A Diagnostic TANK Model for the Housing Market

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The views expressed here are my own and do not necessarily reflect those of the Bank of England.

Presentation outline

1. Motivation
2. Contribution
3. Diagnostic Expectations
4. Model
5. Solution
6. Calibration & Estimation
7. Results
8. Concluding remarks

Motivation

- U.S. Housing market prices & quantities are 3x and 6x more volatile than GDP

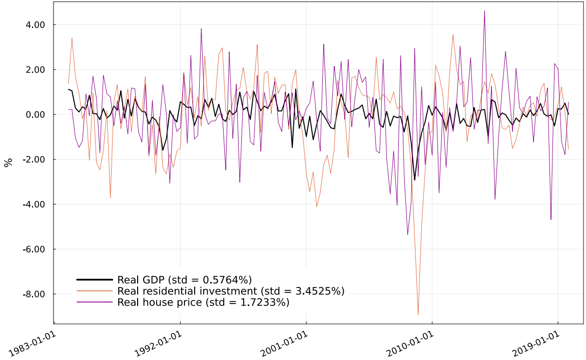

Figure: **Real GDP, real house price and real residential investment.**

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- U.S. Housing market expectations Plot
  1. Strongly track observed house price changes (Adam et al., 2024)
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Why do house prices in the U.S. surge during booms and plummet in downturns, often beyond what fundamentals would suggest? What is the role of expectations?

Contribution

1. Study role of expectations in housing market
    - Incorporate **Diagnostic Expectations** (DE) in a TANK model
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   - DE robust alternative to traditional explanations
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   - DE robust alternative to traditional explanations
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   - Improve the fit of the model vs rational counterpart
3. Policy Implications
   - Anticipate speculative bubbles
   - Design interventions to mitigate financial instability and resource misallocation

Diagnostic Expectations

Diagnostic Expectations describe a cognitive bias based on "representative heuristic"

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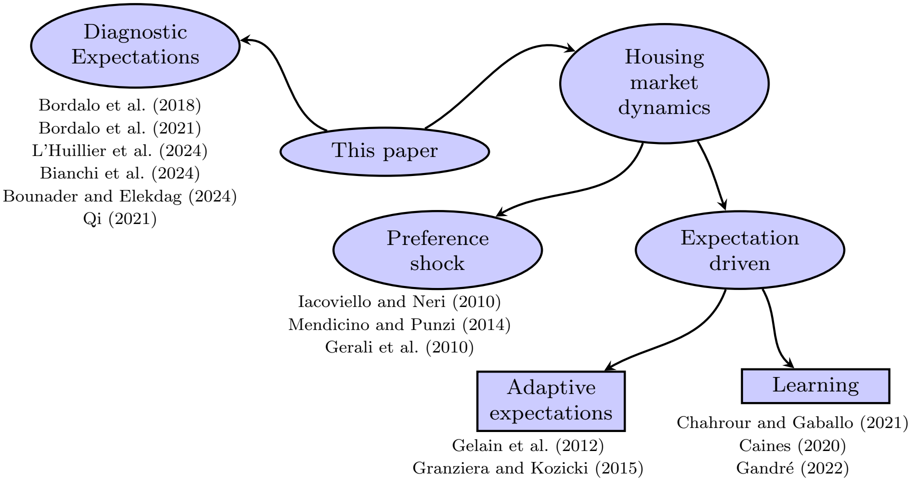
Advantages

✓ Successful in capturing run-ups and sharp declines in financial markets (Bordalo et al., 2018)

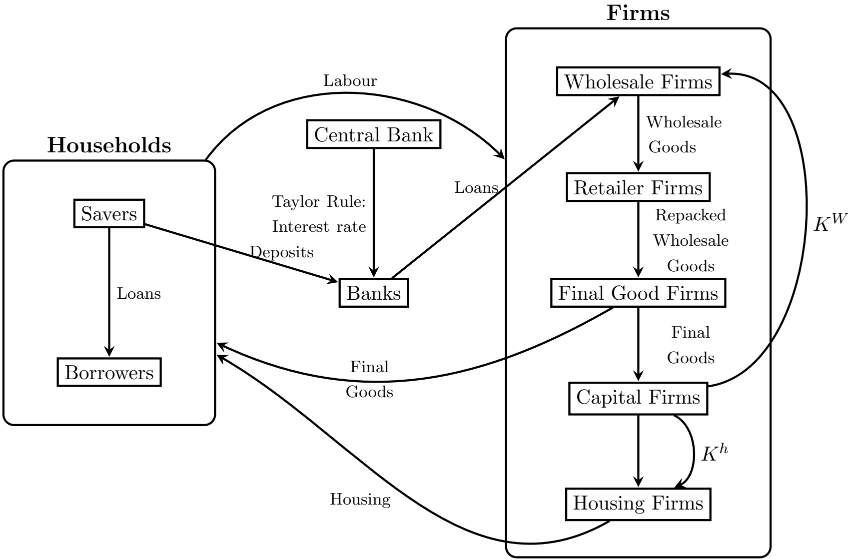
✓ Consistent with forecast data (Bordalo et al., 2020)

