

A Course on DSGE Models with Financial Frictions

Part 3: Asymmetric Information

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From Complete Markets to Financial Frictions

- To introduce financial frictions we need two deviations from the complete markets representative agent setting
 - Incomplete markets
 - Heterogeneous Agents
- A representative agent environment is in a sense an infinite agents setting where they can trade as much as necessary to eliminate idiosyncratic risk
- An example of market incompleteness:
- The Kiyotaki-Moore style collateral constraint $b_t \leq \theta k_t$

Financial Frictions: The BGG Model

- The two main streams of introducing financial frictions in DSGE models are
 - Asymmetric information
 - Limited commitment
- In this lecture we will go through one of the most seminal papers in the literature the [Bernanke *et al.* \(1999\)](#)
- A canonical NK model with a friction between the banks and the firms (called entrepreneurs)
- Eliminates $\mathbb{E}_t[\Lambda_{t,t+1}R_{t+1}] = \mathbb{E}_t[\Lambda_{t,t+1}R_{t+1}^K]$ of the RBC model and introduces a spread between the two discounted expected returns

Summary of the Model

- Main agents in the model: Households, entrepreneurs, retailers, capital producers and the government
- Households work, consume and save in **deposits**
- Entrepreneurs are risk neutral. They purchase physical capital from capital goods producers and produce goods combining capital and labour
- Finance capital purchases with their **net worth** and **bank loans**
- Retailers are present to introduce nominal rigidities without complicating the entrepreneurs problem
 - Production side: NK framework with monopolistic competition and sticky prices
 - We will not go through that today

Entrepreneurs: Overview

- The entrepreneur j borrows loans B_t from the financial intermediary at time t to purchase capital K_t at price Q_t
- **Loans** together with her **net worth** $N_{E,t}$ finance the expenditure on new capital $Q_t K_t$.
- Entrepreneur's balance sheet therefore is:

$$B_t = Q_t K_t - N_{E,t} \tag{1}$$

Entrepreneurs: The Friction

- At every t the entrepreneur receives an **idiosyncratic shock** ω_t
- Results in return on capital: $\omega_t R_t^K$
 - ω_t is iid across all entrepreneurs
 - Drawn from a density $f(\omega_t)$ with mean $E(\omega_t)=1$
- ω_t^j is **only observable** by entrepreneur j
- Costly State Verification (CSV) **Townsend (1979)**: Lenders to observe the state, need to pay a **monitoring cost**, a proportion μ of the gross return $\mu R_{t+1}^K Q_t K_t$

Entrepreneurs: No Aggregate Risk

- We start with the case of no aggregate risk
 - R_{t+1}^K is known in advance and only uncertainty is idiosyncratic to the firm
 - The optimal contract is a risky debt contract (see Appendix A of [Bernanke *et al.* \(1999\)](#) for more)
- Entrepreneurs choose B_t and $Q_t K_t$ given R_t^K
- The optimal contract can be characterized by a **gross non-default loan rate** Z_t and a **threshold value** for the idiosyncratic shock $\bar{\omega}_t$

$$\bar{\omega}_{t+1} = \frac{Z_t B_t}{R_{t+1}^K Q_t k_t} \quad (2)$$

Entrepreneurs: Optimal Contract

- Entrepreneurs who receive a $\omega_t \geq \bar{\omega}_t$
 - Repay the intermediary $Z_t B_t$
 - Keep the difference $\bar{\omega}_{t+1} R_{t+1}^K Q_t k_t - Z_t B_t$
- Entrepreneurs who receive a $\omega_t < \bar{\omega}_t$
 - Default and get nothing
 - Intermediary pays the monitoring costs and gets what it finds: $(1 - \mu) R_{t+1}^K Q_t K_t$

