is given by the s^* that satisfies the following condition:

$$\pi(s^*; p) = c_v$$

given an equilibrium price p . Now instead of considering γ as the probability measure describing the distribution of productivities among entrants, we consider $\hat{\gamma}$ defined as follows

$$\hat{\gamma}(B) = \frac{\gamma(B \cap [s^*, \bar{s}])}{\gamma([s^*, \bar{s}])}$$

for any $B \in \mathcal{S}$, i.e. the measure of entrants with productivity greater than the reservation value s^* .

To make things more concrete and easier to compute, we will assume that s follows a Markov process. To facilitate the exposition, let's make S finite and assume s has the transition matrix Γ . Assume further that Γ is regular enough so that it has a stationary distribution γ^* . For the moment we will not put any additional structure on Γ .

The operating cost c^v is such that the exit decision is meaningful since firms can have negative profits in any given period and thus it is costly to keep doors open. Let's analyze the problem from the perspective of the firm's manager. He has now two things to decide. First, he asks himself the question "Should I stay or should I go?". Second, conditional on staying, he has to decide how much labor to hire. Importantly, notice that this second decision is still a static decision since the manager chooses labor that maximizes the firm's period profits. Later, we will introduce adjustment costs that will make this decision a dynamic one.

Let $\Phi(s; p)$ be the value of the firm before having decided whether to stay in the market or to go. Let $V(s; p)$ be the value of the firm that has already decided to stay. Assuming $w = 1$, $V(s; p)$ satisfies

$$V(s; p) = \max_n \left\{ spf(n) - n - c^v + \frac{1}{1+r} \int_{s' \in S} \Phi(s'; p) \Gamma(s, ds') \right\} \quad (39)$$

Each morning the firm chooses d in order to solve

$$\Phi(s; p) = \max_{d \in \{0,1\}} d V(s; p) \quad (40)$$

Let $d^*(s; p)$ be the optimal decision to this problem. Then $d^*(s; p) = 1$ means that the firm stays in the market. One can alternatively write:

$$\Phi(s; p) = \max_{d \in \{0,1\}} d \left[\pi(s; p) - c^v + \frac{1}{1+r} \int_{s' \in S} \Phi(s'; p) \Gamma(s, ds') \right] \quad (41)$$

or else

$$\Phi(s; p) = \max \left\{ \pi(s; p) - c^v + \frac{1}{1+r} \int_{s' \in S} \Phi(s'; p) \Gamma(s, ds'), 0 \right\} \quad (42)$$

All these are valid. Additionally, one can easily add minor changes to make the exit decision more interesting. For example, things like scrap value or liquidation costs will affect the second argument of the max operator above, which so far was assumed to be zero.

What about $d^*(s; p)$? Given a price, this decision rule can take only finitely many values. Moreover, if

we could ensure that this decision is of the form “stay only if the productivity is high enough and go otherwise” then the rule can be summarized by a unique number $s^* \in S$. Without a doubt that would be very convenient, but we don’t have enough structure to ensure that such is the case. Although the ordering of s is such that $s_1 < s_2 < \dots < s_N$, we need some additional regularity conditions on the transition matrix to ensure that if a firm is in a good state today, it will land in a good state tomorrow with higher probability than a firm that departs today from a worse productivity level.

In order to get a cutoff rule for the exit decision, we need to add an assumption about the transition matrix Γ . Let the notation $\Gamma(\cdot|s)$ indicate the probability distribution over next period’s productivity conditional on being on state s today. You can think of it as being just a row of the transition matrix (given by s). Take two different rows, s and \hat{s} . We will say that the matrix Γ displays first order stochastic dominance (FOSD) if $s > \hat{s}$ implies that $\sum_{s' \leq b} \Gamma(s'|s) \geq \sum_{s' \leq b} \Gamma(s'|\hat{s})$ for any $b \in S$.¹⁴ It turns out that FOSD is a sufficient condition for having a cutoff rule. You can prove that by using the same kind of dynamic programming tricks that have been used in standard search problems for obtaining the reservation wage property. Try it as an exercise.

Finally, we need to mention something about potential entrants. Since we will assume that they have to pay the cost c^E before learning their s , they can leave the industry even before producing anything. That requires us to be careful when we describe industry dynamics.

10.4 Stationary Equilibrium

Now that we have all the ingredients in the table, let’s define the equilibrium formally for the economy with the exit decision.

Definition 22 A stationary equilibrium consists of a list of functions Φ, V^E, π^*, n^* , a productivity threshold s^* , a price p^* , a measure x^* , and mass m^* such that

¹⁴ Recall that a distribution F FOSD G (continuous and defined over the support $[0, \infty]$) iff $F(x) \leq G(x)$ for all x . Also, for any nondecreasing function $u : \mathbb{R} \rightarrow \mathbb{R}$, iff F FOSD G we have that $\int u(x)dF(x) \geq \int u(x)dG(x)$.

1. Given p^* , the functions Φ, π^*, n^* solve the problem of the incumbent firm
2. The reservation productivity s^* is such that the firm stays in the market if $s \geq s^*$
3. Free-entry condition:

$$V^E(p^*) = 0$$

4. For any $B \in \mathcal{S}$,

$$x^*(B) = m^* \gamma(B \cap [s^*, \bar{s}]) + \int_{s^*}^{\bar{s}} \Gamma(s, B \cap [s^*, \bar{s}]) x^*(ds)$$

5. Market clearing:

$$Y^d(p^*) = \int_{s^*}^{\bar{s}} sf(n^*(s; p^*)) x^*(ds)$$

We can now use this model to compute interesting statistics about this industry. For example, the average output of the firm is given by

$$\frac{Y}{N} = \frac{\int_{s^*}^{\bar{s}} sf(n^*(s)) x^*(ds)}{\int_{s^*}^{\bar{s}} x^*(ds)}$$

Suppose that we want to compute the share of output produced by the top 1% of firms. To do so, we first need to find \tilde{s} such that

$$\frac{\int_{\tilde{s}}^{\bar{s}} x^*(ds)}{N} = .01$$

where N is the total measure of firms as defined above. Then the share of output produced by these firms is given by

$$\frac{\int_{\tilde{s}}^{\bar{s}} sf(n^*(s)) x^*(ds)}{\int_{s^*}^{\bar{s}} sf(n^*(s)) x^*(ds)}$$

Suppose now that we want to compute the fraction of firms in the top 1% two periods in a row. If s is a continuous variable, this is given by

$$\int_{s \geq \tilde{s}} \int_{s' \geq \tilde{s}} \Gamma_{ss'} x^*(ds)$$

or if s is discrete, then

$$\sum_{s \geq \tilde{s}} \sum_{s' \geq \tilde{s}} \Gamma_{ss'} x^*(s)$$

10.5 Adjustment Costs

To end with this chapter it is useful to think about environments in which firms' productive decisions are no longer static. A simple way of introducing dynamics is by adding adjustment costs. Since firms only use labor, we will consider labor adjustment costs.¹⁵

Consider a firm that enters period t with n_{t-1} units of labor hired in the previous period and has to choose how many units of labor n_t to hire today. Let the adjustment costs be denoted by $c(n_t, n_{t-1})$ as a result of hiring n_t units of labor in t . We will consider three different specifications for these costs:

- *Convex Adjustment Costs*: if the firm wants to vary the units of labor, it has to pay $\alpha (n_t - n_{t-1})^2$ units of the numeraire good. The cost here depends on the size of the adjustment.
- *Training Costs or Hiring Costs*: if the firm wants to increase labor, it has to pay $\alpha [n_t - (1 - \delta) n_{t-1}]^2$ units of the numeraire good only if $n_t > n_{t-1}$. We can write this as

$$\mathbf{1}_{\{n_t > n_{t-1}\}} \alpha [n_t - (1 - \delta) n_{t-1}]^2,$$

where $\mathbf{1}$ is the indicator function and δ measures the exogenous attrition of workers in each period.

¹⁵ These costs work pretty much like capital adjustment costs, as one might suspect.

- *Firing Costs*: the firm has to pay to reduce the number of workers.

The recursive formulation of the firm's problem can now be expressed as

$$V(s, n_-; p) = \max \left\{ 0, \max_{n \geq 0} p s f(n) - w n - c^v - c(n, n_-) + \frac{1}{(1+r)} \int_{s' \in S} V(s', n; p) \Gamma(s, ds') \right\}, \quad (43)$$

where last period labor is a state and the function $c(\cdot, \cdot)$ gives the specified cost of adjusting n_- to n . Note that we are assuming limited liability for the firm since its exit value is 0 and not $-c(0, n_-)$.

Now a firm is characterized by both its current productivity s and labor in the previous period n_- . Note that since the production function f has decreasing returns to scale, there exists an amount of labor \bar{N} such that none of the firms hire labor greater than \bar{N} . So, $n_- \in N := [0, \bar{N}]$, with \mathcal{N} as a σ -algebra on N . If the labor policy function is $n = g(s, n_-; p)$, then the law of motion for the measure of firms becomes

$$x'(B^S, B^N) = m\gamma(B^S \cap [s^*, \bar{s}]) \mathbf{1}_{\{0 \in B^N\}} + \int_{s^*}^{\bar{s}} \int_0^{\bar{N}} \mathbf{1}_{\{g(s, n_-; p) \in B^N\}} \Gamma(s, B^S \cap [s^*, \bar{s}]) x(ds, dn_-), \quad \forall B^S \in \mathcal{S}, \forall B^N \in \mathcal{N}. \quad (44)$$

Exercise 31 Write the first order conditions for the problem in (43). Define the recursive competitive equilibrium for this economy.

Exercise 32 Another example of labor adjustment costs is when the firm has to post vacancies to attract labor. As an example of such case, suppose the firm faces a firing cost according to the function c . The firm also pays a cost κ to post vacancies and after posting vacancies, it takes one period for the workers to be hired. How can we write the problem of firms in this environment?

Exercise 33 Write the problem of a firm with capital adjustment costs.

Exercise 34 Write the problem of a firm with R&D expenditures that uses labor to improve its productivity.

11 Non-stationary Equilibria

Until now we have focused on *stationary equilibria*, where prices, aggregates, and the distribution of firms are invariant. Next we will delve on non-stationary equilibria and examine how the distribution of firms or individuals shifts over time as a result of some aggregate change. We will do so both in the sequence space as well as in the functional space.

11.1 Sequence vs. Recursive Industry Equilibrium

Up to now the distribution of firms was invariant so that the share of firms that enter and exit the industry is equal. A more interesting case is to look at what happens in a *non-stationary equilibrium* with demand shifters $z_{t+1} = \phi(z_t)$ so that aggregate demand is $D(p_t, z_t)$.

A few remarks regarding the shock. In general, z_t can be *deterministic* or *stochastic*. Deterministic shocks are fully anticipated by agents in the economy, while stochastic shocks are random and agents only know the random process that governs them. Solving the model with deterministic shocks is almost as easy as solving the transitional path of the model without shocks. But models with stochastic shocks are much harder to solve given the possible realizations of the shock going forward. We will consider for now that the shock z_t is deterministic and thus focus on the perfect foresight equilibrium.