✓ Tractable

Related Literature



Model


Firms
Wholesale Firms
Wholesale
Goods
Retailer Firms
Repacked
Wholesale
Goods
Final Good Firms
Final
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Capital Firms
K^W
K^h
Housing Firms
Labour
Central Bank
Households
Loans
Taylor Rule:
Interest rate
Savers
Deposits
Loans
Banks
Borrowers
Final
Goods
Housing

Solution: Including DE

- Consider the exogenous shock processes:

$$x_{t+1} = \rho x_t + \epsilon_{t+1}$$

  with pdf $f(x_{t+1}|x_t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x_{t+1}-\rho x_t)^2}{2\sigma^2}}$

- Diagnostic pdf is defined as

$$f^{\phi}(x_{t+1}|x_t) = \underbrace{f(x_{t+1}|x_t = \bar{x}_t)}_{\text{true pdf}} \underbrace{\left[\frac{f(x_{t+1}|\bar{x}_t)}{f(x_{t+1}|\rho\bar{x}_{t-1})}\right]^{\phi}}_{\text{distortion}} Z \tag{1}$$

  Information set:

  - $\bar{x}_t$: current state at t
  - $\rho\bar{x}_{t-1}$: reference state at $t-1$
  - ϕ: the degree of diagnosticity

Including DE: short-term memory

- DE under short-term memory is:

$$\mathbb{E}_t^{\phi}(x_{t+1}) = \mathbb{E}_t(x_{t+1}) + \phi\left[\mathbb{E}_t(x_{t+1}) - \mathbb{E}_{t-1}(x_{t+1})\right]$$

- Applying the expectations operators

$$\mathbb{E}_t[x_{t+1}] = \rho\bar{x}_t \text{ and } \mathbb{E}_{t-1}[x_{t+1}] = \rho^2\bar{x}_{t-1}$$

- Agents misperceive the state of the economy to be more persistent than it actually is

$$\mathbb{E}_t^{\phi}[x_{t+1}] = \rho\bar{x}_t + \phi(\rho\bar{x}_t - \rho^2\bar{x}_{t-1}) = \rho\bar{x}_t + \phi\rho\bar{\epsilon}_t$$

Extrapolation in the direction of the shock

Including DE: distant memory

- Assume that the agent has a slow moving reference group

$$f^{\phi}(x_{t+1}|x_t) = \underbrace{\frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x_{t+1}-\rho\bar{x}_t)^2}{2\sigma^2}}}_{\text{true pdf}} \underbrace{\left\{ \left[\prod_{s=1}^{S} \frac{\frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x_{t+1}-\rho^s \bar{x}_{t+1-s})^2}{2\sigma^2}}}{\frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x_{t+1}-\rho^{s+1}\bar{x}_{t-s})^2}{2\sigma^2}}} \right]^{\alpha_s} \right\}^{\phi} Z}_{\text{distortion}} \tag{2}$$

- DE can be generalised

$$\mathbb{E}_t^{\phi}(x_{t+1}) = \mathbb{E}_t(x_{t+1}) + \phi \sum_{s=1}^{S} \alpha_s \left[\mathbb{E}_{t+1-s}(x_{t+1}) - \mathbb{E}_{t-s}(x_{t+1})\right]$$

- Agents misperceive the state of the economy as an ARMA(1,S) process:

$$\mathbb{E}_t^{\phi}(x_{t+1}) = \rho x_t + \phi \sum_{s=1}^{S} \rho^s \alpha_s \epsilon_{t+s-1}$$

Calibration & Estimation

- **Data**: GDP, inflation, residential investment, house prices, nominal interest rate, loans, non-residential investment and housing wealth Data
- **Sample**: 1984:Q4-2019:Q4
- I estimate the model using SMC
- SMC is an estimation method that combines features of classic importance sampling and MCMC techniques
  - **Advantages**:
    (i) suitable for parallel computing
    (ii) facilitates re-estimation as new data becomes available
    (iii) approximates the marginal likelihood as a byproduct
    (iv) more efficient exploring high dimensional parameter spaces