Entrepreneurs: Optimal Contract

- Under the optimal contract the lender should receive an expected return equal to its **opportunity cost of funds**
- Here, our bank's balance sheet is $B_t = D_t$ where D_t (deposits by households) is remunerated at the riskless rate R_t
- The loan contract must satisfy the bank's **incentive compatibility constraint** at time t

$$\underbrace{(1 - \mu)R_{t+1}^K Q_t K_t \int_0^{\bar{\omega}_{t+1}} \omega f(\omega) d\omega}_{\text{Default}} + \overbrace{(1 - p(\bar{\omega}_{t+1}))Z_t B_t}^{\text{No default}} = R_t B_t$$

where $p(\bar{\omega}_t)$ is the default probability

Entrepreneurs: Optimal Contract

- Using the $Z_t B_t = \bar{\omega}_{t+1} R_{t+1}^K Q_t k_t$, the constraint becomes

$$R_{t+1}^K Q_t K_t \left((1 - \mu) \int_0^{\bar{\omega}_{t+1}} \omega f(\omega) d\omega + \bar{\omega}_{t+1} (1 - p(\bar{\omega}_{t+1})) \right) \geq R_{t+1} B_t \quad (3)$$

- To simplify notation a bit let $\Gamma(\bar{\omega}_{t+1})$ to be the fraction of net capital received by the lender (the bank)
- $\mu G(\bar{\omega}_{t+1})$ to be monitoring costs:

$$\Gamma(\bar{\omega}_{t+1}) \equiv \int_0^{\bar{\omega}_{t+1}} \omega f(\omega) d\omega + \bar{\omega}_{t+1} (1 - p(\bar{\omega}_{t+1})) \quad (4)$$

$$G(\bar{\omega}_{t+1}) \equiv \int_0^{\bar{\omega}_{t+1}} \omega f(\omega) d\omega \quad (5)$$

Entrepreneurs: Introducing Aggregate Risk

- So far we were abstracting from aggregate risk
- Now price and return of capital are given but uncertain
- $\bar{\omega}_{t+1}$ will now generally depend on the ex-post realization of R_{t+1}^K
- Entrepreneur is willing to offer a return that is free of any aggregate risk
 - Conditional on the return R_{t+1}^K the borrower offers state contingent non-default payment guaranteeing an expected return equal to the riskless rate
 - IC now implies a set of contracts for each realization of R_{t+1}^K

Entrepreneurs: Net Worth and Optimal Choice of Capital

- The entrepreneur's payoff is

$$\mathbb{E}_t \left[R_{t+1}^K Q_t K_t \int_{\bar{\omega}_{t+1}}^{\infty} \omega f(\omega) d\omega - (1 - p(\bar{\omega}_{t+1})) Z_t B_t \right] =$$
$$\mathbb{E}_t \left[(1 - \Gamma(\bar{\psi}_{t+1})) R_{t+1}^K Q_t K_t \right] \quad (6)$$

- She maximizes (6) given the net worth $N_{E,t}$, subject to the incentive compatibility constraint (3) which, using (1), (4) and (5), can be rewritten as

$$\mathbb{E}_t \left[R_{t+1}^K Q_t K_t [\Gamma(\bar{\omega}_{t+1}) - \mu G(\bar{\omega}_{t+1})] \right] \geq R_{t+1} (Q_t K_t - N_{E,t})$$

Entrepreneurs: Solution

- Let λ_t be the Lagrange multiplier associated with the IC constraint. Then the first order conditions are

$$\begin{aligned}K_t &: \mathbb{E}_t \left[(1 - \Gamma(\bar{\omega}_{t+1})R_{t+1}^K + \lambda_t \left[(\Gamma(\bar{\omega}_{t+1}) - \mu G(\bar{\omega}_{t+1}))R_{t+1}^K - R_{t+1} \right] \right] = 0 \\ \bar{\omega}_{t+1} &: \mathbb{E}_t \left[\Gamma'(\bar{\omega}_{t+1}) + \lambda_t (\Gamma'(\bar{\omega}_{t+1}) - \mu G'(\bar{\omega}_{t+1})) \right] = 0\end{aligned}$$

plus the binding IC condition if $\lambda_t > 0$ with $\lambda_t = 0$ if it does not bind.

