

Macro II

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Announcements

- ▶ Exams are in the process of being graded.
- ▶ I heard nothing about the baseball extra credit!
- ▶ Homework 5 due next Thursday, homework 6 due May 4th.
- ▶ Today: Start heterogeneous agent models
- ▶ First: Huggett and Aiyagari.

Thinking about Uncertainty in Macroeconomic Models

- ▶ Typical assumptions in macroeconomics are a convex combination of

1. certainty equivalence:

$$u'(\bar{c}_{i,t}) = \beta E \left[\underbrace{(1 + r_{t+1})}_{GE} \underbrace{u'(\bar{c}_{i,t+1})}_{\text{Closer to Linear}} \right] \quad (1)$$

2. linearized decision rules:

$$\sum_{i=1}^N ((1 + r_{t+1})a_{i,t+1} + w_{i,t+1} - c_{i,t+1} - a_{i,t+2}) = 0 \quad (2)$$

$$\sum_{i=1}^N ((1 + r_{t+1})\beta_a \hat{S}_{i,t+1} + \beta_w (\hat{S}_{i,t+1}) - \beta_c \hat{S}_{i,t+1} - \beta_a \hat{S}_{i,t+2}) = 0 \quad (3)$$

- ▶ Trick in Krusell-Smith: assume that workers make a linear prediction about prices in the future.
- ▶ i.e., workers use OLS to predict future prices.

Heterogeneous Agent Models

- ▶ Workers change their behavior in response to uncertainty.
- ▶ First wave of heterogeneous agent models: how do aggregates change when *individual idiosyncratic* uncertainty is uninsurable.
- ▶ In other words: when agents must accumulate *precautionary savings* to insure against income shocks.
- ▶ Key “first wave” papers (no particular order):
 - ▶ Huggett (1993): Incomplete markets exchange economy with GE interest rate.
 - ▶ Imrohroglu (1989): Individual and aggregate uncertainty with fixed interest rate.
 - ▶ Aiyagari (1994): Incomplete markets production economy with GE interest rate.
 - ▶ Bewley (1986): Individual uncertainty with fixed interest rate.
- ▶ Krusell and Smith (1998): individual and aggregate uncertainty with GE interest rate.
- ▶ Do this using an approximation to the aggregate evolution of capital.

Heterogeneous Agent Models

- ▶ We can write a generic worker's problem as

$$\max_{\{c_t, i_t, l_t\}_{t=0}^{\infty}} E \sum_{t=0}^{\infty} \beta^t u(c_t) \quad (4)$$

$$\text{s.t. } c_t + i_t \leq r_t a_t + w_t l_t \quad (5)$$

$$a_{t+1} = (1 - \delta)a_t + i_t \quad (6)$$

$$a_{t+1} \geq \underline{a}_t \quad (7)$$

$$w_t \sim F \quad (8)$$

$$c_t \geq 0, l_t \geq 0, a_0 \text{ given} \quad (9)$$

- ▶ How we deal with prices r_t , w_t and choices c_t , i_t , l_t is central to equilibrium.

Recursive Formulation

- ▶ Can be written as

$$V(a) = u(c) + \beta E[V(a')] \quad (10)$$

$$\text{s.t. } c + i \leq ra + wl \quad (11)$$

$$a' = (1 - \delta)a + i \quad (12)$$

$$a' \geq \underline{a} \quad (13)$$

$$w \sim F \quad (14)$$

$$c \geq 0, l \geq 0, a_0 \text{ given} \quad (15)$$

- ▶ Under fairly general conditions, this inherits same properties as non-stochastic version.

Huggett (1993)

- ▶ Endowment economy, no aggregate risk.
- ▶ Setup:
 - ▶ Discrete time;
 - ▶ Continuum of heterogeneous agents;
 - ▶ Idiosyncratic endowment risk (labor income stochastic).
- ▶ Single bond, a , can be borrowed or saved.
- ▶ Borrowing limit, $\underline{a} \leq 0 \leq a_{it}$

Idiosyncratic Markov Income Uncertainty

- ▶ Suppose $wl = e$, $F[e'] = \pi(e'|e)$
- ▶ Two states: e_l, e_h
- ▶ Can be written as

$$V(a, e) = u(c) + \beta \sum_{e'} \pi(e'|e) V(a', e') \quad (16)$$

$$\text{s.t. } c + a' \leq (1 + r)a + e \quad (17)$$

$$a' \geq \underline{a} \quad (18)$$

$$c \geq 0, a_0 \text{ given} \quad (19)$$

- ▶ Agents want to build precautionary savings against idiosyncratic risk.