Algorithm

Calibration & Estimation

Table: Calibration Structural parameters

Description	Parameter	Value	Target/Source
Discount factor	β_p	0.9915	Annualized interest rate of 3.52%
Patient housing preference weight	ν_p^h	0.2361	Patient households share of housing wealth = 60%
Impatient housing preference weight	ν_i^h	0.0906	Residential investment/GDP = 3.44%
Loan-to-value ratio	χ	0.8016	Household credit to total housing wealth = 35.24%
Elasticity of final good with respect to capital	α	0.3752	Investment/GDP = 27%
Housing depreciation rate	δ_h	0.0060	Housing wealth/GDP = 143.23%
Proportion of impatient households	n	0.9	Gelain et al. (2012)
Inverse elasticity of labour supply	φ	0.1	Gelain et al. (2012)
Labour disutility	ν_p^n	1.19	Gelain et al. (2012)
Discount factor	β_i	0.9715	Borrowing constraint's binding
Labour disutility	ν_i^n	4.54	Gelain et al. (2012)
Elasticity of substitution	ϵ	11	10% markup
Capital depreciation rate	δ_k	0.025	Typical in macroeconomic model literature
Elasticity of housing with respect to capital	μ_h	0.3	Iacoviello and Neri (2010)
Banks' surviving probability	σ	0.9725	Gertler and Karadi (2011)
Absconding rate of the bankers	ζ	0.383	Gertler and Karadi (2011)
Start up fund for the new bankers	ω	0.003	Gertler and Karadi (2011)

Calibration & Estimation

Table: Estimation: Mean and HPDI*

Description	Parameter	RE		DE Ref: Q1		DE Ref: Q12	
		Mean	[0.05, 0.95]	Mean	[0.05, 0.95]	Mean	[0.05, 0.95]
Diagnostic Parameters							
Diagnostic parameter	ϕ	0.0		0.4555	[0.2819, 0.6629]	0.1303	[0.0050, 0.3265]
1st quarter reference	α_1			1.0		0.6714	[0.2689, 0.9517]
2nd quarter reference	α_2					0.2209	[0.0147, 0.5706]
3rd quarter reference	α_3					0.2054	[0.0055, 0.6358]
4th quarter reference	α_4					0.5226	[0.1065, 0.9487]
5th quarter reference	α_5					0.0990	[0.0057, 0.3096]
6th quarter reference	α_6					0.3797	[0.0380, 0.8109]
7th quarter reference	α_7					0.5930	[0.1513, 0.9603]
8th quarter reference	α_8					0.4963	[0.0910, 0.8893]
9th quarter reference	α_9					0.4775	[0.0829, 0.9068]
10th quarter reference	α_{10}					0.5157	[0.1629, 0.8209]
11th quarter reference	α_{11}					0.5219	[0.1789, 0.8178]
12th quarter reference	α_{12}					0.1340	[0.0087, 0.4000]
Standard Deviation of Shocks							
Goods TFP	$100^*\sigma_{\epsilon^A}$	1.6550	[1.4820, 1.8551]	1.3084	[1.1121, 1.4724]	1.4435	[1.2829, 1.6180]
Housing TFP	$100^*\sigma_{\epsilon^Z}$	3.7089	[3.3996, 4.1035]	3.7382	[3.3965, 4.1451]	3.9204	[3.3804, 3.9830]
Monetary policy	$100^*\sigma_{\epsilon^M}$	0.2959	[0.2286, 0.3771]	0.2222	[0.1719, 0.2794]	0.3107	[0.2416, 0.3896]
Housing demand	$100^*\sigma_{\epsilon^\Gamma}$	11.2891	[7.2150, 16.4806]	7.2345	[4.6284, 10.9440]	5.3588	[4.0070, 6.6326]
Log Marginal Likelihood		591.63		598.91		568.67	

*HPDI: high probability density credible interval

Results

Table: Second-order moments in data and model

	Data	DE Ref:Q12	DE Ref:Q1	RE
Targeted moments				
Standard deviation				
Δ Real GDP	0.5764	0.8625	0.7271	0.8758
Relative standard deviation to GDP growth				
Inflation	0.4262	0.3025	0.3397	0.3057
Δ Real House prices	2.9896	2.4381	3.1882	2.3282
Δ Real Residential Investment	5.9893	5.0424	5.3184	4.7029

Note: Growth rates for real GDP, real house price, real residential investment. Model moments were obtained by averaging over ten thousand simulations of hundred and forty four observations each.