- Combining these two conditions, we arrive at

$$\mathbb{E}_t[R_{t+1}^K] = \mathbb{E}_t[\rho(\bar{\omega}_{t+1})R_{t+1}]$$

where the **premium on external finance**, $\rho(\bar{\omega}_{t+1})$ is given by

$$\rho(\bar{\omega}_{t+1}) = \frac{\Gamma'(\bar{\omega}_{t+1})}{[(\Gamma(\bar{\omega}_{t+1}) - \mu G(\bar{\omega}_{t+1}))\Gamma'(\bar{\omega}_{t+1}) + (1 - \Gamma(\bar{\omega}_{t+1}))(\Gamma'(\bar{\omega}_{t+1}) - \mu G'(\bar{\omega}_{t+1}))]}$$

External Finance Premium

- The external finance premium equation **replaces** the no arbitrage condition between R^K and R in NK and RBC models
- External finance is given by the safe rate, scaled up by a premium term
- Introduces the **spread** $R_t^K - R_t$
- Note that in the limiting case of $\bar{\omega}_{t+1} = 0$ and the probability of default tend to zero and $\mu = 0$, $\Gamma \rightarrow 0$ and the risk premium $\rho(\bar{\omega}_{t+1}) \rightarrow 1$ going back to the frictionless RBC

Aggregation

- To set a limit in net worth accumulation, entrepreneurs **exit** with a fixed probability $(1 - \sigma_E)$
- New entrants get a **start-up transfer** equal to ξ_E of the old entrepreneurs wealth
- Aggregate net worth is

$$N_{E,t} = (\sigma_E + \xi_E)(1 - \Gamma(\bar{\omega}_t))R_t^K Q_{t-1}K_{t-1}$$

- Entrepreneur who exit **consume**

$$C_{E,t} = (1 - \sigma_E)(1 - \xi_E)(1 - \Gamma(\bar{\omega}_t))R_t^K Q_{t-1}K_{t-1}$$

- The economy's resource constraint then is

$$Y_t = C_t + C_{E,t} + G_t + I_t + \mu G(\bar{\psi}_t)R_t^K Q_{t-1}K_{t-1}$$

General Equilibrium

- Households work, consume, save and pay taxes
 - Introduce **habit** in consumption

$$E_t \sum_{i=0}^{\infty} \beta^i [\ln(C_{t+i} - \gamma C_{t+i-1}) - \frac{\chi}{1+\epsilon} L_{t+i}^{1+\epsilon}] \quad (7)$$

- Their budget constraint is:

$$C_t + D_t + T_t = W_t L_t + R_t D_{t-1}$$

- Banks are very simple, get deposits D_t from the households and provide loans B_t to the entrepreneurs at a rate Z_t

$$B_t = D_t$$

- Government has a balanced budget: $G_t = T_t$
- Production side in the BGG is NK
- Here we will just follow the **RBC model** structure on the **real sector**

General Equilibrium

- Capital accumulation with **investment adjustment costs** carried out by **Capital Producers**

$$K_t = (1 - \delta)K_{t-1} + (1 - S(X_t))I_t$$

$$X_t \equiv \frac{I_t}{I_{t-1}}$$

$$S(X_t) = \phi_X(X_t - 1)^2$$

$$S'(X_t) = 2\phi_X(X_t - 1)$$

$$Q_t(1 - S(X_t) - X_t S'(X_t)) + \mathbb{E}_t [\Lambda_{t,t+1} Q_{t+1} S'(X_{t+1}) X_{t+1}^2] = 1$$

- $S(X_t)$ are investment adjustment costs equal to zero in a balance growth steady state

Summary of Equilibrium

$$\begin{aligned}Y_t &= C_t + C_{E,t} + G_t + I_t + \mu G(\bar{\psi}_t)) R_t^K Q_{t-1} K_{t-1} \\C_{E,t} &= (1 - \sigma_E)(1 - \xi_E)(1 - \Gamma(\bar{\psi}_t)) R_t^K Q_{t-1} K_{t-1}\end{aligned}$$

$$\begin{aligned}B_t &= Q_t K_t - N_{E,t} \\ \bar{\omega}_t &= \frac{Z_{t-1} B_{t-1}}{R_t^K Q_{t-1} K_{t-1}} \\ R_t^K &= \frac{r_t^K + (1 - \delta) Q_t}{Q_{t-1}} \\ r_t^K &= \frac{(1 - \alpha) Y_t}{K_{t-1}}\end{aligned}$$

