Solving DSGE Models Without a Law of Motion: An Ergodicity-Based Method and an Application

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Motivation

For an infinite dimensional object Φ_t and the aggregate exogenous state S_t,

$$\Phi_{t+1} = G(\Phi_t, S_t)$$

is approximated by

$$logX_{t+1} = \alpha(S_t) + \beta(S_t) logX_t$$

where X_t is the sufficient statistics of Φ_t or equilibrium objects (price).

What if G is highly nonlinear?

Accuracy matters

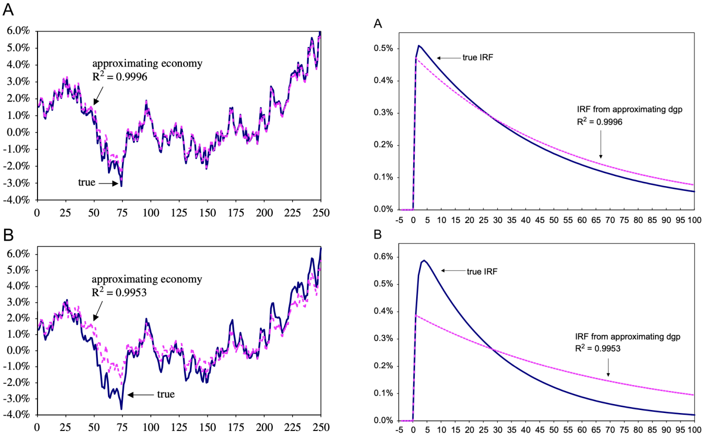


Figure: The figure is from Den Hann (2010)

Why does nonlinearity matter?

"What drives a recession?"

“What drives a recession?”

Let's denote the response of the aggregate allocation as $g(x_t; \Gamma_t, \Delta A_t)$, where

- $\Gamma_t = \{A_t, \Phi_t\}$ is the aggregate states.
- ΔA_t is the magnitude of the impulse.

Suppose we observe a drop of the allocation Δx_t^{Obs}, and we want to explain this.

$$\Delta x_t^{Obs} = g(x_t; \Gamma_t, \Delta A_t)$$

Traditionally,

$$\Delta x_t^{Obs} = g(x_t; \Gamma_{ss}, \Delta A_t)$$

In this paper,

$$\Delta x_t^{Obs} = g(x_t; \Gamma_t, \Delta A)$$

Depending on the aggregate state, the post shock responses of the allocation vary for the same exogenous shock: The focus is on the role of Γ_t – *State dependence* (Hysteresis).

This paper

Research question

How can we accurately solve the nonlinear business cycle models (with heterogeneous agents)?

What this paper does

Develops a novel algorithm called "***the repeated transition method***."

Tests and compares the repeated transition method with the existing methods.

Studies the *business cycle implication of corporate cash holdings* through a lens of a heterogeneous-firm business cycle model.

Overview of the repeated transition method

- Solves nonlinear (HA) business cycle models accurately.
- Does not specify the law of motion.
- Global method.
- No perfect foresight.
- Sequence space based.
- Speed gain from the absence of an external loop
  - Krusell and Smith (1997); Khan and Thomas (2008)
- Builds upon Boppart et al. (2018).

Related papers

- **Solution method for the heterogeneous agent models under the aggregate uncertainty**
  - Global method: den Haan (1996); Krusell and Smith (1998); Rios-Rull (1997); den Haan and Rendahl (2010)
  - Perfect foresight: Boppart et al. (2018)
  - Local linearization (Fast): Reiter (2009); Auclert et al. (2021)
  - Machine learning: Fernandez-Villaverde, Hurtado, and Nuno (2021); Kahou et al. (2021)
- **Linear/nonlinear aggregate dynamics (with heterogeneous agents):**
  - Krusell and Smith (1998); Khan and Thomas (2008); Petrosky-Nadeau and Zhang (2021); Den Haan, Freund, and Rendahl (2021)
  - Fernandez-Villaverde, Hurtado, and Nuno (2021); Lee (2022)
- **Heterogeneous agent models with incomplete market**:
  - Bewely (1977); Huggett (1993); Aiyagari (1994);
- **Corporate saving glut**:
  - Riddick and Whited (2009); Jermann and Quadrini (2012); Khan and Thomas (2013)

A generalized model framework

I introduce a generalized model framework that can nest a broad class of general equilibrium models.