Impulse responses

- Preference shock
- Non-durable TFP shock
- Monetary policy shock
- Housing TFP shock

Counterfactual analysis

Table: Real House price growth second-order moment

	Data	DE Ref:Q12	RE Ref:Q12 Counterfactual	DE Ref:Q1	RE Ref:Q1 Counterfactual
Volatility relative to GDP					
Real House price growth	2.9896	2.4381	1.8877	3.1882	2.4992

Note: House price growth rate is obtained from averaging over ten thousand simulations of hundred and forty four observations each.

Concluding remarks

- Role of expectations as central driver in US housing market
  - TANK + DE with short-term and long-term memory
  - Use SMC to validate DE empirically
  - DE as a more comprehensive alternative to the "catchall of all the unmodeled disturbances that can affect housing demand"
- DE offer crucial insights for modeling & policy
  - Sector's significance in household decision-making
  - Valuable information about ongoing changes in economic activity
  - Lab to study the effect of macro-prudential tools
- Possible extension: allow for heterogeneity in the degree of diagnosticity

Thank you for your attention

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IRF: Preference shock

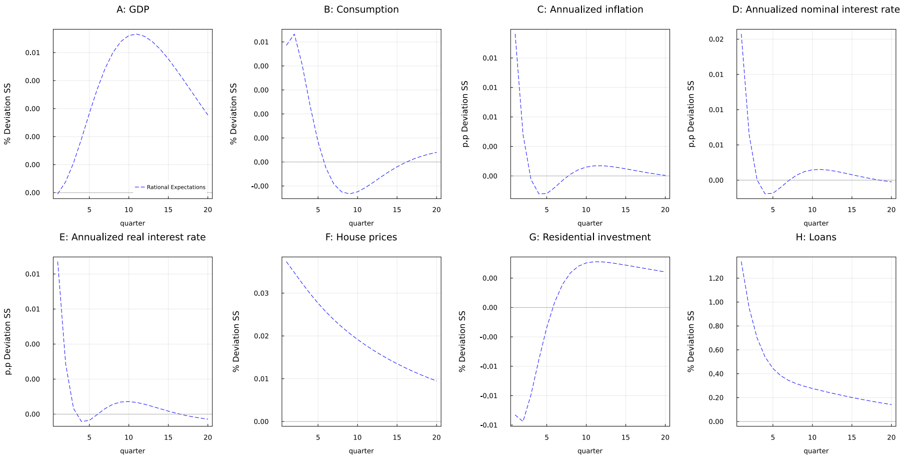

Figure: Impulse responses to non-durable goods productivity shock

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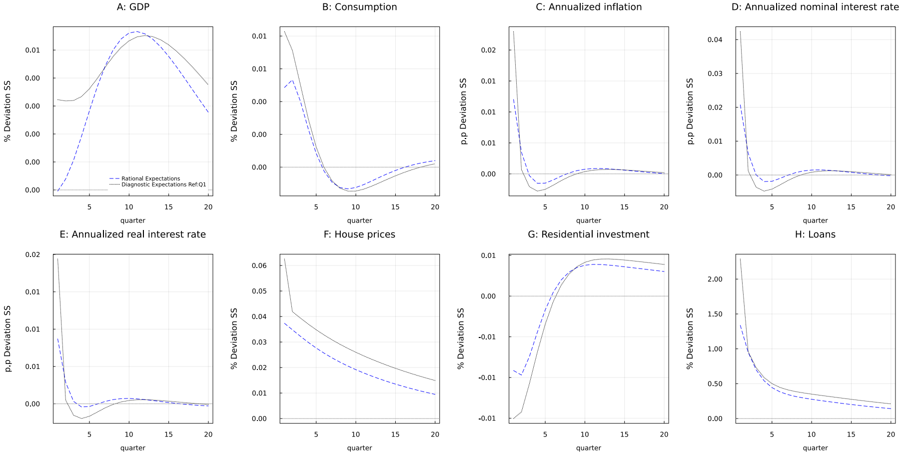