Let's first start with the sequential case introducing a sequence of aggregate shocks $\{z_t\}_{t=0}^{\infty}$. We maintain our baseline model (with entry and exit, but no adjustment costs) and consider the economy starting with some (arbitrary) initial distribution of incumbent firms x_0 . Without any shocks, the firm distribution would converge to the stationary equilibrium distribution x^* defined in section 10.4. On the transitional path towards the stationary equilibrium, firms would face a sequence of prices $\{p_t\}_{t=0}^{\infty}$, which are going to be pinned down by equating the endogenous aggregate industry supply and the exogenous aggregate demand in each period.

The problem of a firm in sequential form is now given by

$$V_t(s) = \max \left\{ 0, \pi_t(s) + \frac{1}{1+r} \int_S V_{t+1}(s') \Gamma(s, ds') \right\}$$

$$\text{s.t.} \quad \pi_t(s) = \max_{n_t \geq 0} p_t s f(n_t) - w n_t - c^v \quad (45)$$

$$x_0 \text{ given} \quad (46)$$

We can maintain the cutoff property of the decision rule to exit the market given the regularity conditions assumed above regarding the matrix of transition probabilities. Let's denote the exit cutoff productivity as s_t^* . In order to solve this problem we need to know how the measure of firms in the industry evolves over time. The law of motion of the measure of firms is such that for each $B \in \mathcal{S}$ we have

$$x_{t+1}(B) = m_{t+1} \gamma(B \cap [s_{t+1}^*, \bar{s}]) + \int_{s_t^*}^{\bar{s}} \Gamma(s, B \cap [s_{t+1}^*, \bar{s}]) x_t(ds) \quad (47)$$

where m_{t+1} is the mass of firms that enter at the beginning of period $t + 1$, which is pinned down by the free-entry condition

$$\int_S V_t(s) \gamma(ds) \leq c^e, \quad (48)$$

with strict equality if $m_t > 0$. The distribution of productivity among entrants γ and the entry cost c^e are exogenously given (and for simplicity constant through time). Finally, the market clearing condition will close the model by pinning down price p_t from

$$D(p_t, z_t) = \int_{s_t^*}^{\bar{s}} p_t s f(n_t(s)) x_t(ds) \quad (49)$$

We can now define the perfect foresight equilibrium in sequence space as follows

Definition 23 *Given a path of shocks $\{z_t\}_{t=0}^{\infty}$ and a initial measure of firms x_0 , a perfect foresight equilibrium (PFE) in sequence space consists of a sequence of numbers $\{p_t, x_t, s_t^*\}_{t=0}^{\infty}$, of measures $\{x_t\}_{t=0}^{\infty}$, and of functions $\{V_t(s), n_t(s)\}_{t=0}^{\infty}$ that satisfy:*

1. *Optimality:* Given $\{p_t\}_{t=0}^{\infty}$, $\{V_t, n_t, s_t^*\}$ solve the firm's problem (45) for each period t .
2. *Free-entry:* $\int_S V_t(s)\gamma(ds) \leq c^e$, with strict equality if $m_t > 0$.
3. *Law of motion:* $x_{t+1}(B) = m_{t+1}\gamma(B \cap [s_{t+1}^*, \bar{s}]) + \int_{s_t^*}^{\bar{s}} \Gamma(s, B \cap [s_{t+1}^*, \bar{s}])x_t(ds)$, $\forall B \in \mathcal{S}$.
4. *Market clearing:* $D(p_t, z_t) = \int_{s_t^*}^{\bar{s}} p_t s f(n_t(s))x_t(ds)$.

Next we can define the same problem in the functional space using the tools of dynamic programming we have developed so far. The time subscripts disappear and we now have to add two aggregate states $\{z, x\}$ and a function G that tells us how the distribution of firms changes, mapping a measure of firms and state today into a measure of firms tomorrow.

Let's rewrite the problem of the firm recursively for the deterministic economy where $z' = \phi(z)$

$$V(s, z, x) = \max \left\{ 0, \pi(s, z, x) + \frac{1}{1+r} \int_S V(s', \phi(z), G(z, x))\Gamma(s, ds') \right\} \quad (50)$$

$$\text{s.t. } \pi(s, z, x) = \max_{n \geq 0} p(z, x) s f(n) - wn - c^v$$

Note that firms take output prices as given and those must clear the market as before. We can now define the PFE in functional space for this economy.

Definition 24 Given ϕ , a perfect foresight equilibrium defined recursively is a list of functions $\{V(s, z, x), n(s, z, x), s^*(s, z, x)\}$ for the firm, pricing function $p(z, x)$, and functions $G(z, x)$ for the measure's law of motion and $m(z, x)$ for the mass of entrants, such that

1. Given prices and law of motion, $\{V(s, z, x), n(s, z, x), s^*(s, z, x)\}$ solve the firm's problem (50).
2. Free-entry condition holds

$$\int_S V(s, z, x)\gamma(ds) \leq c^e, \text{ with strict equality if } m(z, x) > 0.$$

3. The measure evolves according to $\forall B \in \mathcal{S}$

$$G(z, x)(B) = m(z, x)\gamma(B \cap [s^*(s, z, x), \bar{s}]) + \int_{s^*(s, z, x)}^{\bar{s}} \Gamma(s, B \cap [s^*(s, z, x), \bar{s}])x(ds).$$

4. Market clearing:

$$D(p(z, x), z) = \int_{s^*(s, z, x)}^{\bar{s}} p(z, x)sf(n(s, z, x))x(ds).$$

We can see that finding this highly dimensional object G is computationally troublesome. That is why we will go back to the problem in sequence space to solve for the aggregate transition in non-stationary environments. The natural next step is to solve the stochastic equilibrium, in which ϕ is random. For simplicity, we will assume that the shock follows an AR1 process and thus $z_{t+1} = \rho z_t + \varepsilon_{t+1}$. Although the definition of equilibrium resembles the one above, it is a much harder problem to solve. We will resort to some notion of linearization to achieve it in the context of the Neoclassical Growth model in the next subsection.

Exercise 35 *What happens if demand doubles? Sketch an algorithm to find the equilibrium prices.*

Exercise 36 *Write the stochastic version of the non-stationary economy above in both the sequential and recursive forms.*

11.2 Linear Approximation in the Neoclassical Growth model

Solving the previous problem with stochastic shocks can be challenging. To do so, we will resort to a solution method proposed by Boppart et al. (2018), who study the equilibrium response to an MIT shock by exploring the idea that linearization can provide a good approximation for equilibria of economies with aggregate shocks and heterogeneous agents.

To better understand linearization, we will first look at the standard deterministic growth model and

approximate the solution linearly. Consider the social planner's problem (with full depreciation)

$$\begin{aligned}
 V(k_t) &= \max_{c_t, k_{t+1}} u(c_t) + \beta V(k_{t+1}) & (51) \\
 \text{s.t. } & c_t + k_{t+1} \leq f(k_t), \forall t \geq 0 \\
 & c_t, k_{t+1} \geq 0, \forall t \geq 0 \\
 & k_0 > 0 \text{ given.}
 \end{aligned}$$

We can show that $\{c_t, k_{t+1}\}_{t=0}^{\infty}$ is a solution to the above social planner's problem if and only if

$$u'(c_t) = \beta u'(c_{t+1}) f'(k_{t+1}), \forall t \geq 0 \quad (52)$$

$$c_t + k_{t+1} = f(k_t), \forall t \geq 0 \quad (53)$$

$$\lim_{t \rightarrow \infty} \beta^t u'(c_t) k_{t+1} = 0 \quad (54)$$

Exercise 37 *Derive the above equilibrium conditions.*

We will focus on cases where a steady state k^* exists. The goal is to do a linear approximation of the Euler equation. Note that the above necessary and sufficient conditions give us a second order difference equation (which we denote as $\psi(k_t, k_{t+1}, k_{t+2}) = 0$), with exactly two boundary conditions (given by k_0 and the steady state k^*). This second order difference equation is the residual function from the Euler equation, i.e.

$$\psi(k_t, k_{t+1}, k_{t+2}) = u_c(f(k_t) - k_{t+1}) - \beta u_c(f(k_{t+1}) - k_{t+2}) f_k(k_{t+1}) = 0. \quad (55)$$

So how do we solve this model. One obvious option is to find the global solution. For instance, you can guess a k_1 , use k_0 and $\psi(k_t, k_{t+1}, k_{t+2}) = 0$ to get k_2, k_3, \dots forward up until some k_T , and adjust k_1 to make sure k_T is close enough to the steady state k^* (this is called forward shooting). Or you can guess a k_{T-1} and do it backward (which is called reverse shooting). Or you can guess and adjust the whole path (which is called the extended path method). All these methods will give you a numerical

solution for the path of k starting from the arbitrary k_0 (that's why we call it a *global* solution).

As you may have done it in another course, the above process can be computationally time consuming. Linearization is a short cut that can yield a good approximation of the solution *locally*, that is, around the neighborhood of some point (usually, around the steady state). The idea is simple. We know the true solution is in the form of $k_{t+1} = g(k_t)$. Let's conjecture a linear function to approximate the true solution $g(\cdot)$ and denote it by $\hat{g}(\cdot)$. Since we are interested in a linear approximation, we assume that $k_{t+1} = \hat{g}(k_t) = a + bk_t$. Then we only need to figure out two numbers: a and b . We thus need two conditions to pin them down.

Since we know the steady state is k^* and that the solution must hold in the steady state, we have that $k^* = a + bk^*$ and therefore $a = (1 - b)k^*$. So we got one condition for free. How do we find the second condition regarding b ? We can find it in ψ and our criteria is that we are going to choose b such that the slope of \hat{g} exactly matches the slope of the true decision rule g *at the steady state* k^* . So we take a first order Taylor expansion of the residual function $\psi[k_t, g(k_t), g(g(k_t))]$ around k^* and obtain

$$\psi[k, g(k_t), g(g(k_t))] \approx \psi(k^*, k^*, k^*) + \psi_k(k^*, k^*, k^*) \underbrace{(k_t - k^*)}_{\hat{k}_t} \quad (56)$$

where \hat{k}_t is deviation of capital from its steady state value. We know the residual function $\psi[k, g(k), g(g(k))]$ = 0 by definition since the Euler equation must hold for all k . For k_t in the neighborhood of k^* , we have that the derivative of the second order difference equation satisfies

$$\psi_k(k^*, k^*, k^*) = \psi_1^* + \psi_2^* g'(k^*) + \psi_3^* g'(g(k^*)) g'(k^*) = 0. \quad (57)$$

Solving this equation gives us $g'(k^*)$, which is exactly what we need (note ψ_1, ψ_2 , and ψ_3 may also involve $\hat{g}'(k^*)$). We then let $b = g'(k^*) = \hat{g}'(k)$. We now have all the ingredients to compute $\hat{g}(k_t) = a + bk_t$ to approximate the solution near the steady state. From any k_0 we can now compute the full of $\left\{ \hat{k}_{t+1} \right\}_{t=0}^{\infty}$ for the deterministic economy.

Comment 3 *In practice, it's messy to do the total derivative as above. A cleaner way is to linearize*

the system directly with k_t, k_{t+1}, k_{t+2} and then solve the linear system using whatever method you like. Usually, we cast the system in its state space representation and solve it using matrix algebra (here it helps to know some econometrics).

Exercise 38 Suppose $f(k_t) = k_t^\alpha$, $u(c_t) = \ln c_t$. Verify that the solution to the social planner's problem is $k_{t+1} = \alpha\beta k_t^\alpha$. Get the linearized solution around the steady state and compare it with the closed form solution. How precise is the linear approximation?