$$V(x;X) = \max_{y,a'} \; f(y,a',x;X) + \mathbb{E}m(X,X')V(a',s';X')$$
$$\text{s.t.} \quad (y,x') \in \mathcal{B}(x;X,X',q), \quad \Phi' = F(X)$$

where

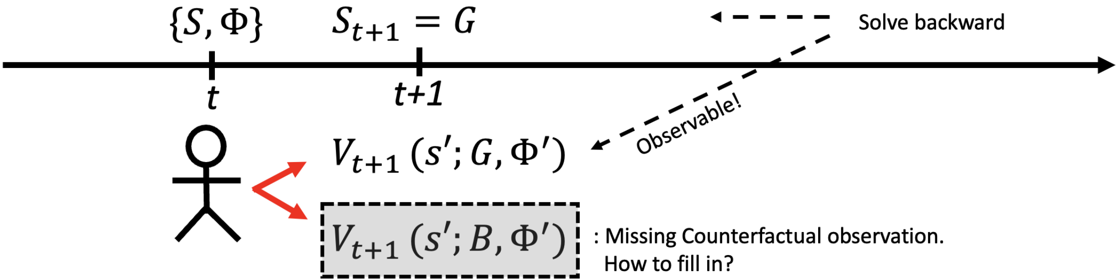
$$[\text{Individual state}]: \quad x = \{a,s\}$$
$$[\text{Aggregate state}]: \quad X = \{\Phi, S\},$$

and in the equilibrium,

$$[\text{Market clearing}]: \quad p(X,X') = \arg_{\widetilde{p}}\{Q(\widetilde{p},X,X') = 0\}$$

Conceptual hurdle: a counter-factual realization

- Suppose the aggregate state variables at period t are $\{\Phi, S\}$.
- A rational agent should rationally expect the future period $t+1$:
  - The future realization with the state G
  - The future realization with the state B
- If we simulate an aggregate shock, only a single state is realized at $t+1$. (Say $S_{t+1} = G$)
- No one can observe the counter factual observation: the world with $S_{t+1} = B$.
- Then, how can we specify the mysterious counter-factual world as a possible future outcome? (Specifically, the value function)
- It is like Marvel's multiverse, where the world is diverging into the different universe with different outcomes at each second:
  - In one counterfactual world, due to a Thanos' mistake, a world still has Iron man alive. But this is not observable to an econometrician (only to Dr. Strange).



State-space modelling:

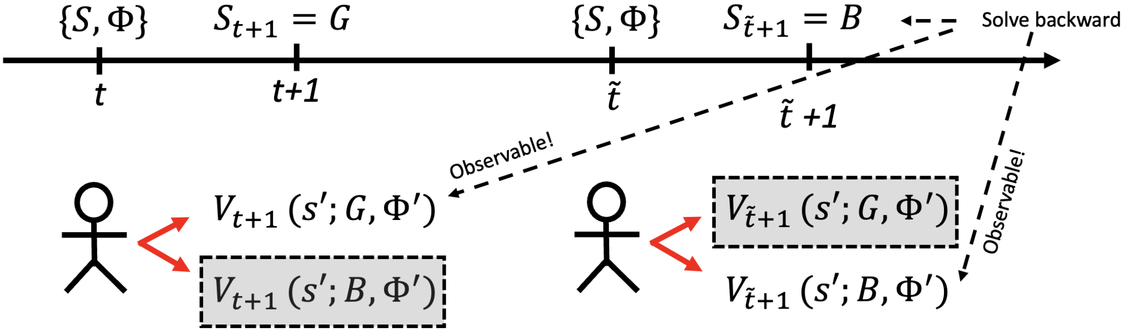
1. Remove time index in the value function.
2. Assume $M(K) = K'$. (the law of motion)
3. Solve for $V = V(s; S, K)$, assuming K is the sufficient statistics.
4. Obtain $V^B_{t+1} = V(s_{t+1}; S_{t+1} = B, K')$, using $M(K)$ and interpolation.

Unresolved issue: 1) the sufficient statistics K and 2) M's parametric form.

Repeated transition method

Repeated transition method

- It relies on the *ergodic theorem*:
  - If a simulation path is long enough, the simulation path captures all possible aggregate state realizations.
- If the simulation path is long enough, there *exists* a period $\tilde{t}+1$ such that
  1. the endogenous aggregate allocations are the same as period $t+1$: $\Phi_{t+1} = \Phi_{\tilde{t}+1}$.
  2. the counter-factual shock of period $t+1$ is realized at $\tilde{t}+1$: $S_{\tilde{t}+1} = B$.
- We can use $V_{\tilde{t}+1}(s'; B, \Phi')$ to fill up the missing counter-factual value function at period t.



Repeated transition method:

1. For each t, find the period $\tilde{t}$.
2. Obtain $V^G_{t+1} = V(s;G,K')$ and $V^B_{t+1} = V_{\tilde{t}+1}(s;B,K')$. Then, discount them to form RE.

- *No law of motion is needed.*

Implementation

1. Simulate a long enough aggregate shock path $\mathcal{S} = \{S_t\}_{t=1}^T$.

2. Given nth guess $\{p_t^{(n)}, V_t^{(n)}, \Phi_t^{(n)}\}_{t=0}^T$, solve $\{\widehat{V}_t^*\}_{t=0}^T$ from backward by properly forming the rational expectation using ***the technique*** based on $\{V_t^{(n)}, \Phi_t^{(n)}\}_{t=0}^T$. *(Detail: next slide)*

3. Given the value functions $\{V_t^*\}_{t=0}^T$, (and the inter-temporal policy functions), compute $\{\Phi_t^*\}_{t=0}^T$ by a forward simulation.