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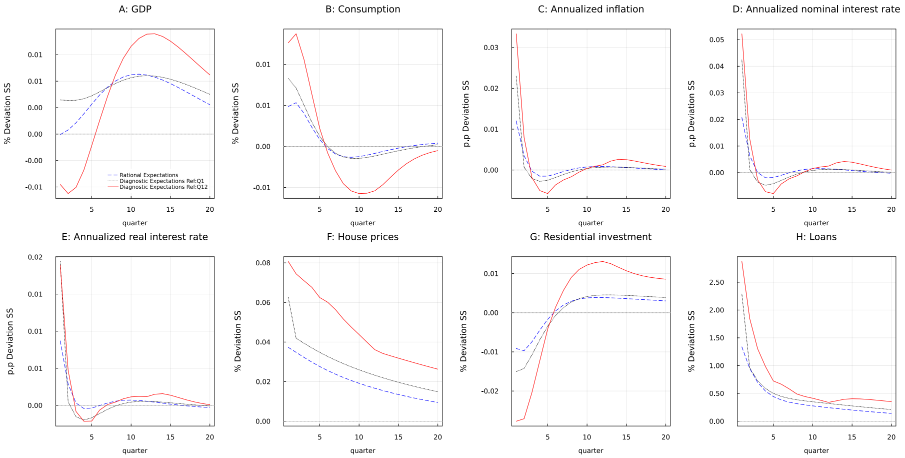

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Presentation

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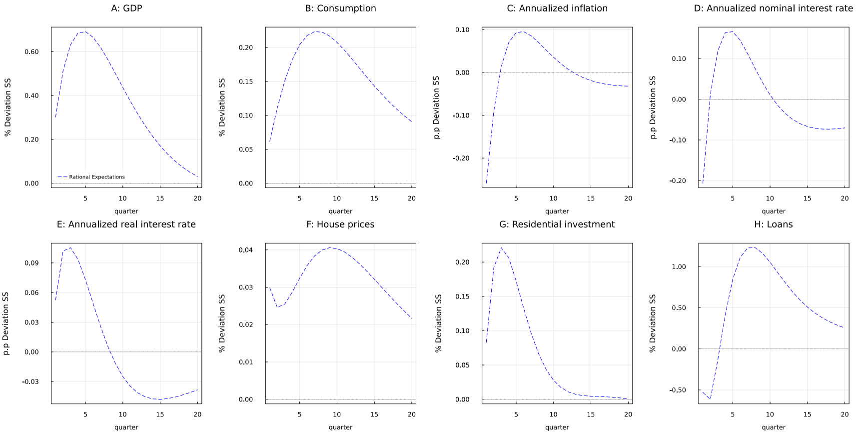

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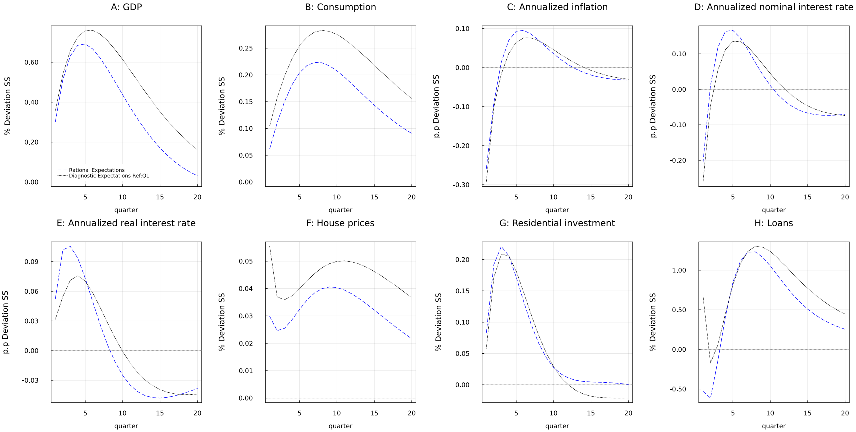

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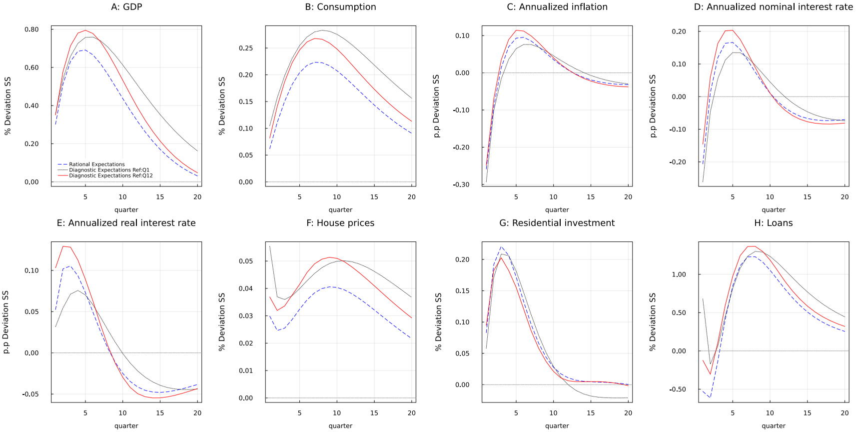

