Leverage Restrictions in a Business Cycle Model

Lawrence J. Christiano
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Disclaimer: The views expressed are those of the authors and do not necessarily reflect those of the Bank of Japan.
Increasing interest in the following sorts of questions:

– What restrictions should be placed on bank leverage?
– How should those restrictions be varied over the business cycle?
– How should monetary policy react to bank leverage, if at all?
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What We Do

Modify a standard medium-sized DSGE model to include a banking sector.

**Assets**
- Loans and other securities

**Liabilities**
- Deposits
- Banker net worth

Job of bankers is to identify and finance good investment projects. Doing this requires exerting costly effort.

Agency problem between bank and its creditors:
- Banker effort is not observable.

Consequence: leverage restrictions on banks generate a very substantial welfare gain in steady state.

Explore some of the dynamic implications of the models.
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Outline

• Model
  – first, without leverage restriction
    • observable effort benchmark
    • unobservable case
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• Steady state properties of leverage restrictions
• Implications for dynamic effects of shocks
Standard Model

Firms

Labor market

household

$L$
Standard Model

Firms

Market for Physical Capital

Labor market

household

$K$

$L$
Standard Model

Firms

Labor market

household

Market for Physical Capital

L

C

I

K
Standard Model with Banking

- Firms
- Labor market
- Household
- Entrepreneurs

\[ L \rightarrow \gamma K, \gamma \sim F, \alpha_t \rightarrow \]
Entrepreneur pays everything to the bank and has nothing.
Standard Model with Banking

- Firms
- Entrepreneurs
- Capital Producers
- household
- banks
- Mutual funds
- Labor market
Entrepreneurs

After goods production in period $t$:
- Purchase raw capital from capital producers, for price $P_k^0_t$.
- Entrepreneurs have no resources of their own and must obtain financing from banks.
- Entrepreneurs convert raw capital into effective capital.
- Some are good at it and some are bad.
- In period $t + 1$:
  - Entrepreneurs rent capital to goods-producers in competitive markets, at rental rate, $r_{t+1}$.
  - After production, sell undepreciated capital back to capital producers at price, $P_k^0_{t+1}$.
  - Entrepreneurs pay all earnings to bank at end of $t + 1$, keeping nothing.
- No agency problems between entrepreneurs and banks.
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Earnings of Entrepreneurs

there are good entrepreneurs and bad entrepreneurs.

bad: 1 unit, raw capital

e\_b\_t units, effective capital

good: 1 unit, raw capital

e\_g\_t units, effective capital

return to capital enjoyed by entrepreneurs:

\[ R_{gt} + 1 = e_{gt} R_{kt} + 1, \]
\[ R_{bt} + 1 = e_{bt} R_{kt} + 1 \]

In effect, entrepreneurs operate linear investment technologies,
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$$R_{t+1}^k = \frac{r_{t+1}^k P_{t+1} + (1 - \delta) P_{k,t+1}}{P_{k',t}}$$
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- In effect, entrepreneurs operate linear investment technologies,

\[ R^g_{t+1} > R^b_{t+1} \]
Bankers each has net worth, $N_t$. A banker can only invest in one entrepreneur (asset side of banker balance sheet is risky). By exerting effort, $e_t$, a banker finds a good entrepreneur with probability $p$: $p(e_t) = \bar{a} + \bar{b}e_t$. In $t$, bankers seek to optimize:

$$E_t \lambda t + 1 f p(e_t) h R_t + 1 (N_t + d_t) R_{db, t} + 1 d_t i + (1 - p(e_t)) h R_{bt} + 1 (N_t + d_t) R_{db, t} + 1 d_t i + (1 - p(e_t)) h R_{bt} + 1 (N_t + d_t) R_{db, t} + 1 d_t i$$

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  + (1 - p(e_t)) \left[ R^b_{t+1} (N_t + d_t) - R^d_{b,t+1} d_t \right] \right\} - \frac{1}{2} e_t^2
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- Bankers have a cash constraint:
  \[ R_{t+1}^b (N_t + d_t) \geq R_{b,t+1}^d d_t \]
Bankers and Mutual Funds interact in competitive markets for loan contracts:

\[ (d_t, e_t, R_{g,t+1}^d, R_{b,t+1}^d) \]
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Free entry and competition among mutual funds implies:

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- Two scenarios:
  - banker effort, \( e_t \), is observed by mutual fund
  - banker effort, \( e_t \), is unobserved.
Observed Effort Benchmark

- Set of contracts available to bankers is the \( \left( d_t, e_t, R^d_{g,t+1}, R^d_{b,t+1} \right) \)'s that satisfy

  MF zero profits : \( p(e_t) R^d_{g,t+1} + (1 - p(e_t)) R^d_{b,t+1} = R_t, \)
  cash constraint : \( R_{t+1}^b (N_t + d_t) \geq R^d_{b,t+1} d_t \)
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- Each banker chooses the most preferred contract from the menu.
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- Each banker chooses the most preferred contract from the menu.
- Key feature of observed effort equilibrium:

  \[
  e_t = E_t \lambda_{t+1} p_t'(e_{t+1}) \left( R_{t+1}^g - R_{t+1}^b \right) (N_t + d_t)
  \]
Unobserved Effort

- In this case, banker always sets $e_t$ to its privately optimal level, whatever $e_t$ is specified in the loan contract:

\[
\text{incentive : } e_t = E_t \lambda_{t+1} p_t' (e_t) \left[ \left( R_{t+1}^g - R_{t+1}^b \right) (N_t + d_t) \right.
\]
\[
- \left( R_{g,t+1}^d - R_{b,t+1}^d \right) d_t ].
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  \left( d_t, e_t, R^d_{g,t+1}, R^d_{b,t+1} \right) \text{’s that satisfy ‘incentive’ in addition to:}
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Two factors can make $e_t$ inefficiently low:

- $R^d_{g,t+1} > R^d_{b,t+1}$
- $N_t + d_t$ low.
Law of Motion of Net Worth

- Bankers live in a large representative household, with workers (as in Gertler-Karadi, Gertler-Kiyotaki).
  - Bankers pool their net worth at the end of each period (we avoid worrying about banker heterogeneity)
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Law of motion of banker net worth

\[
N_{t+1} = \gamma_{t+1} \left\{ p(e_t) \left[ R^g_{t+1} (N_t + d_t) - R^d_{g,t+1} d_t \right] \right. \\
+ \left. (1 - p(e_t)) \left[ R^b_{t+1} (N_t + d_t) - R^d_{b,t+1} d_t \right] \right\} \\
+ \overbrace{\text{lump sum transfer, households to their bankers}}^{T_{t+1}}
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Law of motion of banker net worth

\[ N_{t+1} = \gamma_t \{ p(e_t) \left[ R^g_{t+1} (N_t + d_t) - R^d_{g,t+1} d_t \right] + (1 - p(e_t)) \left[ R^b_{t+1} (N_t + d_t) - R^d_{b,t+1} d_t \right] \} + T_{t+1} \]
The model assumes that when bankers want funds, issuing equity is not an option.

This shows how major debt instruments were used at private depository institutions in the wake of the crisis.
• The model assumes that when bankers want funds, issuing equity is not an option.
‘Crisis’

- Suppose something makes banker net worth, $N_t$, drop.
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- Suppose something makes banker net worth, $N_t$, drop.
- For given $d_t$, bank cash constraint gets tighter:

$$R_{t+1}^b (N_t + d_t) \geq R_{b,t+1}^d d_t.$$
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So, interest rate spread, $R_{g,t+1}^d - R_t$, high, banker effort low.
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- Banks get riskier (cross sectional mean return down, standard deviation up).
Leverage Restrictions

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  - Second effect of leverage restriction,
    - leverage restriction in effect implements collusion among bankers
Leverage Restrictions

• Banks face the following restriction:

\[ L_t \geq \frac{N_t + d_t}{N_t}. \]

• What is the consequence of this restriction?
  – With less \( d_t \), banks with bad assets more able to cover losses
    • interest rate spread, \( R_d^b - R \), falls, so banker effort rises.
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    - make profits on demand deposits....lots of profits:

\[
\bigg[ p(e_t) \left( R^g_{t+1} - R^d_{g,t+1} \right) + (1 - p(e_t)) \left( R^b_{t+1} - R^d_{b,t+1} \right) \bigg] \frac{d_t}{N_t}
\]
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\]

- makes \( N_t \) grow, offseting incentive effects of decline in \( d_t \).
Macro Model