4. Given $\{V_t^*, \Phi_t^*\}_{t=0}^T$, compute the implied price levels $\{p_t^*\}_{t=0}^T$.

5. Evaluate the following Cauchy criterion.

$$\sup_{BurnIn \leq t \leq T - BurnIn} ||p_t^{(n)} - p_t^*||_\infty < tol$$

   If the criterion is not satisfied, update the guess $\{p_t^{(n+1)}, V_t^{(n+1)}, \Phi_t^{(n+1)}\}_{t=0}^T$ using convex combination. (Go back to step 2)

- Once converged, $R^2 = 1$, and $MSE < tol$: High accuracy!
- No market clearing step (internal loop) is needed: Speed boost!
- The convergence of this method hinges on the *stability* of recursive competitive equilibrium. If the simulated path is not stable, the convergence may break down.

Non-trivial step: Filling in the missing values

- How can we find the period $\widetilde{t}+1$ that corresponds to $t+1$ with a different aggregate shock?
- **In theory,**
  - Consider a time partition $\mathcal{T}_B = \{t | S_t = B\}$. Then,

$$\widetilde{t}+1 = \arg \inf_{\tau \in \mathcal{T}_B} ||\Phi_{\tau}^{(n)} - \Phi_{t+1}^{(n)}||_{\infty}.$$

- **In practice,**
  - Consider a time partition $\mathcal{T}_B = \{t | S_t = B\}$. Then, for a sufficient statistics K (possibly a vector),

$$\widetilde{t}+1 = \arg \inf_{\tau \in \mathcal{T}_B} ||K_{\tau}^{(n)} - K_{t+1}^{(n)}||_{\infty},$$

  - Or find the closest one from above $\widetilde{t}^{up}+1$ and the closest one from below $\widetilde{t}^{dn}+1$ (w.r.t K)

$$V_{t+1}^{B} = w_{up} V_{\widetilde{t}^{up}+1}^{B} + (1-w_{up}) V_{\widetilde{t}^{dn}+1}^{B}$$

    where w_{up} is determined by the distances in K.

Implementation (cont'd)

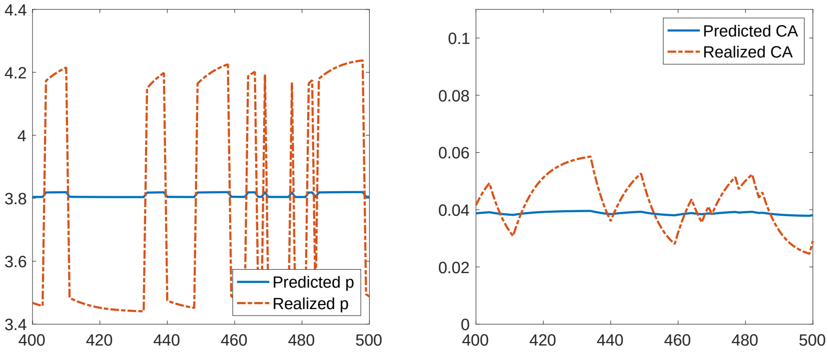


Figure: The video clip of RTM implementation

- The video is from the baseline model to be introduced later.
- *Predicted* time series is *nth* guess, and *realized* time series is the *optimal* allocation given the guess.

The repeated transition method

- ☑ Free from the parametric form of the law of motion.
- ☑ Global method.
- ☑ No perfect foresight.
- ☑ Sequence space based.
- ☑ Speed gain from the absence of an external loop
- ☐ Accuracy validation.
  - Krusell and Smith (1997); Khan and Thomas (2008)
- ☐ A sufficient condition.

Accuracy: Krusell and Smith (1998) model

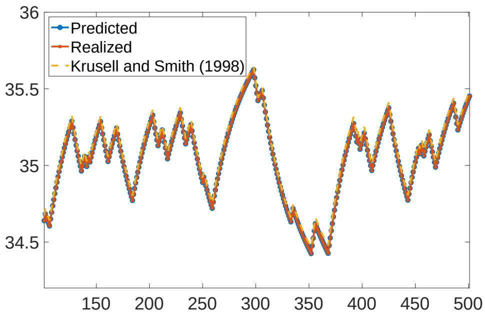


Figure: Computed dynamics in aggregate wealth (Krusell and Smith, 1998)

- In the models where general equilibrium effect is strong, the dynamics of aggregate allocations is flattened to be log-linear (Krusell and Smith, 1998).
- In those models, Krusell and Smith (1998) algorithm is as fast as the repeated transition method.
- Accuracy is also almost identical between the two methodologies.