Steady State Equilibrium

- The zero growth steady state is given by

$$\begin{aligned}R_k &= \rho(\bar{\psi})R \\N_E &= (\sigma_E + \xi_E)(1 - \Gamma(\bar{\psi}))R_k QK \\R_k QK [\Gamma(\bar{\psi}) - \mu G(\bar{\psi})] &= R(QK - N_E) \text{ or} \\R_k [\Gamma(\bar{\psi}) - \mu G(\bar{\psi})] &= R(\phi - 1)\end{aligned}$$

- where $\phi \equiv \frac{QK}{N_E}$ and

$$\rho(\bar{\psi}) = \frac{\Gamma'(\bar{\psi})}{[(\Gamma(\bar{\psi}) - \mu G(\bar{\psi}))\Gamma'(\bar{\psi}) + (1 - \Gamma(\bar{\psi}))(\Gamma'(\bar{\psi}) - \mu G'(\bar{\psi}))]}$$

Steady State Equilibrium

- with resource constraint

$$\begin{aligned}Y &= C + C_E + G + I + \mu G(\bar{\psi})R_k QK \\C_E &= (1 - \sigma_E)(1 - \xi_E)(1 - \Gamma(\bar{\psi}))R_k QK\end{aligned}$$

- and post-recursive equations

$$\begin{aligned}L &= QK - N_E \\R_l &= \frac{\bar{\psi}R_k QK}{L} \\R_k &= \frac{Z + (1 - \delta)Q}{Q} \\Z &= \frac{(1 - \alpha)Y}{K}\end{aligned}$$

The Density Function

- BGG choose a **log-normal distribution**
- Thus $\omega_t = e^{x_t}$ where $x_t \sim N(-\frac{1}{2}\sigma_\omega^2, \sigma_\omega^2)$
- This guarantees that $\mathbb{E}[\omega_t] = 1$

Steady State Solution Strategy

- Steady state is **not straightforward** for this kind of models
- Firstly solve the financial sector problem
- Then go to the real sector and find all the variables as shares of capital

Steady State Solution Strategy

- Find two equations with only unknowns the entrepreneurial leverage (ϕ^E) and the return on capital (R^K).

$$\phi^E = \frac{QK}{N^E}$$

Rearranging,

$$\frac{N^E}{K} = \frac{1}{\phi^E}$$

- From entrepreneurs net worth N^E , divide with capital and substituting $Q = 1$ we have:

$$\frac{N_E}{K} = (\sigma^E + \xi^E)(1 - \Gamma(\bar{\omega}))R^k$$

Steady State Solution Strategy

- From entrepreneurs balance sheet constraint $L = QK - N^E$, dividing with K^s we have

$$\frac{N_E}{K} = 1 - \frac{L}{K} = \frac{1}{\phi^E}$$

- Hence and using the fact that $R^K = \rho(\omega)R$,

$$\phi_E = \frac{1}{(\sigma_E + \xi_E)(1 - \Gamma(\bar{\omega}))\rho(\omega)R}$$

which is **the first equation** for the system

Steady State Solution Strategy

- From the Zero Profit Condition , solving for ϕ_E we get

$$\phi_E = -\frac{R}{R^K(\Gamma(\bar{\omega}) - \mu G(\bar{\omega})) - R}$$

- Substituting again:

$$\boxed{\phi_E = -\frac{R}{\rho(\bar{\omega})R(\Gamma(\bar{\omega}) - \mu G(\bar{\omega})) - R}}$$

yields **the second equation** for the system

- We have 2 equations and 2 unknowns $(\bar{\omega}, \phi_E)$
- Actually we treat ϕ_E as known equal to 2 in SS and we calibrate σ_E to match this leverage

Steady State Calibration

- Production parameters, same as in the simple RBC
- For NK extension see code in GitHub
- Additional financial parameters to calibrate are σ_ω , σ_E , and μ .
- These three parameters are calibrated to hit four targets:
 - (1) μ such as a default probability $p(\bar{\psi}) = 0.03$,
 - (2) σ_ω for $\rho(\bar{\psi}) = 1.0025$ corresponding to a credit spread of 100 basis points as in GK,
 - (3) σ_E for an entrepreneur leverage $\frac{QK}{N_E} = 2$ as in BGG