- Sticky wages and prices
- Investment adjustment costs
- Habit persistence in consumption
- Monetary policy rule
## Calibration targets

Table 2: Steady state calibration targets for baseline model

<table>
<thead>
<tr>
<th>Variable meaning</th>
<th>variable name</th>
<th>magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-sectional standard deviation of quarterly non-financial firm equity returns</td>
<td>$s^b$</td>
<td>0.20</td>
</tr>
<tr>
<td>Financial firm interest rate spreads (APR)</td>
<td>$400(R_g^d - R)$</td>
<td>0.60</td>
</tr>
<tr>
<td>Financial firm leverage</td>
<td>$L$</td>
<td>20.00</td>
</tr>
<tr>
<td>Allocative efficiency of the banking system</td>
<td>$p(e)e^g + (1 - p(e))e^b$</td>
<td>1</td>
</tr>
</tbody>
</table>
Data behind calibration targets

Figure 1: Cross-section standard deviation financial firm quarterly return on equity, HP-filtered US real GDP

Cross-section volatility (left scale)
Data behind calibration targets

Figure 1: Cross-section standard deviation financial firm quarterly return on equity, HP-filtered US real GDP

Cross-section volatility (left scale)

HP-filtered GDP (right scale)
<table>
<thead>
<tr>
<th>Panel A: financial parameters</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>return parameter, bad entrepreneur</td>
<td>$b$</td>
<td>-0.09</td>
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<tr>
<td>return parameter, good entrepreneur</td>
<td>$g$</td>
<td>0.00</td>
</tr>
<tr>
<td>constant, effort function</td>
<td>$\hat{a}$</td>
<td>0.83</td>
</tr>
<tr>
<td>slope, effort function</td>
<td>$\hat{b}$</td>
<td>0.30</td>
</tr>
<tr>
<td>lump-sum transfer from households to bankers</td>
<td>$\tilde{T}$</td>
<td>0.38</td>
</tr>
<tr>
<td>fraction of banker net worth that stays with bankers</td>
<td>$\gamma$</td>
<td>0.85</td>
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<table>
<thead>
<tr>
<th>Panel B: Parameters that do not affect steady state</th>
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<tr>
<td>steady state inflation (APR)</td>
<td>$400(\pi - 1)$</td>
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<tr>
<td>Taylor rule weight on inflation</td>
<td>$\hat{\alpha}_s$</td>
<td>1.50</td>
</tr>
<tr>
<td>Taylor rule weight on output growth</td>
<td>$\hat{\alpha}_{\Delta y}$</td>
<td>0.50</td>
</tr>
<tr>
<td>smoothing parameter in Taylor rule</td>
<td>$\rho_p$</td>
<td>0.80</td>
</tr>
<tr>
<td>curvature on investment adjustment costs</td>
<td>$S''_w$</td>
<td>5.00</td>
</tr>
<tr>
<td>Calvo sticky price parameter</td>
<td>$\zeta_p$</td>
<td>0.75</td>
</tr>
<tr>
<td>Calvo sticky wage parameter</td>
<td>$\zeta_w$</td>
<td>0.75</td>
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</table>

<table>
<thead>
<tr>
<th>Panel C: Nonfinancial parameters</th>
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<tbody>
<tr>
<td>steady state gdp growth (APR)</td>
<td>$\mu_{z^*)}$</td>
<td>1.65</td>
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<tr>
<td>steady state rate of decline in investment good price (APR)</td>
<td>$\gamma$</td>
<td>1.69</td>
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<tr>
<td>capital depreciation rate</td>
<td>$\delta$</td>
<td>0.03</td>
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<tr>
<td>production fixed cost</td>
<td>$\Phi$</td>
<td>0.89</td>
</tr>
<tr>
<td>capital share</td>
<td>$\alpha$</td>
<td>0.40</td>
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<tr>
<td>steady state markup, intermediate good producers</td>
<td>$\lambda_f$</td>
<td>1.20</td>
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<tr>
<td>habit parameter</td>
<td>$b_u$</td>
<td>0.74</td>
</tr>
<tr>
<td>household discount rate</td>
<td>$100(\beta^{-\delta} - 1)$</td>
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<tr>
<td>steady state markup, workers</td>
<td>$\lambda_w$</td>
<td>1.05</td>
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<tr>
<td>Frisch labor supply elasticity</td>
<td>$1/\sigma_L$</td>
<td>1.00</td>
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<tr>
<td>weight on labor disutility</td>
<td>$\psi_L$</td>
<td>1.00</td>
</tr>
<tr>
<td>steady state scaled government spending</td>
<td>$\hat{\gamma}$</td>
<td>0.89</td>
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</table>
Steady State Calculations