Non-trivial market clearing condition

Consider a labor demand decision problem of a firm with k, where $\alpha + \gamma < 1$.

$$\max_{n_d} \quad k^{\alpha} n_d^{\gamma} - w n_d$$

The *static* optimality condition leads to

$$n_d^*(k) = \left(\frac{\gamma k^{\alpha}}{w}\right)^{\frac{1}{1-\gamma}}$$

Then, in the market clearing condition,

$$L^S = \int n_d^*(k) d\Phi = \int \left(\frac{\gamma k^{\alpha}}{w}\right)^{\frac{1}{1-\gamma}} d\Phi = \left(\frac{\gamma}{w}\right)^{\frac{1}{1-\gamma}} \int k^{\frac{\alpha}{1-\gamma}} d\Phi$$

$$\neq \left(\frac{\gamma}{w}\right)^{\frac{1}{1-\gamma}} \left(\int k d\Phi\right)^{\frac{\alpha}{1-\gamma}} = \left(\frac{\gamma}{w}\right)^{\frac{1}{1-\gamma}} K^{\frac{\alpha}{1-\gamma}}$$

Tracking K is not enough to clear the market. Φ is needed.

$$L^S = \int n_d^*(k) d\Phi \neq n_d^*\left(\int k d\Phi\right) = n_d^*(K)$$

Non-trivial market clearing condition (cont'd)

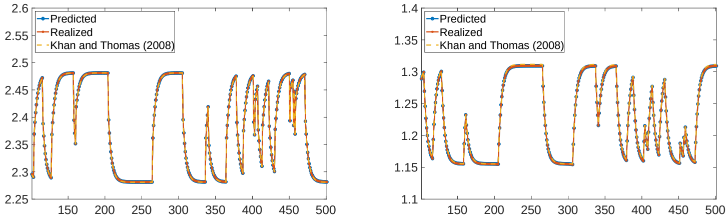
In the repeated transition method, the implied price w^* is obtained by simply equating the market clearing condition:

$$L^S(w^{(n)}) = \left(\frac{\gamma}{w^*}\right)^{\frac{1}{1-\gamma}} \int k^{\frac{\alpha}{1-\gamma}} d\Phi,$$

where $L^S(w^{(n)})$ is the labor supply when the price is at the nth iteration.

$$w^* = \gamma \left(\frac{\int k^{\frac{\alpha}{1-\gamma}} d\Phi}{L^S(w^{(n)})}\right)^{1-\gamma}$$

This implied price does not clear the market. But as $||w^{(n)} - w^*||_\infty \to 0$, it clears the market in the limit.



(a) Price p_t $(= 1/C_t)$

(b) Aggregate capital stocks K_t

Figure: Computed dynamics in aggregate capital stocks (Khan and Thomas, 2008)

- Khan and Thomas (2008) model also features log-linear dynamics but it includes non-trivial market clearing condition in the computation: necessity of external loop for market clearing price.
- The repeated transition method does not need the external loop: the prices and the allocations are computed directly at each point on the simulation.
- The repeated transition method is faster by a factor of 10.

A sufficient condition

Proposition 1 (A sufficient condition for the sufficient statistic approach)

For a sufficiently large T, if there exists a time series of an aggregate allocation $\{e_t\}_{t=0}^{T}$ such that for each time partition $\mathcal{T}_S = \{t | S_t = S\}, \forall S \in \{B, G\}$ and for $\forall (a, z)$,

$$(i) \quad e_{\tau_0} < e_{\tau_1} \iff V_{\tau_0}^{(n)}(a, z) < V_{\tau_1}^{(n)}(a, z) \text{ for any } \tau_0, \tau_1 \in \mathcal{T}_S$$

or

$$(ii) \quad e_{\tau_0} < e_{\tau_1} \iff V_{\tau_0}^{(n)}(a, z) > V_{\tau_1}^{(n)}(a, z) \text{ for any } \tau_0, \tau_1 \in \mathcal{T}_S$$

then x_t is the sufficient statistics of the endogenous aggregate state Φ_t for $\forall t$.

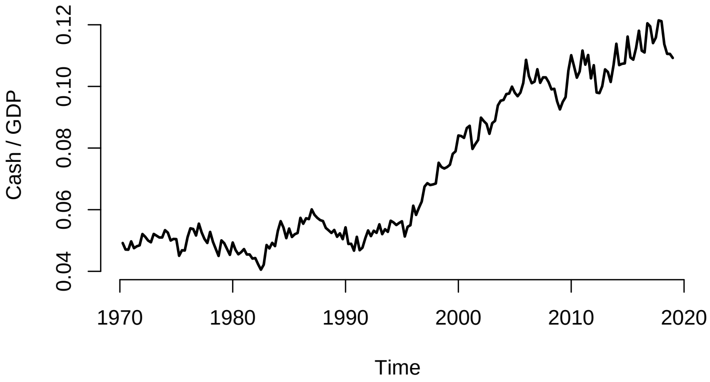
- **Intuition:**
  1. The *rankings* of the values in a period with e^0 and a period with e^1 are the same if $e^0 = e^1$.
  2. Among all the possible allocations (ergodic theorem), if the *ranking* is known, the *level* is determined.
- **This is a theoretical sufficient condition but not a constructive statement.**
  - A sufficient condition can be checked only after the convergence of the algorithm. (Later in the baseline model)
  - However, it helps understand *why the sufficient statistics works.*