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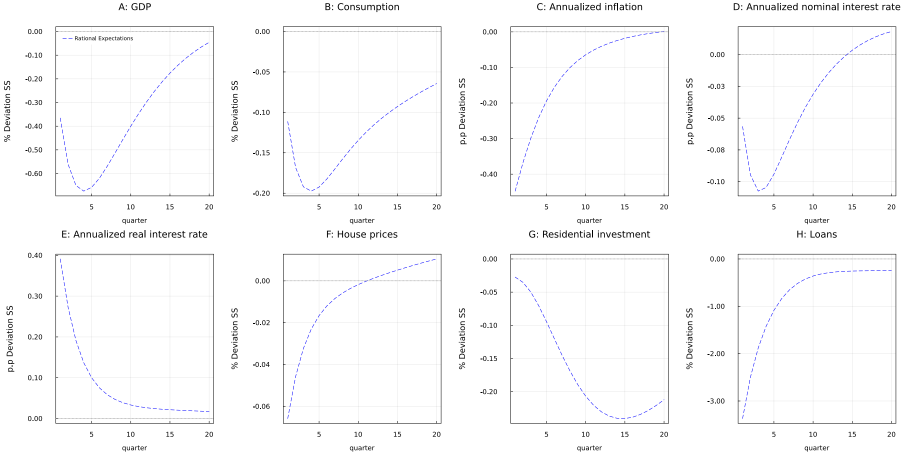

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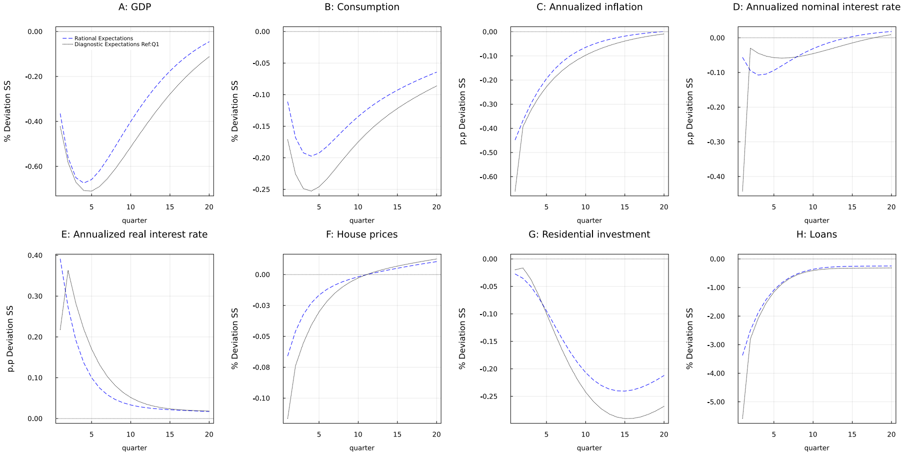

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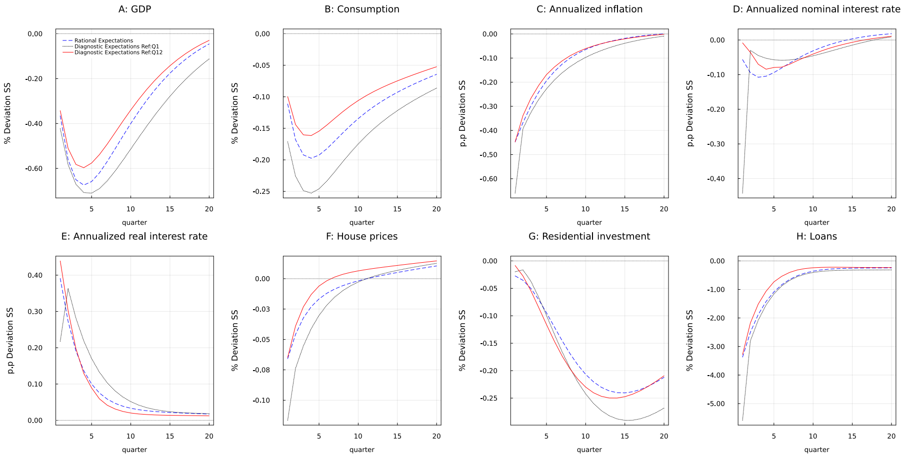