Inside the Code: Steady State

```
1 R          = 1/betta;  
2 Lambda     = betta;  
3  
4 % Targets  
5 p_mom      = 0.03;      % steady state default  
6 p          = p_mom;  
7 rho_mom    = 1 + 0.02/4; % steady state premium  
8 rho        = rho_mom;  
9 phie_mom   = 2;         % steady state leverage  
10 phie       = phie_mom;
```

Inside the Code: Steady State

```
1 % give initial values
2 x0=[0.98,0.3, 0.49, 0.008, 0.98, 0.30, 0.2, 0.49];
3 fun = @(c) myfun_BGG_calib(c,p_mom,ksie,rho,phie_mom,R);
4 options=optimset('MaxFunEvals',1000);
5 c      = fsolve(fun,x0,options);
6 sigmae = c(1); %parameter
7 sigma_omega_ss = c(2); %parameter
8 fnGam = c(3);
9 fnG    = c(4);
10 DGam  = c(5);
11 DG     = c(6);
12 mon    = c(7); %parameter
13 omega  = exp(c(8));
```

Inside the Code: Steady State

```
1 function F = myfun_BGG_calib(c,p_mom,ksie,rho,phie_mom,R)
2 F=[phie_mom-1/((c(1)+ksie)*(1-c(3))*rho*R); %Eq 1
3 phie_mom + (R/((rho*R)*(c(3)-c(7)*c(4))-R)); %Eq 2
4 rho - (c(5)/((c(3)-c(7)*c(4))*c(5)+(1-c(3))*(c(5)-c(7)*c(6)))); %rho
5 p_mom - (logncdf(exp(c(8)), -0.5*(c(2))^2, c(2))); %p
6 c(4) - (1- normcdf((0.5*(c(2))^2 - log(exp(c(8))))/c(2), 0, 1)); %fnG
7 c(3) - (c(4)+exp(c(8))*(1-p_mom)); %fnGam
8 c(5) - (1-p_mom); %DGam
9 c(6) - (1/(exp(c(8))*c(2)*sqrt(2*(4*atan(1))))*exp(-((log(exp(c(8)))
    +.5*(c(2))^2)/(2*(c(2))^2)));]; %DG
10 end
```

Steady State: Real Sector

- To find Z we go to the only equation that has it:

$$Z = \bar{\omega} R^K Q \frac{K}{L}.$$

From the entrepreneurs leverage we know

$$\frac{K}{L} = \frac{1}{1 - \frac{1}{\phi^E}} = \frac{\phi^E}{\phi^E - 1}$$

$$r_K = R^k + \delta - 1$$

- For the real sector variables: define all variables as share of capital first

$$\frac{C_e^{ss}}{K^{ss}} = (1 - \sigma^e)(1 - \xi^e)(1 - \Gamma(\psi^{\bar{ss}}))R_{k,ss}Q^{ss}$$

Steady State: Real Sector

- The resource constraint is $Y^{ss} = C^{ss} + I^{ss} + G^{ss} + \mu G(\bar{\psi}_t) R_k^{ss} Q^{ss} K^{ss}$
- Using the production function,

$$C^{ss} = L^{1-\alpha} K^\alpha - \delta K^{ss} - \eta L^{1-\alpha} K^\alpha - C_e - \mu G(\bar{\psi}_t) R_k^{ss} Q^{ss} K^{ss}$$

where $\eta = G^{ss}/Y^{ss}$

- Rearranging terms we get :

$$\frac{C^{ss}}{K^{ss}} = (1 - \eta) \left(\frac{L^{ss}}{K^{ss}} \right)^{1-\alpha} - \delta - \frac{C_e}{K^{ss}} - \mu G(\bar{\psi}_t) R_k^{ss} Q^{ss}$$