Equilibrium

- ▶ Define a distribution of agents over assets a and endowments e, ψ .
- ▶ Stationary equilibrium: aggregate state (ψ) is unchanging.
- ▶ Agents move around distribution, but LLN $\rightarrow \psi' = \psi$
- ▶ Define $\psi(B)$ such that given transition function P :

$$\psi(B) = \int_S P(x, B) d\psi \quad (20)$$

- ▶ $P(x, B)$ the probability that an agent with state x will have state $B \in \beta_S$ next period.
- ▶ B is a subset of the state space.

Stationary Equilibrium

- ▶ Roughly summarizing Huggett, 1993: A stationary equilibrium for this economy is a tuple (c, a', r, ψ) that satisfy
 1. c and a' solve the workers problem taking prices as given.
 2. Markets clear:
 - 2.1 consumption = production: $\int c(x)d\psi = \int ed\psi$
 - 2.2 no net savings: $\int a(x)d\psi = 0$
 3. ψ is stationary:

$$\psi(B) = \int_S P(x, B)d\psi \quad (21)$$

for all $B \in \beta_S$

Aiyagari (1994)

- ▶ Production economy, no aggregate risk.
- ▶ Firms employ capital, households save using capital (really assets loaned/borrowed from firm).
- ▶ Setup:
 - ▶ Discrete time;
 - ▶ Continuum of heterogeneous agents;
 - ▶ Idiosyncratic hours shocks (labor supply stochastic).
- ▶ Capital, k , can be borrowed or saved.
- ▶ Borrowing limit, $\underline{k} \leq 0 \leq k_{it}$

Heterogeneous Agent Production Economy

- ▶ In a production economy, the agent's problem is given by

$$V(k, \epsilon; \psi) = u(c) + \beta E[V(k' \epsilon'; \psi')] \quad (22)$$

$$\text{s.t. } c + k' \leq (1 + r(K, L) - \delta)k + w(K, L)\epsilon \quad (23)$$

$$k' \geq \underline{k} \quad (24)$$

$$\epsilon \sim \text{Markov}P(\epsilon'|\epsilon) \quad (25)$$

$$\psi' = \Psi(\psi) \quad (26)$$

$$c \geq 0, k \geq 0, k_0 \text{ given} \quad (27)$$

- ▶ ϵ is a markov process that yields hours worked.
- ▶ Ψ is an unspecified evolution of the aggregate state (k, ϵ) .
- ▶ Prices are determined from the firm's problem

Prices - The Firm's Problem

- ▶ How we handle prices determines the difficulty of this problem.
- ▶ In this economy, a single firm produces using labor (hours) and capital.

$$\Pi = \max_{K,L} F(K, L) - wL - rK \quad (28)$$

- ▶ This yields standard competitive prices for the rental rates.

Information

- ▶ What information do workers need in order to be able to solve this problem?
- ▶ Current period:
 - ▶ interest rate, $r(K, L)$. This is known from being told the aggregates at the beginning of the period.
 - ▶ wage rate, $w(K, L)$. This is known from being told the aggregates at the beginning of the period.
- ▶ Future:
 - ▶ interest rate and wage rate next period.
 - ▶ These depend on capital and labor next period.
 - ▶ Thus, workers need to predict capital and labor in future.
- ▶ Rep. Agent model: just need to know their own decision rule.
- ▶ Here: need to know distribution across workers, and their decision rules.

Stationary Recursive Competitive Equilibrium

- A stationary RCE is given by pricing functions r, w , a worker value function $V(k, \epsilon; \psi)$, worker decision rules k', c , a type-distribution $\psi(k, \epsilon)$, and aggregates K and L that satisfy
1. k' and c are the optimal solutions to the worker's problem given prices.
 2. Prices are formed competitively from the firm's problem.
 3. Consistency between aggregate evolution and individual decision rules: ψ is the stationary distribution implied by worker decision rules.
 4. Aggregates are consistent with individual policy rules:
$$K = \int k d\psi, L = \int \epsilon d\psi$$

Return to Capital

- ▶ How does return to capital vary by
 - ▶ serial corr. (ρ) in labor income (think AR1 process)
 - ▶ and CRRA (μ)?

TABLE II

A. Net return to capital in %/aggregate saving rate in % ($\sigma = 0.2$)			
$\rho \backslash \mu$	1	3	5
0	4.1666/23.67	4.1456/23.71	4.0858/23.83
0.3	4.1365/23.73	4.0432/23.91	3.9054/24.19
0.6	4.0912/23.82	3.8767/24.25	3.5857/24.86
0.9	3.9305/24.14	3.2903/25.51	2.5260/27.36

B. Net return to capital in %/aggregate saving rate in % ($\sigma = 0.4$)			
$\rho \backslash \mu$	1	3	5
0	4.0649/23.87	3.7816/24.44	3.4177/25.22
0.3	3.9554/24.09	3.4188/25.22	2.8032/26.66
0.6	3.7567/24.50	2.7835/26.71	1.8070/29.37
0.9	3.3054/25.47	1.2894/31.00	-0.3456/37.63

- ▶ Higher ρ or μ , more saving, lower return.