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Presentation

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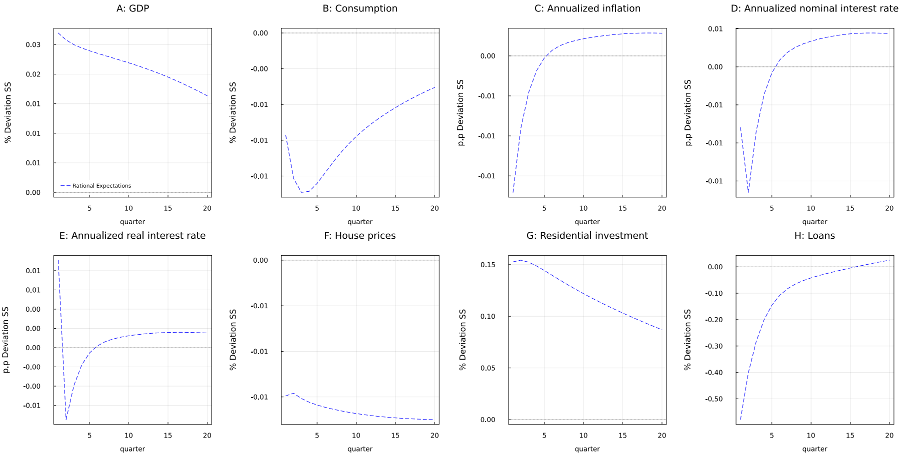

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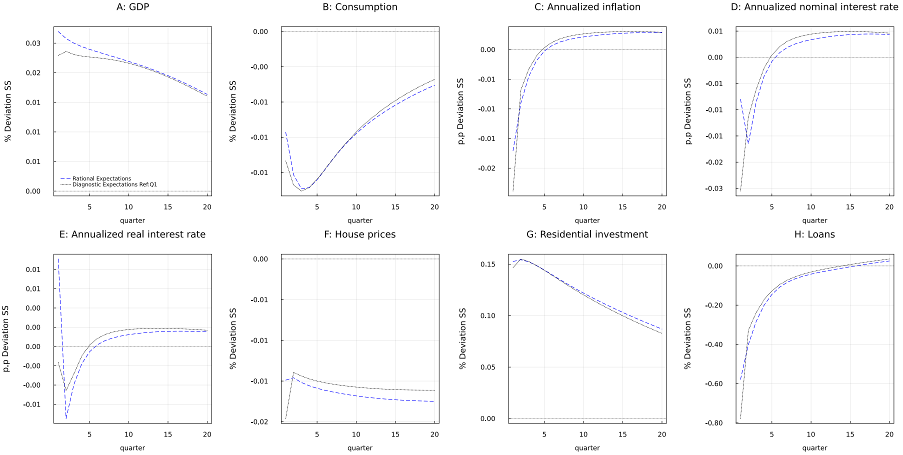

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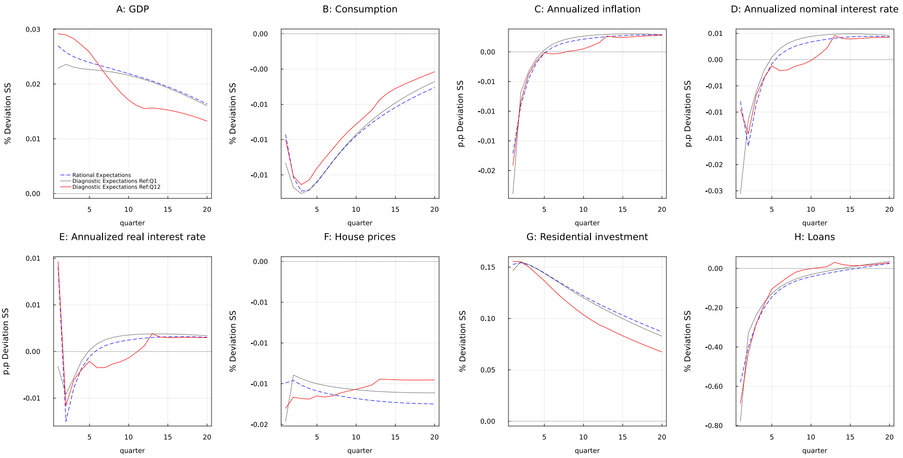