- From the resource constraint we have

$$\frac{Y^{ss}}{K^{ss}} = \left(\frac{C^{ss}}{K^{ss}} + \delta + \frac{C_e}{K^{ss}} + \mu G(\bar{\psi}_t) R_k^{ss} Q^{ss} \right) \frac{1}{1 - \eta}$$

Steady State: Real Sector

- The labour leisure F.O.C in steady state is

$$(L^{ss})^\epsilon \chi = [W^{ss}((1 - \gamma)c)^{-1}(1 - \beta\gamma)]$$

- Substituting for the wage it yields:

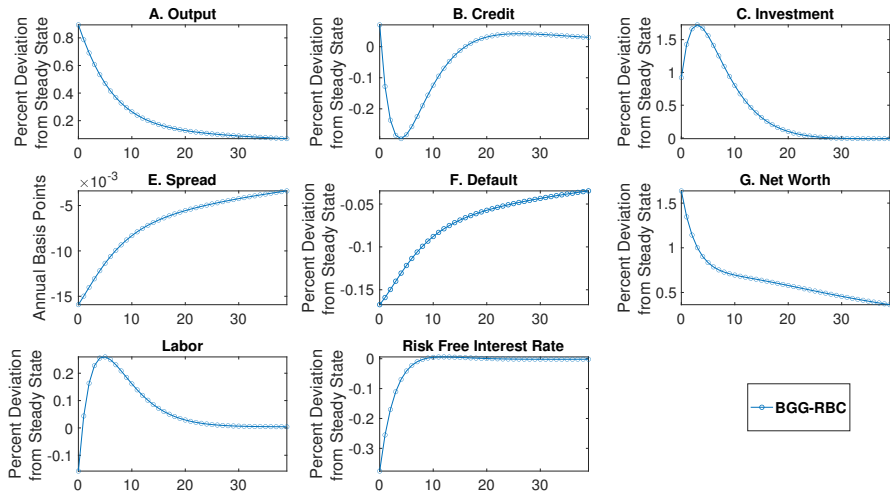
$$(L^{ss})^{1+\epsilon} = \frac{(1 - \beta\gamma)(1 - \alpha) Y^{ss}}{\chi(1 - \gamma)} \frac{Y^{ss}}{C^{ss}}$$

- By knowing $\frac{C^{ss}}{K^{ss}}$ and $\frac{Y^{ss}}{K^{ss}}$ is straightforward to calculate $\frac{Y^{ss}}{C^{ss}}$ and find L^{ss} .
- Finally, knowing L^{ss} and $\frac{Y^{ss}}{K^{ss}}$ from the production function we find the capital

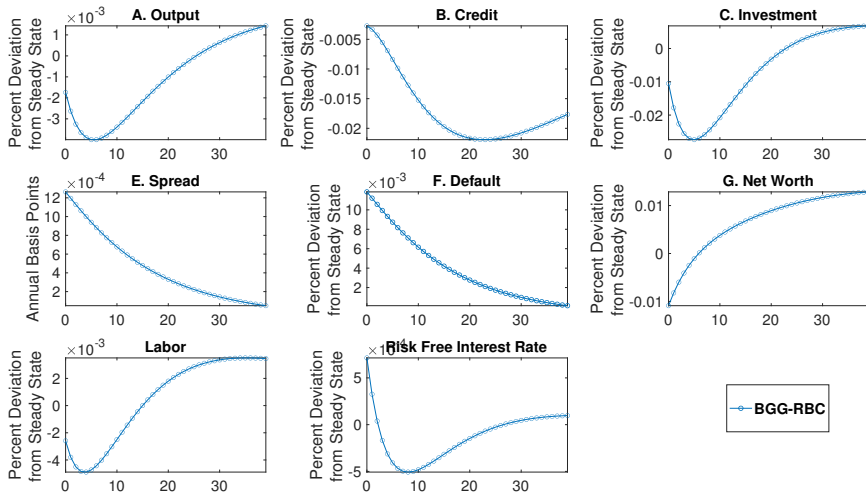
$$K^{ss} = \left(\frac{\frac{Y^{ss}}{K^{ss}}}{L^{1-\alpha}} \right)^{\frac{1}{\alpha-1}}$$