A heterogeneous-firm business cycle model with cash

Before the model section

- What are the economically meaningful nonlinear dynamics?
  - Many of firm-side decisions are highly nonlinear.
  - Firm-level lumpy investments; *Cash dynamics*
    - A corporate cash holding model is an immediate firm-side counterpart of the heterogeneous-household models (Krusell and Smith, 1998)
- The repeated transition method can accurately solve the equilibrium dynamics:
  - Detailed analysis on the macroeconomic role of the nonlinear dynamics.
- A representative-agent model framework is also in the future research agenda:
  - Nonlinear dynamics of the SaM models in NK framework.
  - NK framework with a zero lower bound without approximation.

Rising corporate cash holdings



- Cash is from the Flow of Funds; GDP is from NIPA.

Overview of the model economy

Firms

Heterogeneous firms holding cash operate using only labor

Costly external financing

Household

A representative household consumes, works, and saves (claim for all firms).

Competitive market

Costly external financing

- Why does a corporate save?
  - Precautionary motivation (future financial constraint)
  - Dividend smoothing motivation
  - Frictional external financing
  - Agency cost

Costly external financing

- Why does a corporate save?
  - Precautionary motivation (future financial constraint)
  - Dividend smoothing motivation
  - Frictional external financing
  - Agency cost
- An external financing cost is one way of capturing the corporate saving glut (Riddick and Whited, 2009)

$$C(d) := \frac{\mu}{2}\mathbb{I}\{d < 0\}d^2$$

Note: The net dividend is $d_{it} - \frac{\mu}{2}\mathbb{I}\{d_{it} < 0\}d_{it}^2$: A temporal component of the objective function belongs to $\mathcal{C}^1$.

- Internal financing is cheaper than external financing:

$$R^{ss} = 1/\beta - 1 > R^{ca}$$

- Cash is an internal asset of a firm and NOT PRICED in the market.

Recursive formulation

- Heterogeneous firms operate using only labor; pay out dividends; and save cash.

$$[\text{Firm}] \quad J(ca, z; X) = \max_{ca', d} \quad d - C(d) + \mathbb{E}(q(X, X')J(ca', z'; X'))$$

$$\text{s.t.} \quad d + \frac{ca'}{1 + r^{ca}} = \pi(z; A, \Phi) + ca$$

$$ca' \geq 0, \quad \Phi' = G(\Phi, A)$$

$$[\text{Operating profit}] \quad \pi(z; A, \Phi) := \max_n zAn^{\gamma} - w(A, \Phi)n - \xi$$

$$[\text{Idiosyncratic productivity}] \quad z' = G_z(z) \text{ (AR(1) process)}$$

$$[\text{External financing cost}] \quad C(d) := \frac{\mu}{2}\mathbb{I}(d < 0)d^2$$

$$[\text{Aggregate state}] \quad X := \{A, \Phi\}$$

A stand-in household holds the dividend claim of all the firms.

Calibration

Proposition 2 (The existence of target cash stock)

Suppose policy functions are non-trivial: $ca'(ca, z) > 0$ *and* $d(ca, z) > 0$ *for some* $ca > 0$*, given* z*. Then, there exists* $\overline{ca}(z) > 0$ *such that* $ca'(ca, z) \leq \overline{ca}(z)$ *for* $\forall ca \geq 0$*.*

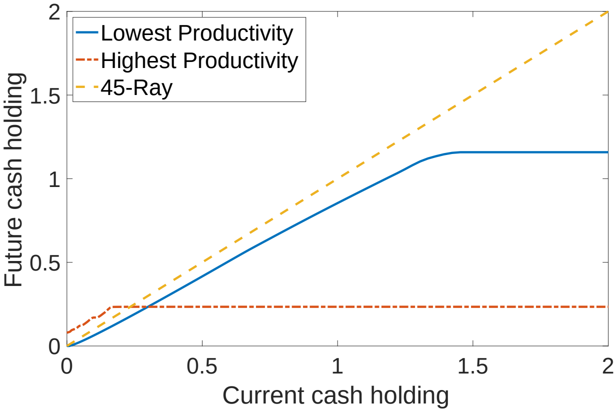
Suppose a firm has abundant cash stocks where there is no concern about tomorrow's dividend being negative:

$$d + q^{ca}ca' = \underbrace{\pi(z; S) + ca}_{\text{Liquidity on hands}}$$

The marginal gain out of saving ($\Delta ca'$) is $\frac{q^{ss}}{q^{ca}} < 1$, while the marginal gain of dividend (Δd) is 1.