Krussell-Smith (1998)

- ▶ In the previous model, we relied on the aggregate *certainty* of $\psi(k, \epsilon)$ for a solution by appealing to the law of large numbers.
- ▶ i.e., individuals move around the distribution, but those shocks offset and in the aggregate the distribution is unchanged.
- ▶ But what happens if there is aggregate *uncertainty*?
- ▶ Now the distribution changes in the equilibrium, and we need a way to incorporate this into worker decision rules.
- ▶ Krussell-Smith: Aiyagari + aggregate shocks.
- ▶ Some details:
 - ▶ Idiosyncratic labor shock $\{0,1\}$ markov.
 - ▶ Aggregate shocks.
 - ▶ Idiosyncratic shock prob. changes with agg. shocks.

Aggregate Uncertainty

- ▶ In a production economy, the agent's problem is given by

$$V(k, \epsilon, z; \psi) = u(c) + \beta E[V(k'\epsilon', z'; \psi')] \quad (29)$$

$$\text{s.t. } c + k' \leq (1 + r(z, K, L) - \delta)k + w(z, K, L)\epsilon \quad (30)$$

$$k' \geq \underline{k} \quad (31)$$

$$z' = \text{Markov}P(z'|z) \quad (32)$$

$$\epsilon \sim \text{Markov}P(\epsilon'|\epsilon, z') \quad (33)$$

$$\psi' = \Psi(\psi, z, z') \quad (34)$$

$$c \geq 0, k \geq 0, k_0 \text{ given}, z_0 \text{ given} \quad (35)$$

- ▶ ϵ is a markov process for employment $\epsilon \in \{0, 1\}$
- ▶ Ψ is an unspecified evolution of the aggregate state.
- ▶ z *also* evolves as a markov process.
- ▶ Prices are determined from the firm's problem.

Prices - The Firm's Problem

- ▶ How we handle prices determines the difficulty of this problem.
- ▶ In this economy, a single firm produces using labor (hours) and capital.

$$\Pi = \max_{K,L} zF(K, L) - wL - rK \quad (36)$$

- ▶ This yields standard competitive prices for the rental rates.

Laws of Motion

- ▶ The future aggregate state enters the probability of employment.
- ▶ This means that it impacts **all** of the laws of motion:

$$z' = \text{Markov}P(z'|z) \quad (37)$$

$$\epsilon \sim \text{Markov}P(\epsilon'|\epsilon, z') \quad (38)$$

$$k' \leq (1 + r(z, K, L) - \delta)k + w(z, K, L)\epsilon - c \quad (39)$$

$$\psi' = \Psi(\psi, z, z') \quad (40)$$

- ▶ Because shocks to z change employment status and prices.

Recursive Competitive Equilibrium

- ▶ An RCE is given by pricing functions r, w , a worker value function $V(k, \epsilon, z; \psi)$, worker decision rules k', c , a type-distribution $\psi(k, \epsilon)$, and aggregates K and L that satisfy
 1. k' and c are the optimal solutions to the worker's problem given prices.
 2. Prices are formed competitively from the firm's problem.
 3. Consistency between aggregate evolution and individual decision rules: ψ is the distribution implied by worker decision rules given the aggregate state.
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Type Distribution

- ▶ The type distribution is a problem.
- ▶ Each policy function and transition depends on the type distribution.
- ▶ But the type distribution is time-varying in response to aggregate shocks.
- ▶ Alternative: use a smaller number of moments that can be calculated quickly to characterize the type distribution.
- ▶ Like a “sufficient statistic” for the type distribution.
- ▶ Discuss the solution to this next time.

Business Cycle Effects

- ▶ This model is built to handle stochastic shocks.
- ▶ How do heterogeneous agents respond over a business cycle?

TABLE 2
AGGREGATE TIME SERIES

Model	Mean (k_t)	Corr(c_t, y_t)	Standard Deviation (i_t)	Corr(y_t, y_{t-4})
Benchmark:				
Complete markets	11.54	.691	.031	.486
Incomplete markets	11.61	.701	.030	.481
$\sigma = 5$:				
Complete markets	11.55	.725	.034	.551
Incomplete markets	12.32	.741	.033	.524
Real business cycle:				
Complete markets	11.56	.639	.027	.342
Incomplete markets	11.58	.669	.027	.339
Stochastic- β :				
Incomplete markets	11.78	.825	.027	.459

Conclusion

- ▶ Next time: Solving heterogeneous agent models.