- Hence, having capital, by reverse engineering we can find the values for $(I^{ss}, C^{ss}, C_e^{ss}, Y^{ss})$

Impulse Responses: Productivity Shock (positive)



Impulse Responses: Risk Shock (negative)



Christiano, Motto and Rostagno (2014) extension

- Identify the *Risk Shock*
- Built on the *Bernanke et al. (1999)*
- Under a NK framework
- Lots of additional frictions and shocks (capacity utilization rate, taxes, long-term bonds...)
- *Estimated* for the US economy

The Risk Shock

- They refer to as risk the time period t cross-sectional standard deviation of $\log(\omega)$
- Risk is high in periods when $\sigma_{\omega,t}$ is high, and there is substantial dispersion in the outcomes across entrepreneurs
- Model estimation assigns a large role to $\sigma_{\omega,t}$
- Disturbances in $\sigma_{\omega,t}$ trigger responses in the model that resemble actual business cycles
- They find that fluctuations in $\sigma_{\omega,t}$ account for 60 percent of the fluctuations in the growth rate of aggregate US output since the mid-1980s

The Risk Shock

- Essentially from being a parameter $\sigma_{\omega,t}$ now follows an AR(1) process
$$\log(\text{sigma_omega} / \text{sigma_omega_ss}) = \text{rho_sigma} * \log(\text{sigma_omega}(-1) / \text{sigma_omega_ss}) + \text{e_RS};$$
- Where e_RS is the risk shock

Unanticipated and News Shocks

- A standard assumption in estimated equilibrium models is that a shock's statistical innovation becomes known to agents only when the innovation is realized
- Literature document that people receive information about the period t statistical innovation **before** the innovation is realized

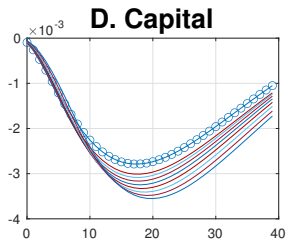
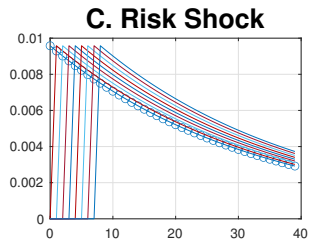
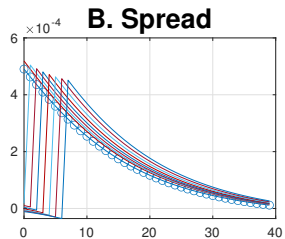
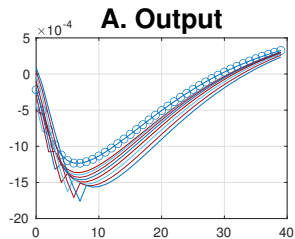
Unanticipated and News Shocks

- CMR (2014) consider the following shock representation

$$x_t = \rho_x x_{t-1} + \xi_0 + \xi_{1,t-1} + \dots + \xi_{p,t-p}$$

- x_t is the log deviation of the shock from its non-stochastic steady state
- ξ_0 is the **unanticipated** component of the statistical innovation and $\xi_{1,t-1} + \dots + \xi_{p,t-p}$ the **anticipated**, or **news** components
- They estimate the model for giving this structure to technology, monetary policy, government spending, equity, and risk shocks
- They find that the model that has the highest marginal likelihood is the one with news on the risk shock

Risk Shock (Unanticipated + Anticipated Components)



Homework

- Continue with part 2 of previous week
- Work with `BGGflexi.mod` and `BBGsticky.mod`
- Provide the impulse responses of both models in the same graph for output, consumption, investment, spread, loans and entrepreneurs' new worth
- For the case of a positive productivity shock and a risk shock
- Make sure that they have the same std and AR(1) parameter
- File `BGGplots_lecture.m` is the file I used for the lecture plots, it will help!

- Bernanke, B. S., Gertler, M., and Gilchrist, S. (1999). The financial accelerator in a quantitative business cycle framework. *Handbook of macroeconomics*, **1**, 1341–1393.
- Townsend, R. M. (1979). Optimal contracts and competitive markets with costly state verification. *Journal of Economic theory*, **21**(2), 265–293.