With stochastic productivity shocks, the second order difference equation would include the current as well as next period's realization of the shock and thus $\psi(k_t, k_{t+1}, k_{t+2}, z_t, z_{t+1}) = 0$. The idea above follows through with some additional notation. What Boppart et al. (2018) suggest is to use the path of $\{\hat{k}_{t+1}\}_{t=0}^\infty$ and a sequence of shocks $\{\varepsilon_{t+1}\}_{t=0}^\infty$ to approximate the impulse response of the fully stochastic economy $\{\tilde{k}_{t+1}\}_{t=0}^\infty$ (where $z_{t+1} = \rho z_t + \varepsilon_{t+1}$).

To see this, consider the model above. The resource constraint is now $c_t + k_{t+1} = z_t f(k_t)$, with $z_0 = 1$. We want to solve first for the deterministic transition with $\varepsilon_t = 0 \forall t$ and thus $z_{t+1} = \rho^{t+1}$. In that case, the second order difference equation is

$$\psi(k_t, k_{t+1}, k_{t+2}, z_t) = u_c(z_t f(k_t) - k_{t+1}) - \beta u_c(\rho z_t f(k_{t+1}) - k_{t+2}) \rho z_t f_k(k_{t+1}) = 0. \quad (58)$$

As before, we conjecture an approximation of the solution $k_{t+1} = g(k_t, z_t)$ using the linear function $\hat{g}(k_t, z_t)$ given by

$$k_{t+1} = a + b k_t + f z_t. \quad (59)$$

Now we need to pin down three numbers: a, b , and f . We can use the linear rule evaluated at the steady state to find $a = (1 - b)k^* - f$. Next, we proceed as before by taking a first-order Taylor expansion of $\psi(k_t, g(k_t), g(g(k_t)), z_t)$, with b and f satisfying the following expression

$$\psi_1^* \hat{k}_t + (\psi_2^* + b\psi_3^*) \hat{k}_{t+1} + (\psi_3^* k^* f \rho + \psi_4^*) \hat{z}_t = 0, \quad (60)$$

which we can solve for \hat{k}_{t+1} . Recall that $\hat{k}_{t+1} = k_{t+1} - k^*$ and using the approximating function \hat{g} we have $\hat{k}_{t+1} = b\hat{k}_t + f\hat{z}_t$. We now have two equations and two unknowns to pin down b and f .

Exercise 39 *Describe a log-linear approximation of the Euler equation of the growth model.*

Now that we have found the linear approximation for the path of aggregate capital in the perfect foresight model, we can use that path to solve for the sequence of capital in the stochastic economy given any sequence of randomly drawn innovations ε_t . Denote the deviation of capital from steady state in the stochastic economy by $\tilde{k}_t(\{\hat{k}_t\}; \{\varepsilon_t\}, k_0, z_0)$. We can now compute the impulse response to a sequence of shocks as

$$\begin{aligned}\tilde{k}_1 &= \varepsilon_0 \hat{k}_1 \\ \tilde{k}_2 &= \varepsilon_0 \hat{k}_2 + \varepsilon_1 \hat{k}_1 \\ &\vdots \\ \tilde{k}_{t+1} &= \sum_{\tau=0}^{t+1} \varepsilon_\tau \hat{k}_{t+1-\tau}\end{aligned}$$

or in the MIT shock scenario with $\varepsilon_0 = 1$ standard deviation and $\varepsilon_t = 0 \forall t \neq 0$.

Thus, the model with aggregate shocks can be obtained by a simple simulation based on the deterministic path of the aggregate variable. The solution corresponds to the superposition of non-linear impulse response functions derived from the PFE. This can then be applied to our non-stationary industry equilibria or any other economy with heterogeneous agents. The computational cost is linear (not exponential) in the number of shocks. Yet, we do not know how to use this procedure for asymmetric shocks (e.g. when there is downward wage rigidity).

Exercise 40 *Describe an algorithm to approximate the solution to an industry subject to demand shocks that follow an AR1 process.*

Exercise 41 *Describe how to compute the evolution of the Gini index or the Herfindahl index of an industry over the first fifteen periods.*

12 Incomplete Market Models

We now turn to models with incomplete asset markets and thus agents will not be able to fully insure in all possible states of the world.

12.1 A Farmer's Problem

We start with a simple Robinson Crusoe economy with coconuts that can be stored. Consider the problem of a farmer given by

$$\begin{aligned} V(s, a) = \max_{c, a'} & u(c) + \beta \sum_{s'} \Gamma_{ss'} V(s', a') & (61) \\ \text{s.t.} & c + qa' = a + s \\ & c \geq 0 \\ & a' \geq 0, \end{aligned}$$

where a is his holding of coconuts, which can only take positive values, c is his consumption, and s is amount of coconuts that nature provides. The latter follows a Markov chain, taking values in a finite set S , and q is the fraction of coconuts that can be stored to be consumed tomorrow. Note that the constraint on the holdings of coconuts tomorrow (a') is a constraint imposed by nature. Nature allows the farmer to store coconuts at rate $1/q$, but it does not allow him to *transfer coconuts* from tomorrow to today (i.e. borrow).

We are going to consider this problem in the context of a partial equilibrium setup in which q is given. What can be said about q ?

Remark 9 Assume there are no shocks in the economy, so that s is a fixed number. Then, we could

write the problem of the farmer as

$$V(a) = \max_{c, a' \geq 0} \{u(a + s - qa') + \beta V(a')\}. \quad (62)$$

We can derive the first order condition as

$$q u_c \geq \beta u'_c \quad (63)$$

If u is assumed to be logarithmic, the FOC for this problem simplifies to

$$\frac{c'}{c} \geq \frac{\beta}{q}, \quad (64)$$

and with equality if $a' > 0$. Therefore, if $q > \beta$ (i.e. nature is more stingy, or the farmer is less patient than nature), then $c' < c$ and the farmer dis-saves (at least, as long as $a' > 0$). But, when $q < \beta$, consumption grows without bound. For that reason, we impose the assumption that $\beta/q < 1$ in what follows.

A crucial assumption to bound the asset space is that $\beta/q < 1$, which states that agents are sufficiently impatient so that they want to consume more today and thus decumulate their assets when they are richer and far away from the non-negativity constraint, $a' \geq 0$. However, this does not mean that when faced with the possibility of very low consumption, agents would not save (even though the rate of return, $1/q$, is smaller than the rate of impatience $1/\beta$).

The first order condition for farmer's problem (61) with s stochastic is given by

$$u_c(c(s, a)) \geq \frac{\beta}{q} \sum_{s'} \Gamma_{ss'} u_c(c(s', a'(s, a))), \quad (65)$$

with equality when $a'(s, a) > 0$, where $c(\cdot)$ and $a'(\cdot)$ are policy functions from the farmer's problem. Notice that $a'(s, a) = 0$ is possible for an appropriate stochastic process. Specifically, it depends on the value of $s_{\min} := \min_{s_i \in S} s_i$.

The solution to the problem of the farmer, for a given value of q , implies a distribution of coconut holdings in each period. This distribution, together with the Markov chain describing the evolution of s , can be summed together as a single probability measure for the distribution of shocks and assets (coconut holdings) over the product space $E = S \times \mathbb{R}_+$, and its σ -algebra, \mathcal{B} . We denote that measure by X . The evolution of this probability measure is then given by

$$X'(B) = \sum_s \int_0^{\bar{a}} \sum_{s' \in B_s} \Gamma_{ss'} \mathbf{1}_{\{a'(s,a) \in B_a\}} X(s, da), \quad \forall B \in \mathcal{B}, \quad (66)$$

where B_s and B_a are the S -section and \mathbb{R}_+ -section of B (projections of B on S and \mathbb{R}_+), respectively, and $\mathbf{1}$ is an indicator function. Let $\tilde{T}(\Gamma, a', \cdot)$ be the mapping associated with (66) (the adjoint operator), so that

$$X'(B) = \tilde{T}(\Gamma, a', X)(B), \quad \forall B \in \mathcal{B}. \quad (67)$$

Define $\tilde{T}^n(\Gamma, a', \cdot)$ as

$$\tilde{T}^n(\Gamma, a', X) = \tilde{T}\left(\Gamma, a', \tilde{T}^{n-1}(\Gamma, a', X)\right). \quad (68)$$

Then, we can define the following theorem.

Theorem 3 *Under some conditions on $\tilde{T}(\Gamma, a', \cdot)$,¹⁶ there is a unique probability measure X^* , so that:*

$$X^*(B) = \lim_{n \rightarrow \infty} \tilde{T}^n(\Gamma, a', X_0)(B), \quad \forall B \in \mathcal{B}, \quad (69)$$

for all initial probability measures X_0 on (E, \mathcal{B}) .

A condition that makes things considerably easier for this theorem to hold is that E is a compact set. Then, we can use Theorem (12.12) in Stokey, Lucas, and Prescott (1989) to show this result holds.

¹⁶ As in the previous section, we need Γ to be monotone, enough mixing in the distribution, and that \tilde{T} maps the space of bounded continuous functions to itself.

Given that S is finite, this is equivalent to a compact support for the distribution of asset holdings. We discuss this in further detail in Appendix A.

12.2 Huggett Economy

Now we modify the farmer's problem in (61) a little bit, in line with Huggett (1993). Look carefully at the borrowing constraint in what follows

$$\begin{aligned}
 V(s, a) &= \max_{c, a'} u(c) + \beta \sum_{s'} \Gamma_{ss'} V(s', a') & (70) \\
 \text{s.t. } & c + qa' = a + s \\
 & c \geq 0 \\
 & a' \geq \underline{a},
 \end{aligned}$$

where $\underline{a} < 0$. Now farmers can borrow and lend among each other, but up to a borrowing limit. We continue to make the same assumption on q ; i.e. that $\beta/q < 1$. As before, solving this problem gives the policy function $a'(s, a)$. It is easy to extend the analysis in the last section to show that there is an upper bound on the asset space, which we denote by \bar{a} , so that for any $a \in A := [\underline{a}, \bar{a}]$, $a'(s, a) \in A$, for any $s \in S$.

Remark 10 *One possibility for \underline{a} is what we call the natural borrowing limit. This limit ensures the agent can pay back his debt with certainty, no matter what the nature unveils (i.e. whatever sequence of idiosyncratic shocks is realized). This is given by*

$$a^n := -\frac{s_{\min}}{(q-1)}. \tag{71}$$

If we impose this constraint on (70), the farmer can fully pay back his debt in the event of receiving an infinite sequence of bad shocks by setting his consumption equal to zero forever.

But, what makes this problem more interesting is to tighten this borrowing constraint more. The natural

borrowing limit is very unlikely to be binding. One way to restrict borrowing further is to assume no borrowing at all, as in the previous section. Another case is to choose $0 > \underline{a} > a^n$, which we will consider in this section.