- Next study steady state impact of leverage
  - Quantify role of hidden effort in the analysis (essential!)
<table>
<thead>
<tr>
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<th>Variable name</th>
<th>Unobserved Effort</th>
<th>Observed Effort</th>
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<tr>
<td></td>
<td></td>
<td>Leverage Restriction</td>
<td>Leverage Restriction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>non-binding</td>
<td>binding</td>
</tr>
<tr>
<td></td>
<td></td>
<td>non-binding</td>
<td>binding</td>
</tr>
<tr>
<td>Spread</td>
<td>$400(R^d_e - R)$</td>
<td>0.600</td>
<td></td>
</tr>
<tr>
<td>scaled consumption</td>
<td>$c$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>labor</td>
<td>$h$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>scaled capital stock</td>
<td>$k$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bank assets</td>
<td>$N + d$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bank net worth</td>
<td>$N$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bank deposits</td>
<td>$d$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bank leverage</td>
<td>$(N + d)/N$</td>
<td>20.00</td>
<td></td>
</tr>
<tr>
<td>bank return on equity (APR)</td>
<td>$400\left(\frac{p(\epsilon)}{N_{t+1}^e(1-p(\epsilon))}R_{t+1}^R - \frac{R_{t+1}^R}{N_{t+1}^e(1-p(\epsilon))} - 1\right)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fraction of firms with good balance sheets</td>
<td>$p(e)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benefit of leverage (in $c$ units)</td>
<td>$100\chi$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benefit of making effort observable (in $c$ units)</td>
<td>$100\chi$</td>
<td></td>
<td></td>
</tr>
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<td>$c$</td>
<td>1.84</td>
<td></td>
</tr>
<tr>
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<td>1.18</td>
<td></td>
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<td>51.52</td>
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<td>$N$</td>
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<tr>
<td>bank deposits</td>
<td>$d$</td>
<td>48.94</td>
<td></td>
</tr>
<tr>
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<td>20.00</td>
<td></td>
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<td>bank return on equity (APR)</td>
<td>$400\left(\frac{p(\varepsilon)\theta^e_{t+1} + (1-p(\varepsilon))\theta^c_{t+1}}{\lambda_t} - R_{td_t} - R_{td_t} - 1\right)$</td>
<td>4.59</td>
<td></td>
</tr>
<tr>
<td>fraction of firms with good balance sheets</td>
<td>$p(\varepsilon)$</td>
<td>0.962</td>
<td></td>
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<tr>
<td>Benefit of leverage (in c units)</td>
<td>$100\chi$</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Benefit of making effort observable (in c units)</td>
<td>$100\chi$</td>
<td>NA</td>
<td></td>
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</tbody>
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<td>Spread</td>
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<td>0.600</td>
<td>NA</td>
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<tr>
<td>scaled consumption</td>
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<td>1.84</td>
<td>2.01</td>
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<td>$h$</td>
<td>1.18</td>
<td>1.15</td>
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<td>bank net worth</td>
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<td>2.58</td>
<td>2.58</td>
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<tr>
<td>bank deposits</td>
<td>$d$</td>
<td>48.94</td>
<td>56.98</td>
</tr>
<tr>
<td>bank leverage</td>
<td>$(N + d)/N$</td>
<td>20.00</td>
<td>23.12</td>
</tr>
<tr>
<td>bank return on equity (APR)</td>
<td>$400 \left( \frac{[p(e)R_{tt}^e + (1-p(e))R_{tt1}^e]}{X_t} - R_{tt} \right) / N_t + d_t \right) - 1$</td>
<td>4.59</td>
<td>4.59</td>
</tr>
<tr>
<td>fraction of firms with good balance sheets</td>
<td>$p(e)$</td>
<td>0.962</td>
<td>1.000</td>
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<tr>
<td>Benefit of leverage (in $c$ units)</td>
<td>$100X$</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Benefit of making effort observable (in $c$ units)</td>
<td>$100X$</td>
<td>NA</td>
<td>6.11</td>
</tr>
</tbody>
</table>