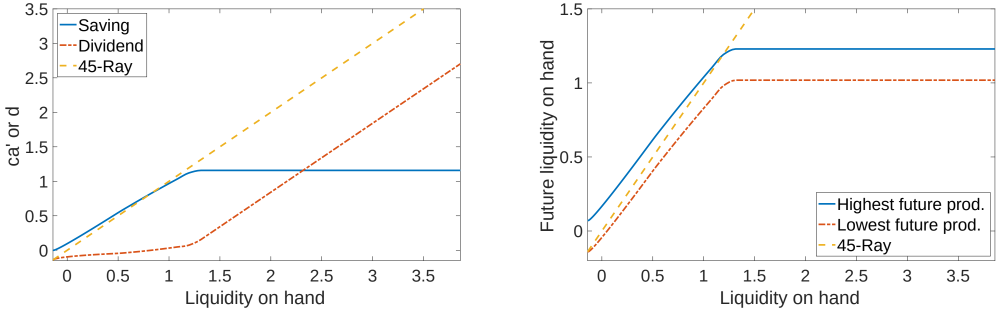
- Therefore, there exists a hand-to-dividend region: any extra liquidity immediately goes to households.

High vs. Low current productivity



- The lowest-productivity firms gradually reduce the cash holdings.
- The highest-productivity firms gradually increase the cash holdings until the target level.

Liquidity on hands $:= \pi(z;S) + ca$



(a) Allocation of liquidity on hands

(b) Evolution of liquidity on hands

Figure: Cash-holding policies in the stationary equilibrium (when $z = min\mathbb{Z}$)

λ is the slackness coefficient for the borrowing limit $ca' \geq 0$.

$$1 - \mu \mathbb{I}\{\widehat{d} < 0\}\widehat{d} = \frac{q^{ss}}{q^{ca}} \mathbb{E} J_1(ca', z') + \frac{\lambda(ca, z)}{q^{ca}}$$

Incomplete market and precautionary motivation

λ is the slackness coefficient for the borrowing limit $ca' \geq 0$.

$$1 - \mu \mathbb{I}\{\widehat{d} < 0\}\widehat{d} = \frac{q^{ss}}{q^{ca}} \mathbb{E} J_1(ca', z') + \frac{\lambda(ca, z)}{q^{ca}}$$

$$= \frac{q^{ss}}{q^{ca}} \mathbb{E}\left(\frac{q^{ss}}{q^{ca}} \mathbb{E} J_1(ca'', z'') + \frac{\lambda(ca', z')}{q^{ca}}\right) + \frac{\lambda(ca, z)}{q^{ca}}$$

$$= \frac{q^{ss}}{q^{ca}} \mathbb{E}\left(\frac{q^{ss}}{q^{ca}} \mathbb{E}\left(\frac{q^{ss}}{q^{ca}} \mathbb{E} J_1(ca''', z''') + \frac{\lambda(ca'', z'')}{q^{ca}}\right) + \frac{\lambda(ca', z')}{q^{ca}}\right) + \frac{\lambda(ca, z)}{q^{ca}}$$

$$= \dots$$

- The slackness condition increases the marginal benefit of cash holding. (LHS)
  - The current coefficient $\lambda(ca, z)$ shifts down the dividend. (increase in cash holding)
  - Despite $\lambda(ca, z) = 0$, the *future possibility of binding constraint* shifts down the dividend. (increase in cash holding)
- If all firms are with enough cash, the economy converges to the canonical RBC world.

Dynamic Stochastic General Equilibrium

The aggregate uncertainty

- As in Krusell and Smith (1998),

$$\Gamma_A = \begin{bmatrix} 0.8750 & 0.1250 \\ 0.1250 & 0.8750 \end{bmatrix}$$
$$A \in \{0.99, 1.01\}.$$

  where the unit period is a quarter.

- The aggregate shock is simulated for 1,000 periods.

- I use the histogram method (Young, 2010) for the forward evolution of the firm distribution.

- Solve the dynamic stochastic general equilibrium using the *repeated transition method*
  - Aggregate cash holding is the sufficient statistics to be used.