Now suppose there is a (unit) mass of farmers with distribution function $X(\cdot)$, where $X(D, B)$ denotes the fraction of people with shock $s \in D$ and $a \in B$, where D is an element of the power set of S , $P(S)$ (which, when S is finite, is the natural σ -algebra over S), and B is a Borel subset of \mathcal{A} ($B \in \mathcal{A}$). Then the distribution of farmers tomorrow is given by

$$X'(D', B') = \sum_{s \in S} \int_A \mathbf{1}_{\{a'(s,a) \in B'\}} \sum_{s' \in D'} \Gamma_{ss'} X(s, da), \quad (72)$$

for any $D' \in P(S)$ and $B' \in \mathcal{A}$.

Implicitly this defines an operator T such that $X' = T(X)$. If T is *sufficiently nice* (as defined above and in the previous footnote), then there exists a unique X^* such that $X^* = T(X^*)$ and $X^* = \lim_{n \rightarrow \infty} T^n(X_0)$ for any initial distribution over the product space $S \times A$, X_0 . Note that the decision rule is obtained for a given price q . Hence, the resulting stationary distribution X^* also depends on q . So, let us denote it by $X^*(q)$.

To determine the equilibrium value of q in a general equilibrium setting consider the following variable (as a function of q):

$$\int_{A \times S} a dX^*(q). \quad (73)$$

This expression gives us the average asset holdings, given the price q (assuming s is a continuous variable). What we want to do is to determine the endogenous q that clears the asset market. Recall that we assumed that there is no storage technology so that the supply of assets is 0 in equilibrium. Hence, the price q should be such that the asset demand equals asset supply, i.e.

$$\int_{A \times S} a dX^*(q) = 0. \quad (74)$$

In this sense, the equilibrium price q is the price that generates the stationary distribution of asset holdings that clears the asset market.

We can now show that a solution exists by invoking the intermediate value theorem. We need to ensure that the following three conditions are satisfied (note that $q \in [\beta, \infty]$)

1. $\int_{A \times S} a dX^*(q)$ is a continuous function of q ;
2. $\lim_{q \rightarrow \beta} \int_{A \times S} a dX^*(q) \rightarrow \infty$; (As $q \rightarrow \beta$, the interest rate $R = 1/q$ increases up to $1/\beta$, which is the steady state interest rate in the representative agent economy. Hence, agents would like to save more. Adding to this the precautionary savings motive, agents would want to accumulate an unbounded amount of assets in the stationary equilibrium); and,
3. $\lim_{q \rightarrow \infty} \int_{A \times S} a dX^*(q) < 0$. (This is also intuitive: as $q \rightarrow \infty$, the interest rate $R = 1/q$ converges to 0. Hence, everyone would rather borrow).

12.3 Aiyagari Economy

The Aiyagari (1994) economy is one of the workhorse models of modern macroeconomics. It features incomplete markets and an endogenous wealth distribution, which allows us to examine interactions between heterogeneous agents and distributional effects of public policies. The setup will be similar to the one above, but now physical capital is introduced. Then, the average asset holdings in the economy that we computed above must be equal to the average amount of (physical) capital K . Keeping the notation from the previous section (i.e. the stationary distribution of assets is X^*), then we have that

$$\int_{A \times S} a dX^*(q) = K, \tag{75}$$

where A is the support of the distribution of wealth. (It is not difficult to see that this set is compact.)

We will now assume that the shocks affect labor income. We can think of these shocks as fluctuations in the employment status of individuals. Now the restriction for the existence of a stationary equilibrium

is $\beta(1+r) < 1$. Thus, the problem of an individual in this economy can be written as

$$\begin{aligned}
 V(s, a) = \max_{c, a'} & \quad u(c) + \beta \int_{s'} V(s', a') \Gamma(s, ds') \\
 \text{s.t.} & \quad c + a' = (1+r)a + ws \\
 & \quad c \geq 0 \\
 & \quad a' \geq \underline{a},
 \end{aligned} \tag{76}$$

where r is the return on savings and w is the wage rate. Then,

$$\int_{A \times S} s dX^*(q) \tag{77}$$

gives the average labor in this economy. If agents are endowed with one unit of time, we can think of the expression as determining the *effective labor supply*.

We also assume the standard constant returns to scale production technology for the firm as

$$F(K, L) = AK^{1-\alpha}L^\alpha, \tag{78}$$

where A is TFP and L is the average amount of labor in the economy. Let δ be the rate of depreciation of capital. Hence, solving for the firm's FOC we have that factor prices satisfy

$$\begin{aligned}
 r &= F_k(K, L) - \delta \\
 &= (1-\alpha)A \left(\frac{K}{L}\right)^{-\alpha} - \delta \\
 &=: r \left(\frac{K}{L}\right),
 \end{aligned}$$

and

$$\begin{aligned}
 w &= F_l(K, L) \\
 &= \alpha A \left(\frac{K}{L} \right)^{1-\alpha} \\
 &=: w \left(\frac{K}{L} \right).
 \end{aligned}$$

The prices faced by agents are functions of the capital-labor ratio. As a result, we may write the stationary distribution of assets as a function of the capital-labor ratio as well and thus $X^* \left(\frac{K}{L} \right)$. The equilibrium condition now becomes

$$\frac{K}{L} = \frac{\int_{A \times S} a dX^* \left(\frac{K}{L} \right)}{\int_{A \times S} s dX^* \left(\frac{K}{L} \right)}. \quad (79)$$

Using this condition, one can solve for the equilibrium capital-labor ratio and study the distribution of wealth in this economy.

Remark 11 *Note that relative to Huggett (1993), the price of assets q is now given by*

$$q = \frac{1}{(1+r)} = \frac{1}{[1 + F_k(K, L) - \delta]}. \quad (80)$$

Exercise 42 *Show that aggregate capital is higher in the stationary equilibrium of the Aiyagari economy than it is the standard representative agent economy.*

12.3.1 Policy Changes and Welfare

Let the model parameters in an In Aiyagari or Huggett economy be summarized by $\theta = \{u, \beta, s, \Gamma, F\}$. The value function $V(s, a; \theta)$ as well as $X^*(\theta)$ can be obtained in the stationary equilibrium as functions of the model parameters, where $X^*(\theta)$ is a mapping from the model parameters to the stationary distribution of agent's asset holding and shocks. Suppose now there is a policy change that shifts θ

to $\hat{\theta} = \{u, \beta, s, \hat{\Gamma}, F\}$. Associated with this new environment there is a new value function $V(s, a; \hat{\theta})$ and a new distribution $X^*(\hat{\theta})$. Now define $\eta(s, a)$ to be the solution of

$$V(s, a + \eta(s, a); \hat{\theta}) = V(s, a; \theta), \quad (81)$$

which corresponds to the transfer necessary to make the agent indifferent between living in the old environment and living in the new one (say from an initial steady state to a final steady state). Hence, the total transfer needed to compensate the agent for this policy change is given by

$$\int_{A \times S} \eta(s, a) dX^*(\theta). \quad (82)$$

Remark 12 Notice that the changes do not take place when the government is trying to compensate the households and that is why we use the original stationary distribution associated with θ to aggregate the households ($X^*(\theta)$).

If $\int_{A \times S} V(s, a) dX^*(\hat{\theta}) > \int_{A \times S} V(s, a) dX^*(\theta)$, does this necessarily mean that households are willing to accept this policy change? Not necessarily! Recall that comparing welfare requires us to compute the transition from one world to the other. Then, during the transition to the new steady state, the welfare losses may be very large despite agents being better off in the final steady state.

12.4 Business Cycles in an Aiyagari Economy

12.4.1 Aggregate Shocks

In this section, we consider an economy that is subject to both aggregate and idiosyncratic shocks. Consider the Aiyagari economy again, but with a production function that is subject to an aggregate shock z so that we have $zF(K, \bar{N})$.

Then the current aggregate capital stock is given by

$$K = \int a dX(s, a). \quad (83)$$

and next period aggregate capital is

$$K' = G(z, K) \quad (84)$$

The question is what are the sufficient statistics to predict the aggregate capital stock and, consequently, prices tomorrow? Are z and K sufficient to determine capital tomorrow? The answer to these questions is no, in general. It is only true if, and only if, the decision rules are linear. Therefore, X , the distribution of agents in the economy becomes a state variable (even in the stationary equilibrium).¹⁷

Then, the problem of an individual becomes

$$\begin{aligned} V(z, X, s, a) = \max_{c, a'} & u(c) + \beta \sum_{z', s'} \Pi_{zz'} \Gamma_{ss'}^{z'} V(z', X', s', a') \\ \text{s.t.} & c + a' = azf_k(K, \bar{N}) + szf_n(K, \bar{N}) \\ & K = \int adX(s, a) \\ & X' = G(z, X) \\ & c, a' \geq 0, \end{aligned} \quad (85)$$

where we replaced factor prices with marginal productivities. Computationally, this problem is a beast! So, how can we solve it? To fix ideas, we will first consider an economy with *dumb* agents!

Consider an economy in which people are stupid. By stupid, we mean that people believe tomorrow's capital depends only on K and not on X . This, obviously, is not an economy with rational expectations.

¹⁷ Note that with X we can compute aggregate capital.

The agent's problem in such a setting is

$$\begin{aligned}
\tilde{V}(z, X, s, a) &= \max_{c, a'} u(c) + \beta \sum_{z', s'} \Pi_{zz'} \Gamma_{ss'}^{z'} \tilde{V}(z', X', s', a') & (86) \\
s.t. \quad c + a' &= azf_k(K, \bar{N}) + szf_n(K, \bar{N}) \\
K &= \int adX(s, a) \\
X' &= \tilde{G}(z, K) \\
c, a' &\geq 0.
\end{aligned}$$

The next step is to allow people to become slightly smarter, by letting them use extra information, such as the mean and variance of X , to predict X' . Does this economy work better than our *dumb benchmark*? Computationally no! This answer, as stupid as it may sound, has an important message: agents' decision rules are approximately linear. It turns out that the approximations are quite reliable in the Aiyagari economy!

12.4.2 Linear Approximation Revisited

Let's now revisit our discussion of linear approximation in the context of the Aiyagari economy. As we can see in section 12.4.1, solving the heterogeneous agent model with aggregate shocks is computationally hard. We need to guess a reduced form rule to approximate the distribution for agents to forecast future prices, and when the model has frictions on several dimensions, there is little we can say on how to choose such a rule.

We can, however, use a linear approximation to obtain the model's solution around the steady state. The idea is as follows: starting from the steady state, we obtain the the impulse responses of the perfect foresight economy given a sequence of small deterministic shocks. Then, we use these responses to approximate the behavior of the main aggregates in the economy with heterogeneous agents by adding small stochastic shocks around the steady state. This method was recently proposed by Boppart,

Krusell, and Mitman (2018).¹⁸.

To fix ideas, let's consider the above Aiyagari economy with a TFP shock z . Let $\log(z_t)$ follow an AR(1) process with ρ as the autocorrelation parameter as $\log(z_t) = \rho \log(z_{t-1}) + \epsilon_t$. First, compute the path of the (log of the) shock by letting ϵ will go up by, say, one unit in period 0. Rewriting the process in its MA form, we have the full sequence of values $(1, \rho, \rho^2, \rho^3, \dots)$ to pin down the TFP path. Then, we can compute the transition path in the deterministic economy, with the agent taking as given the sequence of prices. Thus, solving the deterministic path is straightforward: we guess a path for price (or else we could also guess the path for an aggregate variable), solve the household's problem backwards from the final steady state back to initial steady state, and then derive the aggregate implications of the households' behavior and update our guess for the price path. This iterative procedure is also standard and fully nonlinear.