Making effort observable makes things a lot better, equivalent to a 6% permanent jump in consumption!
Table 3: Steady State Properties of the Model

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<td>binding</td>
</tr>
<tr>
<td>Spread</td>
<td>$400(R^d_{t} - R)$</td>
<td>0.600</td>
<td>NA</td>
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<tr>
<td>scaled consumption</td>
<td>$c$</td>
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<td>2.58</td>
<td>2.58</td>
</tr>
<tr>
<td>bank deposits</td>
<td>$d$</td>
<td>48.94</td>
<td>56.98</td>
</tr>
<tr>
<td>bank leverage</td>
<td>$(N + d)/N$</td>
<td>20.00</td>
<td>23.12</td>
</tr>
<tr>
<td>bank return on equity (APR)</td>
<td>$100\left(\frac{p(e)\rho^c_{t+1}+(1-p(e))\rho^c_{t}}{3}\right)^{(N+1)/N)}-R_{t+1}-1$</td>
<td>4.59</td>
<td>4.59</td>
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<tr>
<td>fraction of firms with good balance sheets</td>
<td>$p(e)$</td>
<td>0.962</td>
<td>1.000</td>
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<tr>
<td>Benefit of leverage (in c units)</td>
<td>$100\chi$</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Benefit of making effort observable (in c units)</td>
<td>$100\chi$</td>
<td>NA</td>
<td>6.11</td>
</tr>
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</table>

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Interestingly, leverage goes up.
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<tr>
<td></td>
<td></td>
<td>non-binding</td>
<td>binding</td>
</tr>
<tr>
<td>Spread</td>
<td>$400(R^e \delta - R)$</td>
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<td>0.211</td>
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<td>1.88</td>
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<tr>
<td>labor</td>
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<td>1.16</td>
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<td>17.00</td>
</tr>
<tr>
<td>bank return on equity (APR)</td>
<td>400$$\left( p(e)c(N + d) + (1 - p(e))\beta k \right)$$</td>
<td>4.59</td>
<td>14.96</td>
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<td>0.982</td>
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<td>Benefit of leverage (in $c$ units)</td>
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<td>Benefit of making effort observable (in $c$ units)</td>
<td>$100\xi$</td>
<td>NA</td>
<td>NA</td>
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Cut in leverage in the unobserved effort economy moves things towards observed effort.
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<td></td>
<td>non-binding</td>
<td>binding</td>
</tr>
<tr>
<td>Spread</td>
<td>$400(R_t^d - R)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>scaled consumption</td>
<td>$c$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>labor</td>
<td>$h$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>scaled capital stock</td>
<td>$k$</td>
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<td></td>
</tr>
<tr>
<td>bank assets</td>
<td>$N + d$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bank net worth</td>
<td>$N$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bank deposits</td>
<td>$d$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bank leverage</td>
<td>$(N + d)/N$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bank return on equity (APR)</td>
<td>$400 \left( \frac{p(e)R_t^c(1-p(e))R_t^d}{N/d} \right) - 1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fraction of firms with good balance sheets</td>
<td>$p(e)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benefit of leverage (in $c$ units)</td>
<td>$100\chi$</td>
<td></td>
<td></td>
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<tr>
<td>Benefit of making effort observable (in $c$ units)</td>
<td>$100\chi$</td>
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Hidden effort assumption is essential. Otherwise, leverage restriction reduces utility.
Here, we consider the dynamic effects of two shocks

- shock to monetary policy
- lump sum shock to net worth
\[ R_t = 0.80R_{t-1} + (1 - 0.80)[1.5\pi_{t+1} + 0.5g_{y,t}] + \varepsilon_t^p \]

\[ \varepsilon_0^p = + 25 \text{ annual basis points} \]
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$$\varepsilon_0^p = +25 \text{ annual basis points}$$

Contractionary M policy shock:
- fall in: $c$, $i$, $y$, bank net worth, $N$, inflation
- Rise in:
  leverage
cross-sectional dispersion of bank performance
\[
\log\left(\frac{T_t}{T}\right) = 0.95 \log\left(\frac{T_{t-1}}{T}\right) + \varepsilon_t^T \\
\varepsilon_0^T = -0.10
\]
\[
\log \left( \frac{T_t}{T} \right) = 0.95 \log \left( \frac{T_{t-1}}{T} \right) + \epsilon^T_t
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Negative shock to bank net worth:
fall in:
\(c, i, y,\)
bank net worth, \(N,\)
inflation