- Then I do: 1) Solution; 2) Recovering the true law of motions; 3) Out-of-sample fitting; 4) Monotonicity check

Nonlinear business cycle

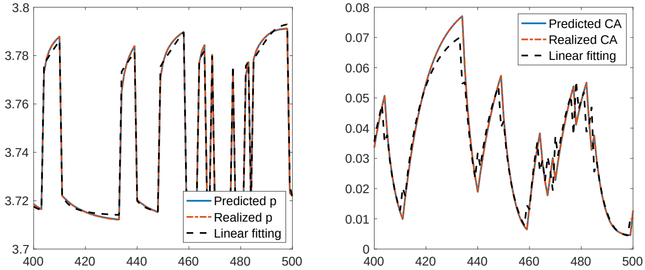


Figure: Aggregate fluctuations in the economy

When fitted into the log-linear law of motions:

$$log(CA_{t+1}) = -0.5742 + 0.9061 * log(CA_t), \quad \text{if } S_t = B, \text{ and } R^2 = 0.9971, \; MSE = 0.0017$$

$$log(CA_{t+1}) = -0.8949 + 0.6829 * log(CA_t), \quad \text{if } S_t = G, \text{ and } R^2 = 0.9823, \; MSE = 0.0039$$

$$log(p_t) = 1.3232 - 0.0018 * log(CA_t), \quad \text{if } S_t = B, \text{ and } R^2 = 0.8828, \; MSE = 0.0000$$

$$log(p_t) = 1.3093 - 0.0011 * log(CA_t), \quad \text{if } S_t = G, \text{ and } R^2 = 0.8928, \; MSE = 0.0000$$

	# of lagged	order	Goodness of fitness: R^2			
			CA_{t+1} : *Good*	CA_{t+1} : *Bad*	p_t : *Good*	p_t : *Bad*
Contemp.	0	1	0.8956	0.9452	0.9922	0.9966
	0	2	0.9839	0.9952	0.9927	0.9976
	0	3	0.9973	0.9995	0.9930	0.9976
	0	4	0.9993	0.9999	0.9932	0.9976
	0	5	0.9996	1.0000	0.9933	0.9976
Add. history	1	3	0.9999	1.0000	0.9987	0.9979
	2	3	0.9999	1.0000	0.9997	0.9984
	3	3	0.9999	1.0000	0.9998	0.9987
	4	3	0.9999	1.0000	0.9998	0.9991
	5	3	0.9999	1.0000	0.9998	0.9994
	6	3	0.9999	1.0000	0.9998	0.9996
	7	3	0.9999	1.0000	0.9998	0.9997

Table: The fitness of law of motion across different specifications

Out-of-sample fitting

- I test the validity of the law of motions that utilizes historical allocations using the out-of-sample simulation.

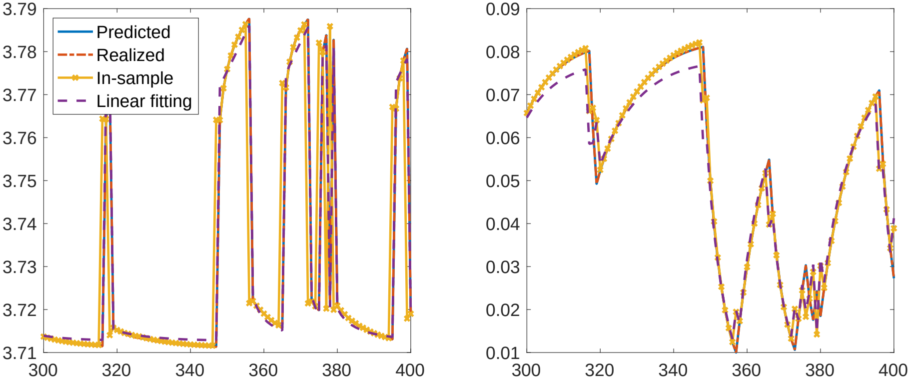
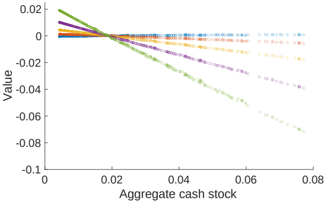
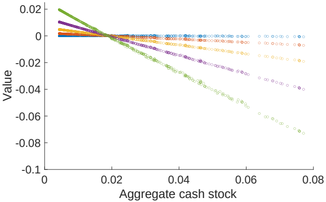


Figure: Fitting into the out-of-sample path

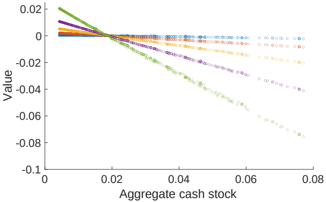
Monotonicity of value function in the aggregate state