After solving the PFE, we have a sequence of aggregates we care about. We choose one of those, call it x , and we thus have a sequence $\{x_0, x_1, x_2, \dots\}$. Now consider the same economy subject to recurring aggregate shocks to z . Now we want to approximate the object of interest in that economy, call it \hat{x} . The key assumption behind this procedure is that we regard the \hat{x} as well approximated by a linear system of the sequence of x computed as a response to the one-time shock. A linear system means that the effects of shocks are linearly scalable and additive so that the *level* of \hat{x} at some future time T , after a sequence of random shocks to z is given by

$$\hat{x}_T \approx x_0 \epsilon_T + x_1 \epsilon_{T-1} + x_2 \epsilon_{T-2} + \dots$$

or in deviation from steady state

$$(\hat{x}_T - x_{ss}) \approx (x_0 - x_{ss}) \epsilon_T + (x_1 - x_{ss}) \epsilon_{T-1} + (x_2 - x_{ss}) \epsilon_{T-2} + \dots$$

where ϵ_t is the innovation to $\log(z_t)$ at period t . Thus, the model with aggregate shocks can be obtained by mere simulation based on the one deterministic path. It corresponds to the superposition of non-linear impulse response functions derived from the PFE.

¹⁸ The description of the method below is from that paper with minor modifications.

12.5 Aiyagari Economy with Job Search

In the Aiyagari model we have seen, the labor market is assumed to be competitive and everybody is employed at the wage rate w . Now, we want to add the possibility of agents being in one of two labor market status: $\varepsilon = \{0, 1\}$, where 0 stands for unemployment and 1 for the case in which the agent is employed.

Agents can now exert effort h while searching for a job. Although exerting search effort provides some disutility, it also increases the probability of finding a job. Call that probability $\phi(h)$, with $\phi' > 0$. An employed worker, on the other hand, does not need to search for a new job and so $h = 0$, but his job can be destroyed with some exogenous probability δ . Let s be an employed worker's stochastic labor productivity, which is a first order Markov process with transition probabilities given by Γ .

The unemployed worker's problem is given by

$$V(s, 0, a) = \max_{c, a', h} u(c, h) + \beta \sum_{s'} \Gamma_{ss'} [\phi(h)V(s', 1, a') + (1 - \phi(h))V(s', 0, a')] \quad (87)$$

$$s.t. \quad c + a' = h + (1 + r)a$$

$$a' \geq 0.$$

Similarly, the employed worker's problem is as follows

$$V(s, 1, a) = \max_{c, a'} u(c) + \beta \sum_{s'} \Gamma_{ss'} [\delta V(s', 0, a') + (1 - \delta)V(s', 1, a')] \quad (88)$$

$$s.t. \quad c + a' = sw + (1 + r)a$$

$$a' \geq 0.$$

Exercise 43 Solve for the FOC and define the stationary equilibrium for this economy.

12.6 Aiyagari Economy with Entrepreneurs

Next, we will introduce entrepreneurs into the Aiyagari world. Suppose every period agents choose an occupation: to be either an entrepreneur or a worker. Entrepreneurs run their own business, by managing a project that combines her entrepreneurial ability (ϵ), capital (k), and labor(n); while workers supply labor in the market.

Let's denote $V^w(s, \epsilon, a)$ the value of a worker labor productivity s , and entrepreneurial ability ϵ , and wealth a . Similarly, denote $V^e(s, \epsilon, a)$ the value of an entrepreneur. The worker's problem is to choose tomorrow's occupation and wealth level as well as today's consumption for a given wage rate w and interest rate r .

$$V^w(s, \epsilon, a) = \max_{c, a', d \in \{0,1\}} u(c) + \beta \sum_{s', \epsilon'} \Gamma_{ss'} \Gamma_{\epsilon\epsilon'} [dV^w(s', \epsilon', a') + (1-d)V^e(s', \epsilon', a')] \quad (89)$$

$$s.t. \quad c + a' = ws + (1+r)a$$

$$a' \geq 0$$

Similarly, the entrepreneur's problem can be formulated as follows

$$V^e(s, \epsilon, a) = \max_{c, a', d \in \{0,1\}} u(c) + \beta \sum_{s', \epsilon'} \Gamma_{ss'} \Gamma_{\epsilon\epsilon'} [dV^w(s', \epsilon', a') + (1-d)V^e(s', \epsilon', a')] \quad (90)$$

$$s.t. \quad c + a' = \pi(s, \epsilon, a)$$

$$a' \geq 0$$

Note the entrepreneur's income is from profits $\pi(a, s, \epsilon)$ rather than wage. We assume entrepreneurs have access to a DRS technology f that produces output using as inputs (k, n) . After paying factors

and loans needed to operate the business, the entrepreneurs' profits are given by

$$\pi(s, \epsilon, a) = \max_{k, n} \epsilon f(k, n) + (1 - \delta)k - (1 + r)(k - a) - w \max\{n - s, 0\} \quad (91)$$

$$s.t. \quad k - a \leq \phi a$$

The constraint here reflects the fact that entrepreneurs can only make loans up to a fraction ϕ of his total wealth. A limit of this model is that entrepreneurs never make an operating loss within a period, as they can always choose $k = n = 0$ and earn the risk free rate on saving. In this model, agents with high entrepreneurial ability have access to an investment technology f that provides higher returns than workers with high labor productivity and therefore the entrepreneurs accumulate wealth faster.

So, who is going to be an entrepreneur in this economy? In a world without financial constraints, wealth will play no role. There would be a threshold ϵ^* above which an agent would decide to become an entrepreneur. With financial constraints, this changes and wealth now plays an important role. Wealthy individuals with high entrepreneurial ability will certainly be entrepreneurs, while the poor with low entrepreneurial ability will become workers. For the other cases, it depends. If the entrepreneurial ability is persistent, poor individuals with high entrepreneurial ability will save to one day become entrepreneurs, while rich agents with low entrepreneurial ability will lend their assets and become workers.

Exercise 44 *Solve for the FOC and define the RCE for this economy.*

12.7 Other Extensions

There are many more interesting applications. One of these is the economy with unsecured credit and default decisions. The price of lending will now incorporate the possibility of default. For simplicity, assume that if the agent decides to default, she live in autarky forever after. In that case, she is excluded from the financial market and has to consume as much as her labor earnings allow. Let the

individual's budget constraint in the case of no default be given by

$$c + q(a')a' = a + ws,$$

where s is labor productivity with transition probabilities given by $\Gamma_{ss'}$. The problem of an agent is thus given by

$$V(s, a) = \max \left\{ u(ws) + \beta \sum_{s'} \Gamma_{ss'} \bar{V}(s'), u(ws + a - q(a')a') + \beta \sum_{s'} \Gamma_{ss'} V(s', a') \right\} \quad (92)$$

$$s.t. \quad a' \geq 0,$$

where $\bar{V}(s') = \frac{1}{1-\beta} u(ws')$ is the value of autarky.

13 Monopolistic Competition

13.1 Benchmark Monopolistic Competition

The two most important macroeconomic variables are perhaps output and inflation (movement in the aggregate price). In this section we take a first step in building a theory of aggregate price. To achieve this, we need a framework in which firms can choose their own prices and yet the aggregate price is well defined and easy to handle. The setup of Dixit and Stiglitz (1977) with monopolistic competition is such a framework.

In an economy with monopolistic competition, firms are sufficiently "different" so that they face a downward sloping demand curve and thus price discriminate, but also sufficiently small so that they ignore any strategic interactions with their competitors. We thus assume there are infinitely many measure 0 firms, each producing one variety of goods. Varieties span on the $[0, n]$ interval and are imperfect substitutes. Consumers have a "taste for variety" in that they prefer to consume a diversified bundle of goods (this gives firms some market power as we want). The consumer's utility function will

have the constant elasticity of substitution (CES) form

$$u\left(\{c(i)\}_{i \in [0, n]}\right) = \left(\int_0^n c(i)^{\frac{\sigma-1}{\sigma}} di\right)^{\frac{\sigma}{\sigma-1}}$$

where σ is the elasticity of substitution, which is a constant (as the name CES suggests), and $c(i)$ is the quantity consumed of variety i . For simplicity, we will rename $c(i) = c_i$. For now, we will assume the agent receives the exogenous *nominal* income I and is endowed with one unit of time.

We can now solve the household problem

$$\begin{aligned} \max_{\{c_i\}_{i \in [0, n]}} & \left(\int_0^n c_i^{\frac{\sigma-1}{\sigma}} di\right)^{\frac{\sigma}{\sigma-1}} \\ \text{s.t.} & \int_0^n p_i c_i di \leq I \end{aligned}$$

and derive the FOC, which relates the demand for any varieties i and j as

$$c_i = c_j \left(\frac{p_i}{p_j}\right)^{-\sigma}$$

Multiplying both sides by p_i and integrating over i , we get the downward sloping demand curve faced by an individual firm producing variety i as

$$c_i^* = \frac{I}{\int_0^n p_j^{1-\sigma} dj} p_i^{-\sigma}$$

We can see that the demand for variety i depends both on the price of variety i and some measure of “aggregate price”. It is actually convenient to define the aggregate price index P as follows

$$P = \left(\int_0^n p_j^{1-\sigma} dj\right)^{\frac{1}{1-\sigma}}$$

and thus the demand faced by the firm producing variety i can be reformulated as

$$c_i^* = \frac{I}{P} \left(\frac{p_i}{P}\right)^{-\sigma}$$

where the first term is real income and the second is a measure of relative price of variety i .

Exercise 45 Show the following within the monopolistic competition framework above:

1. σ is the elasticity of substitution between varieties.
2. Price index P is the expenditure to purchase a unit-level utility for consumers.
3. Consumer utility is increasing in the number of varieties n .

We are now ready to characterize the firm's problem. Let's assume that the production technology is linear in its inputs and so one unit of output is produced with one unit of labor linearly, i.e., $f(\ell_j) = \ell_j$. Let the nominal wage rate be given by W . Also, recall that the quantity of variety j demanded by the representative agent is such that $f(\ell_j) = c_j^*$. Then, the firm producing variety j solves the following problem

$$\begin{aligned} \max_{p_j} \pi(p_j) &= p_j c_j^*(p_j) - W c_j^*(p_j) \\ \text{s.t. } c_j^* &= \frac{I}{P} \left(\frac{p_j}{P} \right)^{-\sigma} \end{aligned}$$

Recall that we assume firms are sufficiently small so they would ignore the effect of their own pricing strategies on aggregate price index P , which greatly simplify the algebra. By solving for the FOC, we get the straightforward pricing rule

$$p_j^* = \frac{\sigma}{\sigma - 1} W \quad \forall j$$

where $\frac{\sigma}{\sigma - 1}$ is a constant mark-up over the marginal cost, which reflects the elasticity of substitution of consumers. When varieties are very close substitutes ($\sigma \rightarrow \infty$), price just converge to the factor price W . Note that all firms follow the same pricing strategy, which is independent of the variety j .

We can now define an equilibrium for this simple economy.