Rise in:
leverage
cross-sectional dispersion of bank performance
Cyclicality of Leverage

- The model appears to imply countercyclical leverage.
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- We took data from the Flow of Funds accounts to measure leverage.
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• We took measures of $L^f$ for three components of financial business, over a period for which $L^f$ does not behave strangely, the 2000s.
Holding Companies (L.128)
liability growth - asset growth (yoy)

Private Depository Institutions (L.109)
liability growth - asset growth (yoy)

Security Brokers and Dealers (L.127)
liability growth - asset growth (yoy)

liability growth - S&P500 growth (yoy)
Conclusion

- Described a model in which there is a problem that is mitigated by the introduction of leverage restrictions.
- Described some loose tests of the model by looking at its dynamic implications.
- Plan to study implications of the model for a broader class of leverage rules.
Bankers and their Creditors

No agency problems on asset side of bank balance sheet. Problems are on liability side. Bankers receive credit, \( d_t \), from mutual funds. Mutual funds deal with households.
Bankers and their Creditors

<table>
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Risky Bankers Funded By Mutual Funds

Household

Household

Household

Diversified, competitive mutual funds

banker

banker

banker

banker
\begin{align*}
L^e_t &= \frac{a^f_t}{a^f_t - \ell^f_t} \\
\frac{dL^e_t}{dt} &= \frac{\frac{d}{dt}a^f_t}{a^f - \ell^f} - \frac{a^f_t}{(a^f - \ell^f)^2} \left( \frac{d}{dt}a^f_t - dl^f_t \right) \\
&= \frac{a^f_t}{a^f - \ell^f} \hat{a}^f_t - \frac{a^f_t}{(a^f - \ell^f)^2} \left( a^f_t \hat{a}^f_t - \ell \hat{\ell}^f_t \right) \\
\hat{L}^e_t &= \hat{a}^f_t - \frac{1}{a^f - \ell^f} \left( a^f_t \hat{a}^f_t - \ell \hat{\ell}^f_t \right) \\
&= \frac{\ell}{a^f - \ell^f} \left( \hat{\ell}^f_t - \hat{a}^f_t \right) 
\end{align*}
\[
L_t = \frac{a_t^{nf} + a_t^f}{a_t^{nf} + a_t^f - l_t^f}
\]

\[
L \hat{L}_t = \frac{a^{nf}}{a^{nf} + a^f - l^f} \hat{a}_t^{nf} + \frac{a^f}{a^{nf} + a^f - l^f} \hat{a}_t^f
\]

\[
- \frac{a^{nf} + a^f}{(a^{nf} + a^f - l^f)^2} \left( a^{nf} \hat{a}_t^{nf} + a^f \hat{a}_t^f - l^f \hat{l}_t^f \right)
\]

\[
\hat{L}_t = \frac{a^{nf}}{a^{nf} + a^f} \hat{a}_t^{nf} + \frac{a^f}{a^{nf} + a^f} \hat{a}_t^f - \frac{1}{a^{nf} + a^f - l^f} \left( a^{nf} \hat{a}_t^{nf} + a^f \hat{a}_t^f - l^f \hat{l}_t^f \right)
\]

\[
= \left[ \frac{a^{nf}}{a^{nf} + a^f} - \frac{a^{nf}}{a^{nf} + a^f - l^f} \right] \hat{a}_t^{nf} + \left[ \frac{a^f}{a^{nf} + a^f} - \frac{a^f}{a^{nf} + a^f - l^f} \right] \hat{a}_t^f
\]

\[
= \left[ \frac{a^{nf}}{a^{nf} + a^f} - \frac{a^{nf}}{a^{nf} + a^f - l^f} \right] \hat{a}_t^{nf} - \frac{l^f}{(a^{nf} + a^f - l^f) (a^{nf} + a^f)} a^f \hat{a}_t^f
\]

\[
= \frac{l^f a^{nf}}{(a^{nf} + a^f) (a^{nf} + a^f - l^f)} \hat{a}_t^{nf} - \frac{l^f a^f}{(a^{nf} + a^f) (a^{nf} + a^f - l^f)} \hat{a}_t^f
\]