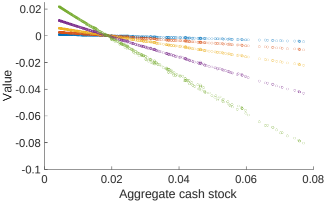
(a) Individual cash = 1e–8



(b) Individual cash = 0.09

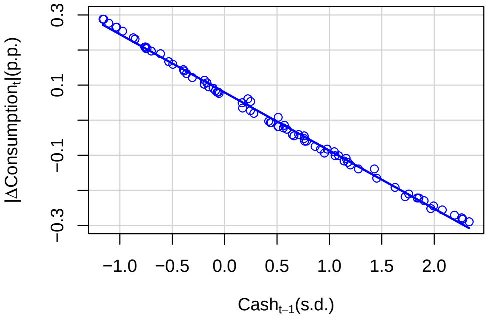


(c) Individual cash = 0.23

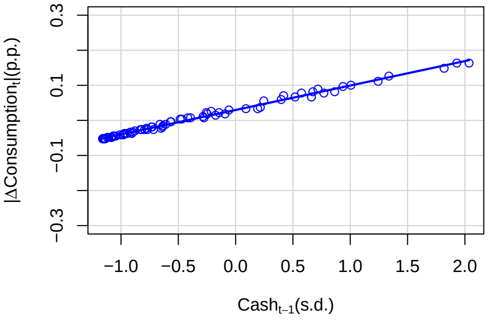


(d) Individual cash = 0.47

Macroeconomic implications



(a) Negative shock



(b) Positive shock

Figure: State-dependent shock responses of consumption

State-dependent responsiveness: Model

	Dep. Var.: $\|log(c_t)\|$ $(p.p.)$	
	Neg. (1)	Pos. (2)
$Cash_{t-1}(s.d.)$	-0.166 (0.001)	0.07 (0.001)
Constant	Yes	Yes
Observations	83	84
R^2	0.996	0.994

Table: State-dependence consumption responses to negative and positive shocks

- State-dependent asymmetric responsiveness (hysteresis):
  - Past cash holding decreases the responsiveness of consumption to the identical negative TFP shock.
  - Past cash holding increases the responsiveness of consumption to the identical positive TFP shock.
  - The insurance effect is asymmetric: a stronger insurance effect on the negative shock.
- Model prediction is well-supported by the data.

This is a recent phenomenon

	Dependent variables:			
	$\lvert log(c_t)\rvert$ $(p.p.)$ before 1980		$\lvert log(c_t)\rvert$ $(p.p.)$ after 1980	
	Neg.	Pos.	Neg.	Pos.
	(1)	(2)	(3)	(4)
$Cash_{t-1}(s.d.)$	-0.108	0.036	-0.226	0.164
	(0.09)	(0.072)	(0.085)	(0.09)
Constant	Yes	Yes	Yes	Yes
Observations	63	49	77	79
R^2	0.023	0.005	0.086	0.041

Table: State-dependence consumption responses to negative and positive shocks: Before vs. After 1980

- State-dependent asymmetric responsiveness:
  - The magnitude is similar to the model counterpart.

Concluding remarks

- The repeated transition method solves nonlinear heterogeneous-agent models with aggregate uncertainty accurately,
  - globally,
  - without a parametric law of motion,
  - without perfect foresight,
  - with a speed gain under the presence of non-trivial market clearing conditions.
- A corporate cash holding behavior leads to highly nonlinear aggregate dynamics, providing a consumption insurance to households through the dividend channel.
  - This is a relatively recent phenomenon in the data.
  - $\boldsymbol{Cash_{t-1}} \uparrow$ by 1 $\boldsymbol{s.d.} \rightarrow |\Delta c_t| \downarrow$ by 0.17 (p.p.) (negative shock)
  - $\boldsymbol{Cash_{t-1}} \uparrow$ by 1 $\boldsymbol{s.d.} \rightarrow |\Delta c_t| \uparrow$ by 0.12 (p.p.) (positive shock)

Appendix

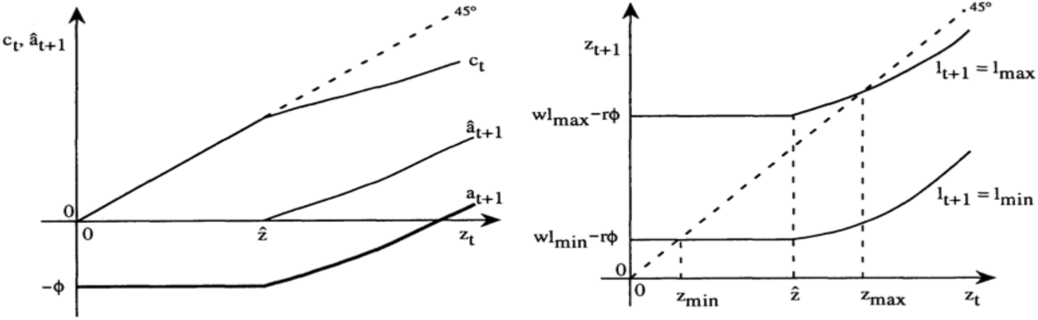


Figure Ia
Consumption and Assets as Functions of Total Resources

Figure Ib
Evolution of Total Resources

Notes: The figure is from Aiyagari (1994).

Calibration

- Three parameters are calibrated.

Parameters	Target Moments	Data	Model	Level
μ	Corporate cash holding/Output (%)	10.00	9.28	0.40
ξ	Consumption/Output (%)	66.00	64.02	0.15
η	Labor supply hours	0.33	0.34	3.90

Table: Calibration target and parameters