Definition 25 Set the wage as the numeraire. An equilibrium consists of prices $\{p_i^*\}_{i \in [0, n]}$, the aggre-

gate price index P , household's consumption $\{c_i^*\}_{i \in [0, n]}$, income I , firm's labor demand $\{\ell_i^*\}_{i \in [0, n]}$ and profits $\{\pi_i^*\}_{i \in [0, n]}$, such that

1. Given prices, $\{c_i^*\}_{i \in [0, n]}$ solves the household's problem
2. Given P and I , p_i^* and π_i^* solve the firm's problem $\forall i \in [0, n]$
3. The aggregate price index satisfies

$$P = \left(\int_0^n p_j^{1-\sigma} dj \right)^{\frac{1}{1-\sigma}}$$

4. Markets clear

$$\begin{aligned} \int \ell_i^* di &= 1 \\ 1 + \int \pi_i^* di &= I \end{aligned}$$

Note that in a symmetric equilibrium we have $c_i^* = \bar{c}$, $p_i^* = \bar{p}$, $n_i^* = \bar{n}$, $\pi_i^* = \bar{\pi}$ for all i .

13.2 Price Rigidity

We now have a simple theory of aggregate price P , which is ultimately shaped by the consumer's elasticity of substitution across varieties. However, we are still silent on inflation. To study inflation, and to have meaningful interactions between output and inflation, we need i) a dynamic model and ii) some source of nominal frictions.

Nominal frictions mean that nominal variables (things measured in dollars, say, quantity of money) can affect real variables. The most popular friction used is called *price rigidity*. With price rigidity, firms cannot adjust their prices freely. Two commonly used specifications to achieve this in the model are *Rotemberg pricing* (menu costs) and *Calvo pricing* (fairy blessing).

In Rotemberg pricing, firms face adjustment cost $\phi(p_j, p_j^-)$ when changing their prices p_j each period from p_j^- . Let S summarize the aggregate state and let $I(S)$, $W(S)$, and $P(S)$. Then the firm's problem under Rotemberg pricing in a dynamic setup is as follows:

$$\Omega(S, p_j^-) = \max_{p_j} p_j c_j^* - W(S) c_j^* - \phi(p_j, p_j^-) + \mathbb{E} \left[\frac{1}{R(G(S))} \Omega(G(S), p_j) \right], \quad (93)$$

where demand is taken as given and thus $c_j^* = \left(\frac{p_j}{P(S)} \right)^{-\sigma} \frac{I(S)}{P(S)}$. Each period, firms choose the price that maximizes the expected present discounted value of the flow profit. Without capital, the aggregate state S includes P^- and the aggregate shocks. Rotemberg is easy in terms of algebra when we assume a quadratic price adjustment cost.

Another popular version of price rigidity is Calvo pricing. Instead of facing adjustment costs, there is some positive probability $(1 - \theta)$ so that the firm cannot adjust its price. When setting the price, the firm now needs to incorporate the possibility of not being allowed to adjust its price. A firm that can change its price is given by

$$\begin{aligned} \Omega^1(S, p_j^-) = & \max_{p_j} p_j c_j^* - W(S) c_j^* + (1 - \theta) \mathbb{E} \left[\frac{1}{R(G(S))} \Omega^0(G(S), p_j^-) \right] \\ & + \theta \mathbb{E} \left[\frac{1}{R(G(S))} \Omega^0(G(S), p_j) \right], \end{aligned} \quad (94)$$

where demand is taken as given and thus $c_j^* = \left(\frac{p_j}{P(S)} \right)^{-\sigma} \frac{I(S)}{P(S)}$, and $\Omega^0(G(S), p_j^-)$ is the value of firm that cannot change its price

$$\begin{aligned} \Omega^0(S, p_j^-) = & [p_j^- - W(S)] c_j^* + (1 - \theta) \mathbb{E} \left[\frac{1}{R(G(S))} \Omega^0(G(S), p_j^-) \right] \\ & + \theta \mathbb{E} \left[\frac{1}{R(G(S))} \Omega^0(G(S), p_j^-) \right]. \end{aligned} \quad (95)$$

Not that the Calvo price setting imposes a nasty restriction on firms that cannot update their prices, which is that they at some point they can sell at a loss and cannot do anything to counteract that. That is even worse if the Calvo fairy imposes wage rigidity, forcing workers to work at a loss.

Exercise 46 *Derive the following for the dynamic model with Calvo pricing*

1. *Solve the firm's problem in sequence space and write the firm's equilibrium pricing $p_{j,t}$ as a function of present and future aggregate prices, wages, and endowments: $\{P_t, W_t, I_t\}_{t=0}^{\infty}$.*
2. *Show that under flexible pricing ($\theta = 1$), the firm's pricing strategy is identical to the static model.*
3. *Show that with price rigidity ($\theta < 1$), the firm's pricing strategy is identical to the static model in the steady state with zero inflation.*

14 Extreme Value Shocks

Now we introduce a tool commonly used in empirical micro, which are extreme value shocks. These are used to make sense of models with discrete choices so that we can group agents in bins. Now, a fraction of agents in each bin will make one choice and their remainder another. In macro models, we have decision rules that are functions of states. But sometimes we want the state to be an important ingredient for the agent, but not the only one. So we want to go from decision rules to decision densities defined as conditional probabilities.

This allows us to let agents make mistakes. For instance, in environments with private information it may be hard to distinguish who is making which decisions, and there may be issues with pooling or separating equilibria. In that regard, extreme value shocks make all equilibria pooling because there is the possibility that all agents make a certain choice, making it infeasible to separate agents. Extreme value shocks also give a natural way to deal with off-equilibrium behavior since all different behavior can now be on the equilibrium path.

Consider the following discrete choice setting. There are finitely many (ranked or not ranked) exogenous states $s \in S$ and an agent $i \in I$ can make two choices by choosing $d \in \{0, 1\}$ that maximizes her utility $\max_d u(s, d)$. Now consider an idiosyncratic extreme value shock ϵ^{id} to an agent in state s if

choice d is made. Then her problem is

$$\max_d u(s, d) + \epsilon^{id}$$

The choice d is now a conditional probability, which depends on the distribution of ϵ and the difference between $u(s, 0)$ and $u(s, 1)$. Assuming it is extreme value makes solving this problem easy. Let $\epsilon \sim G(\mu, \frac{1}{\alpha})$ be extreme value (Gumbel) distributed shocks with cdf $F_\epsilon(x) = e^{-e^{-\alpha(x-\mu)}}$, where μ is the mode and $\alpha > 0$ is a shape parameter. The larger is α , the smaller the variance is (given by $\frac{\pi^2}{6\alpha^2}$). The mean of a Gumbel distributed random variable is $\mathbb{E}[\epsilon] = \mu + \frac{\gamma}{\alpha}$, where $\gamma \approx 0.5772$ is the Euler-Mascheroni constant.

In many occasions we have to deal with the maximum of these extreme value shocks and in particular the expected value of that maximum. For the discrete case, let $X^N = \max\{\epsilon^1, \epsilon^2, \dots, \epsilon^N\}$ and $M^N = \mathbb{E}[X^N]$. Consider the case with the mode $\mu = 0$. Then, if all $\epsilon^i \stackrel{i.i.d.}{\sim} G(0, \frac{1}{\alpha})$ and α is the same across i , then we have that the cdf of X^N is the product of these Gumbel distributions $F_\epsilon(x)$ and thus

$$\begin{aligned} X^N &\sim G\left(\frac{1}{\alpha} \ln(N), \frac{1}{\alpha}\right) \\ M^N &= \frac{1}{\alpha} \ln(N) + \frac{\gamma}{\alpha} \end{aligned}$$

Note that if we want M^N to be independent of the number of realizations so that $M^N = \bar{M}$, then we choose the shape parameter to be $\alpha(N) = \frac{\gamma + \ln(N)}{\bar{M}}$.

The optimal choice of d is now a choice probability that only depends on the difference of utilities and the shape parameter α , which is inversely related to the variance. We now have the probability of making choice $d = 1$ in state s given by the binary logit probability

$$q^1(s) = \frac{1}{1 + e^{\alpha[u(s,0) - u(s,1)]}}$$

where α is a measure of fickleness (i.e. when the variance of the extreme value shock shrinks (or α increases), the probability of choosing $d = 1$ converges to 0).

If the mode $\mu \neq 0$, then

$$\begin{aligned} X^N &\sim G\left(\frac{1}{\alpha} \ln(Ne^{\alpha\mu}), \frac{1}{\alpha}\right) \\ M^N &= \frac{1}{\alpha} \ln(Ne^{\alpha\mu}) + \frac{\gamma}{\alpha} \end{aligned}$$

and M^N is independent of N for $\alpha(N) = \frac{\gamma + \ln(N)}{M - \mu}$, which is still in closed form. Alternatively, if we allow each extreme value shock to have different modes so that $\epsilon^i \sim G(\mu^i, \frac{1}{\alpha})$, then maximum of these shocks and its expected value are respectively

$$\begin{aligned} X^N &\sim G\left(\frac{1}{\alpha} \ln\left(\sum_{i=1}^N e^{\alpha\mu^i}\right), \frac{1}{\alpha}\right) \\ M^N &= \frac{1}{\alpha} \ln\left(\sum_{i=1}^N e^{\alpha\mu^i}\right) + \frac{\gamma}{\alpha} \end{aligned}$$

and if we want M^N to be independent of the number of shocks, we require $\alpha(N) = \frac{\gamma + \ln\left(\sum_{i=1}^N e^{\alpha(N)\mu^i}\right)}{M}$, which has no closed-form solution. This also works when the extreme value shocks have a continuous support. Suppose we have a continuum of choices $S = [\underline{w}, \bar{w}]$. Now

$$\begin{aligned} X^S &= \max\{\epsilon^w | w \in [\underline{w}, \bar{w}]\} \\ M^S &= \mathbb{E}[X^S] \end{aligned}$$

and if we want M^S independent of S , we can set $\alpha(S) = \frac{\gamma + \ln\left(\int e^{\alpha(S)\mu(w)} dw\right)}{M}$.

So now suppose that we want to know what the expected value from choosing $d = \{0, 1\}$ given the extreme value shocks, i.e. we are interested in the Emax operator (for the discrete case)

$$\begin{aligned} \mathbb{E}\left[\max_d (u(s, d) + \epsilon^{id})\right] &= \int \max_d (u(s, d) + \epsilon^{id}) dF_\epsilon \\ &= \mu + \frac{\gamma}{\alpha} + \frac{1}{\alpha} \ln(e^{\alpha u(s,0)} + e^{\alpha u(s,1)}) \end{aligned}$$

15 Macro and Covid-19

15.1 Basic SIR Model

Given the ongoing reach of the coronavirus, it is a timely to think about from a macroeconomic perspective. The idea is to embody a macro model with an epidemiological model. We will consider a short time horizon to avoid introducing investment and focus on optimal policy to reduce the spread of the disease. To study these mitigation policies, we will allow heterogeneity in individuals' age and sectors of activity. The reason is that not everybody faces the same circumstances, older people are more likely to be killed by the disease and younger individuals tend to work in different sectors that are not as affected by the virus. We also have to worry about which allocation mechanism to choose to model this. Since the pandemic involves a large externality and thus people do not internalize take the socially optimal action with respect to social distancing. So all choices are going to be made by the government.

We start with the basic SIR's epidemiological model (S for susceptible, I for infected, and R for recovered). There are thus three health states $j \in \{s, i, r\}$ with associated population shares S, I, R given the initial conditions $S(0), I(0), R(0)$ (all variables are shares of measure 1 population). Let β be the rate of infection of the susceptible and κ the rate of recovery of the infected. The reproduction number that is commonly referred to as R_0 relates the rate of infection with the recovery rate as $R_0 = \frac{\beta}{\kappa}$. Then, the laws of motion are

$$\dot{S}(t) = -\beta S(t)I(t) \tag{96}$$

$$\dot{I}(t) = \beta S(t)I(t) - \kappa I(t) \tag{97}$$

$$\dot{R}(t) = \kappa I(t) \tag{98}$$

Let's start with a small fraction of people infected, with $I(0) = \epsilon$, $S(0) = 1 - \epsilon$, and $R(0) = 0$ for $\epsilon > 0$ very small. For t close to zero (ie the beginning of the pandemic), we have that $I(t) \approx 0$, $S(t) \approx 1$.

Then the growth rate of infections is roughly constant and given by $\frac{\dot{I}(t)}{I(t)} = \beta S(t) - \kappa \approx \beta - \kappa$, while the growth rate of susceptible is $\frac{\dot{S}(t)}{S(t)} = \beta I(t) \approx 0$. We write the fraction of infected as

$$I(t) = I(0)e^{\kappa\left(\frac{\beta}{\kappa}S(0)-1\right)t} \approx I(0)e^{\kappa\left(\frac{\beta}{\kappa}-1\right)t}.$$

So the spread of the virus depends strongly on reproduction number. If $R_0 = \frac{\beta}{\kappa} > 1$, then the share of infected grows exponentially early on. If instead $R_0 = \frac{\beta}{\kappa} < 1$, the share of infected people falls to zero and the virus disappears immediately.

To understand the long-run, let's first look at the ratio of the new infected to the new susceptible as a function of R_0 , given by $\frac{\dot{I}(t)}{\dot{S}(t)} = -1 + \frac{1}{R_0 S(t)}$. Integrating over $S(t)$ yields

$$I(t) = -S(t) + \frac{\ln(S(t))}{R_0} + q, \tag{99}$$

where q is a constant of integration independent of time. Evaluating this expression at $t = 0$ (with $R(0) = 0$ so that $I(0) + S(0) = 1$) gives us an expression for q as $q = 1 - \frac{\ln(S(0))}{R_0}$.

We are interested in the steady state in which the share of population infected is 0 and the share of people susceptible is stable $S^* = S(\infty)$. Using the fact that $I(\infty) = 0$ and evaluating (99) at $t = \infty$ yields the transcendental equation

$$S^* = 1 + \frac{\ln(S^*/S(0))}{R_0},$$

with $I^* = 0$ and $R^* = 1 - S^*$. What are the properties of that steady state? If $R_0 > 1$ and $S(0) < 1$, \exists a unique long-run S^* , which is strictly decreasing in R_0 and strictly increasing in $S(0)$. Alternatively, for $R_0 \approx 1$ (but > 1), $S^* = \frac{1}{R^*}$ and $\hat{R}^* = \frac{R_0-1}{R_0}$. This approximation uses $S(0) \approx 1$ and $\ln(1/R_0) = -\ln(R_0) = -\ln(1 + R_0 - 1) \approx 1 - R_0$.

15.2 SIR with Heterogeneous Agents

Now we add heterogeneous agents to assess two policies: (i) mitigation/shutdown (less output but also less contagion) and (ii) redistribution (towards those whose jobs are shuttered). The idea is to understand what is the optimal amount of transfers the government should give to those that are affected. There is a tradeoff however. Mitigation creates the need for more redistribution because there will be more people in bad shape. At the same time, redistribution is costly because it is expensive to give money to the affected people, so we want less mitigation.

We call this model SAFER for stages of the disease: (i) **S**usceptible, (ii) **I**nfected **A**symptomatic, (iii) **I**nfected with **F**lu-like symptoms, (iv) **I**nfected and needing **E**mergency hospital care, and (v) **R**ecovered (or dead). Now recovery is possible at each stage. The three types of infected people can spread the virus in different ways: those that are A spread it at work, while consuming, and at home; those that are F at home only; and those that are E spread it to health-care workers.

People can either be young or old $i \in \{y, o\}$. Only young work, but they are also more prone to contagion because they work. The old do worse conditional on contagion. There are two sectors of production. The basic sector b includes health-care, food production, etc, and we want to keep that sector running. The luxury sector ℓ includes restaurants, entertainment, etc., and are more prone to shutdown and thus face unemployment risk, but are less likely to get infected.

The interactions between health and wealth are as follows. On one hand, mitigation reduces contagion, the risk of hospital overload, and average consumption, but also increases inequality as a result of more unemployment in the shuttered sectors. On the other hand, redistribution helps the unemployed.

Let the lifetime utility for the old

$$E \left\{ \int e^{-\rho_o t} [u^o(c_t^o) + \bar{u} + \hat{u}_t^j] dt \right\}$$

where ρ_o is the time discount rate, $u^o(c_t^o)$ is the instantaneous utility from old age consumption c_t^o , \bar{u} is the value of life, and \hat{u}_t^j is the intrinsic utility from health status j (zero for $j \in \{s, a, r\}$). Similar

lifetime utility for the *young*, with differences in expected longevity through $\rho_y \neq \rho_o$ (no aging).

Young are permanently assigned to either sector b or ℓ . Each sector operates a linear production technology and so output equals number of workers. Only workers with $j \in \{s, a, r\}$ work. So output in the basic sector is given by

$$y^b = x^{ybs} + x^{yba} + x^{ybr}$$

while output in luxury sector is

$$y^\ell = [1 - m] (x^{y\ell s} + x^{y\ell a} + x^{y\ell r}).$$

Total output is then given by

$$y = y^b + y^\ell.$$

We assume there is a fixed amount of output $\eta\Theta$ that is spent on emergency health care, where Θ measures capacity of emergency health system and η is its unit cost.

The virus transmits according to the following probabilities. At work, young S workers are infected by A workers with probability $\beta_w(m)$. While consuming, young and old S are infected by A people with probability $\beta_c(m) \times y(m)$. While at home, young and old S are infected by A and F with probability β_h . Finally, in the emergency room, basic S workers are infected by E with probability β_e . Note that $\beta_w(m)$ and $\beta_c(m)$ depend on mitigation m . Mitigation reduces the number of active workers, which reduces workplace transmission, but it also reduces output $y(m)$ and thus transmission while consuming. So, what are these probabilities?

$$\beta_w(m) = \frac{y^b}{y(m)} \alpha_w + \frac{y^\ell(m)}{y(m)} \alpha_w (1 - m),$$

where α_w is related to social distancing and m is a policy that can be influenced by policy. The probability $\beta_c(m)$ is defined in a similar fashion.

So what are the flows of susceptible into the asymptomatic? It is given by

$$\begin{aligned}
\dot{x}^{ybs} &= -\beta_w(m) [x^{yba} + (1-m)x^{y\ell a}] x^{ybs} \\
&\quad - [\beta_c(m)x^a y(m) + \beta_h(x^a + x^f) + \beta_e x^e] x^{ybs} \\
\dot{x}^{y\ell s} &= -[\beta_w(m) [x^{yba} + (1-m)x^{y\ell a}] (1-m)x^{y\ell s}] \\
&\quad - [\beta_c(m)x^a y(m) + \beta_h(x^a + x^f)] x^{y\ell s} \\
\dot{x}^{os} &= -[\beta_c(m)x^a y(m) + \beta_h(x^a + x^f)] x^{os}
\end{aligned}$$

Similarly, the flow into other health states is for each type $j \in \{yb, y\ell, o\}$ given by

$$\begin{aligned}
\dot{x}^{ja} &= -\dot{x}^{js} - (\sigma^{jaf} + \sigma^{jar}) x^{ja} \\
\dot{x}^{jf} &= \sigma^{jaf} x^{ja} - (\sigma^{jfe} + \sigma^{jfr}) x^{jf} \\
\dot{x}^{je} &= \sigma^{jfe} x^{jf} - (\sigma^{jed} + \sigma^{jer}) x^{je} \\
\dot{x}^{jr} &= \sigma^{jar} x^{ja} + \sigma^{jfr} x^{jf} + (\sigma^{jer} - \varphi) x^{je} \\
\varphi &= \lambda_o \max\{x^e - \Theta, 0\}.
\end{aligned}$$

The way redistribution happens is true costly transfers between workers and non-workers (old, sick, unemployed). Let c^w be the workers share of consumption level, c^n the non-workers share of consumption level, and $T(c^n)$ the per-capita cost of transferring c^n to non-workers. Then, the aggregate resource constraint is given by

$$\mu^w c^w + \mu^n c^n + \mu^n T(c^n) = \mu^w - \eta\Theta$$

where the measures of non-working and working households satisfy

$$\begin{aligned}
\mu^n &= x^{y\ell f} + x^{y\ell e} + x^{ybf} + x^{ybe} + m(x^{y\ell s} + x^{y\ell a} + x^{y\ell r}) + x^o \\
\mu^w &= x^{ybs} + x^{yba} + x^{ybr} + [1-m](x^{y\ell s} + x^{y\ell a} + x^{y\ell r}) \\
\nu^w &= \frac{\mu^w}{\mu^w + \mu^n}
\end{aligned}$$

The social welfare function that the social planner maximizes is static since consumption allocation does not affect disease dynamics. With log-utility and equal weights, the period social welfare is given by

$$W(x, m) = \max_{c^n, c^w} [\mu^w \log(c^w) + \mu^n \log(c^n)] + (\mu^w + \mu^n) \bar{u} + \sum_{i,j \in \{f,e\}} x^{ij} \hat{u}^j$$

and maximizing it subject to the resource constraint gives $\frac{c^w}{c^n} = 1 + T'(c^n)$. So we can rewrite the period welfare as

$$\begin{aligned} W(x, m) &= [\mu^w + \mu^n] w(x, m) \\ w(x, m) &= \log(c^n) + \nu \log(1 + T'(c^n)) + \bar{u} + \sum_{i,j \in \{f,e\}} \frac{x^{ij}}{\mu^w + \mu^n} \hat{u}^j \end{aligned}$$

and solving this problem can be done in two stages since a path for mitigation redistribution is a simple problem to solve.

Assume $\mu^n T'(c^n) = \mu^w \frac{\tau}{2} \left(\frac{\mu^n c^n}{\mu^w} \right)^2$. Then, the optimal allocation satisfies

$$\begin{aligned} c^n &= \frac{\sqrt{1 + 2\tau \frac{1-\nu^2}{\nu} \tilde{y}} - 1}{\tau \frac{1-\nu^2}{\nu}} \\ c^w &= c^n (1 + T'(c^n)) = c^n \left(1 + \tau \frac{1-\nu}{\nu} c^n \right) \end{aligned}$$

where $\tilde{y} = \nu - \frac{\eta\Theta}{\mu^w + \mu^n}$. Note that $(1 + \tau \frac{1-\nu}{\nu} c^n)$ is the effective marginal cost (MC) of transfers, which is increasing in c^n and τ , but decreasing in the share of workers ν . On the other hand, higher mitigation m reduces ν , and thus increases MC. This gives rise to a policy interaction between m and τ .

A A Farmer's Problem: Revisited

Consider the following problem of a farmer that we studied in class:

$$\begin{aligned}
 V(s, a) = \max_{c, a'} & \left\{ u(c) + \beta \sum_{s'} \Gamma_{ss'} V(s', a') \right\} \\
 \text{s.t.} & \quad c + qa' = a + s \\
 & \quad c \geq 0 \\
 & \quad a' \geq 0.
 \end{aligned} \tag{100}$$

As we discussed, we are in particular interested in the case where $\beta/q < 1$. In what follows, we are going to show that, under monotonicity assumption on the Markov chain governing s , the optimal policy associated with (100) implies a finite support for the distribution of asset holding of the farmer, a .¹⁹

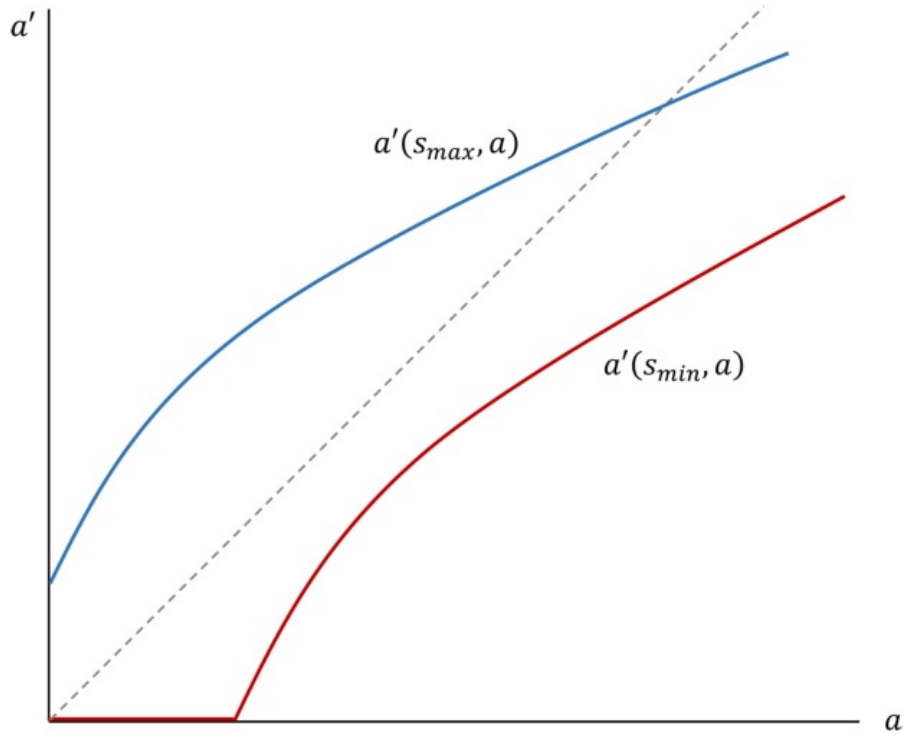
Before we start the formal proof, suppose $s_{\min} = 0$, and $\Gamma_{ss_{\min}} > 0$, for all $s \in S$. Then, the agent will optimally always choose $a' > 0$. Otherwise, there is a strictly positive probability that the agent enters tomorrow into state s_{\min} , where he has no *cash in hand* ($a' + s_{\min} = 0$) and is forced to consume 0, which is extremely painful to him (e.g. when Inada conditions hold for the instantaneous utility). Hence he will raise his asset holding a' to insure himself against such risk.

If $s_{\min} > 0$, then the above argument no longer holds, and it is indeed possible for the farmer to choose zero assets for tomorrow.

Notice that the borrowing constraint $a' \geq 0$ is affecting agent's asset accumulation decisions, even if he is away from the zero bound, because he has an incentive to ensure against the risk of getting a series of bad shocks to s and is forced to 0 asset holdings. This is what we call *precautionary savings motive*.

¹⁹ This section was prepared by *Keyvan Eslami*, at the *University of Minnesota*. This section is essentially a slight variation on the proofs found in ?. However, he accepts the responsibility for the errors.

Figure 1: Policy function associated with farmer's problem.



Next, we are going to prove that the policy function associated with (100), which we denote by $a'(\cdot)$, is similar to that in Figure 1. We are going to do so, under the following assumption.

Assumption 1 *The Markov chain governing the state s is monotone; i.e. for any $s_1, s_2 \in S$, $s_2 > s_1$ implies $E(s|s_2) \geq E(s|s_1)$.*

It is straightforward to show that, the value function for Problem (100) is concave in a , and bounded. Now, we can state our intended result as the following theorem.

Theorem 4 *Under Assumption 1, when $\beta/q < 1$, there exists some $\hat{a} \geq 0$ so that, for any $a \in [0, \hat{a}]$, $a'(s, a) \in [0, \hat{a}]$, for any realization of s .*

To prove this theorem, we proceed in the following steps. In all the following lemmas, we will assume that the hypotheses of Theorem 4 hold.

Lemma 1 *The policy function for consumption is increasing in a and s ;*

$$c_a(a, s) \geq 0 \text{ and } c_s(a, s) \geq 0.$$

Proof 1 *By the first order condition, we have:*

$$u'(c(s, a)) \geq \frac{\beta}{q} \sum_{s'} \Gamma_{ss'} V_a \left(s', \frac{a + s - c(s, a)}{q} \right),$$

with equality, when $a + s - c(s, a) > 0$.

For the first part of the lemma, suppose a increases, while $c(s, a)$ decreases. Then, by concavity of u , the left hand side of the above equation increases. By concavity of the value function, V , the right hand side of this equation decreases, which is a contradiction.

For the the second part, we claim that $V_a(s, a)$ is a decreasing function of s . To show this is the case, first consider the mapping T as follows:

$$\begin{aligned} T v(s, a) &= \max_{c, a'} \left\{ u(c) + \beta \sum_{s'} \Gamma_{ss'} v(s', a') \right\} \\ \text{s.t. } &c + qa' = a + s \\ &c \geq 0 \\ &a' \geq 0. \end{aligned}$$

Suppose $v_a^n(s, a)$ is decreasing in its first argument; i.e. $v_a^n(s_2, a) < v_a^n(s_1, a)$, for all $s_2 > s_1$ and $s_1, s_2 \in S$. We claim that, $v^{n+1} = T v^n$ inherits the same property. To see why, note that for $a^{n+1}(s, a) = a'$ (where a^{n+1} is the policy function associated with n 'th iteration) we must have:

$$u'(a + s - qa') \geq \frac{\beta}{q} \sum_{s'} \Gamma_{ss'} v_a^n(s', a'),$$

with strict equality when $a' > 0$. For a fixed value of a' , an increase in s leads to a decrease in both sides of this equality, due to the monotonicity assumption of Γ , and the assumption on v_a^n . As a result,

we must have

$$u'(a + s_2 - qa^{n+1}(s_2, a)) \leq u'(a + s_1 - qa^{n+1}(s_1, a)),$$

for all $s_2 > s_1$. By Envelope theorem, then:

$$v_a^{n+1}(s_2, a) \leq v_a^{n+1}(s_1, a).$$

It is straightforward to show that v^n converges to the value function V point-wise. Therefore,

$$V_a(s_2, a) \leq V_a(s_1, a),$$

for all $s_2 > s_1$.

Now, note that, by envelope theorem:

$$V_a(s, a) = u'(c(s, a)).$$

As s increases, $V_a(s, a)$ decreases. This implies $c(s, a)$ must increase.

Lemma 2 There exists some $\hat{a} \in \mathbb{R}_+$, such that $\forall a \in [0, \hat{a}]$, $a'(a, s_{\min}) = 0$.

Proof 2 It is easy to see that, for $a = 0$, $a'(a, s_{\min}) = 0$. First of all, note the first order condition:

$$u_c(c(s, a)) \geq \frac{\beta}{q} \sum_{s'} \Gamma_{ss'} u_c(c(s', a'(s, a))),$$

with equality when $a'(s, a) > 0$. Under the assumption that $\beta/q < 1$, we have:

$$\begin{aligned} u_c(c(s_{\min}, 0)) &= \frac{\beta}{q} \sum_{s'} \Gamma_{s_{\min}s'} u_c(c(s', a'(s_{\min}, 0))) \\ &< \sum_{s'} \Gamma_{ss'} u_c(c(s', a'(s_{\min}, 0))). \end{aligned}$$

By Lemma 1, if $a' = a'(0, s_{\min}) > a = 0$, then $c(s', a') > c(s_{\min}, 0)$ for all $s' \in S$, which leads to a contradiction.

Lemma 3 $a'(s_{\min}, a) < a$, for all $a > 0$.

Proof 3 Suppose not; then $a'(s_{\min}, a) \geq a > 0$ and as we showed in Lemma 2:

$$u_c(c(s_{\min}, a)) < \sum_{s'} \Gamma_{ss'} u_c(c(s', a'(s_{\min}, a))).$$

Contradiction, since $a'(s_{\min}, a) \geq a$, and $s' \geq s_{\min}$, and the policy function is monotone.

Lemma 4 There exists an upper bound for the agent's asset holding.

Proof 4 Suppose not; we have already shown that $a'(s_{\min}, a)$ lies below the 45 degree line. Suppose this is not true for $a'(s_{\max}, a)$; i.e. for all $a \geq 0$, $a'(s_{\max}, a) > a$. Consider two cases.

In the first case, suppose the policy functions for $a'(s_{\max}, a)$ and $a'(s_{\min}, a)$ diverge as $a \rightarrow \infty$, so that, for all $A \in \mathbb{R}_+$, there exist some $a \in \mathbb{R}_+$, such that:

$$a'(s_{\max}, a) - a'(s_{\min}, a) \geq A.$$

Since S is finite, this implies, for all $C \in \mathbb{R}_+$, there exist some $a \in \mathbb{R}_+$, so that

$$c(s_{\min}, a) - c(s_{\max}, a) \geq C,$$

which is a contradiction, since c is monotone in s .

Next, assume $a'(s_{\max}, a)$ and $a'(s_{\min}, a)$ do not diverge as $a \rightarrow \infty$. We claim that, as $a \rightarrow \infty$, c must grow without bound. This is quite easy to see; note that, by envelope condition:

$$V_a(s, a) = u'(c(s, a)).$$

The fact that V is bounded, then, implies that V_a must converge to zero as $a \rightarrow \infty$, implying that $c(s, a)$ must diverge to infinity for all values of s , as $a \rightarrow \infty$. But, this implies, if $a'(s_{\max}, a) > a$,

$$u_c(c(s_{\max}, a'(s_{\max}, a))) \rightarrow \sum_{s'} \Gamma_{s_{\max}s'} u_c(c(s', a'(s_{\max}, a))).$$

As a result, for large enough values of a , we may write:

$$\begin{aligned} u_c(c(s_{\max}, a)) &= \frac{\beta}{q} \sum_{s'} \Gamma_{s_{\max}s'} u_c(c(s', a'(s_{\max}, a))) \\ &< \sum_{s'} \Gamma_{s_{\max}s'} u_c(c(s', a'(s_{\max}, a))) \\ &\approx u_c(c(s_{\max}, a'(s_{\max}, a))). \end{aligned}$$

But, this implies:

$$c(s_{\max}, a) > c(s_{\max}, a'(s_{\max}, a)),$$

which, by monotonicity of policy function, means $a > a'(s_{\max}, a)$, and this is a contradiction.