Figure: Impulse responses to non-durable goods productivity shock

Households problem

Patient

$$\max_{c_{p,t},n_{p,t},h_{p,t},d_t^B,d_t^l} U_p = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta_p^t \left[log(c_{p,t} - \gamma c_{p,t-1}) + \Gamma_t \nu_p^h log(h_{p,t}) - \nu_p^n \frac{n_{p,t}^{1+\varphi}}{1+\varphi} \right]$$

$$c_{p,t} + q_t[h_{p,t} - (1-\delta_h)h_{p,t-1}] + d_t^B + d_t^l = \frac{d_{t-1}^B R_{t-1}^d}{\pi_t} + \frac{d_{t-1}^l R_{t-1}^l}{\pi_t} + w_t n_{p,t} + \Pi_{f,t} + \Pi_{B,t}.$$

Back

Households problem

Impatient

$$\max_{c_{i,t},n_{i,t},h_{i,t},l_t} U_i = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta_i^t \left[log(c_{i,t} - \gamma c_{i,t-1}) + \Gamma_t \nu_i^h log(h_{i,t}) - \nu_i^n \frac{n_{i,t}^{1+\varphi}}{1+\varphi} \right]$$

$$c_{i,t} + q_t(h_{i,t} - (1-\delta_h)h_{i,t-1}) + \frac{l_{t-1}R_{t-1}^l}{\pi_t} = w_t n_{i,t} + l_t$$

$$l_t \leq \frac{\chi}{R_t^l} \mathbb{E}_t[q_{t+1}\pi_{t+1}] h_{i,t}$$

Back

Wholesale Firms

- Buy capital from capital producers and hire labour from households
- Cobb-Douglas technology function

$$\max_{N_t^W, K_t^W} \left[P_{m,t} Y_t^W + (1-\delta_k) q_{t-1}^K K_{t-1}^W - R_t^K q_{t-1}^K K_t^W - w_t N_t^W \right]$$

$$Y_t^W = A_t {N_t^W}^{1-\alpha} {K_{t-1}^W}^{\alpha}$$

At the end of each period, these firms obtain funds from the banking sector to finance the acquisition of capital K_t^W. They take S_t loans equal to the number of units of capital acquired and price each at the unit price of capital q_t^K.

$$q_t^K K_t^W = q_t^K S_t$$

Back

Retailer Firms

- Re-package intermediate wholesale production
- It takes one intermediate output to make a unit of retail output
- Price setting style *à la Calvo*

$$\max_{P_t^*(j)} V_t(j) = \mathbb{E}_t \sum_{i=0}^{\infty} (\beta_p \theta)^i \left\{ \frac{\lambda_{p,t+i}}{\lambda_{p,t}} \left[\left(\frac{P_t^*(j)}{P_{t+i}} - mc_{t+i} \right) \left(\frac{P_t^*(j)}{P_{t+i}} \right)^{\epsilon} Y_{t+i} \right] \right\}$$

$$P_t^*(j) = \frac{\epsilon}{\epsilon - 1} \left[\frac{\mathbb{E}_t \sum_{i=0}^{\infty} (\beta_p \theta)^i \lambda_{p,t+i} mc_{t+i} P_{t+i}^{\epsilon} Y_{t+i}}{\mathbb{E}_t \sum_{i=0}^{\infty} (\beta_p \theta)^i \lambda_{p,t+i} P_{t+i}^{\epsilon - 1} Y_{t+i}} \right]$$

Back

Final Good Firms

- Aggregates output of retailer firms according to a Dixit-Stiglitz production technology
- Sells the final product in a perfectly competitive market

$$Y_t = \left[\int_0^1 y_t(j)^{\frac{\epsilon-1}{\epsilon}} di \right]^{\frac{\epsilon}{\epsilon-1}}$$

- Makes zero profit and its price is

$$P_t = \left[\int_0^1 P_t(j)^{1-\epsilon} di \right]^{\frac{1}{1-\epsilon}}$$

Back

Capital Firms

- Owned by patient households
- Transform output in the form of investment and undepreciated capital to produce new capital
- Part of the capital is sold to wholesale firms, and part is rented to housing firms

$$\max_{K_t^W, K_t^h, I_t} \mathbb{E}_0 \sum_{i=0}^{\infty} \beta_p^i \frac{\lambda_{p,t+i}}{\lambda_{p,t}} \left[q_t^K K_t^W - q_t^K (1-\delta_k) K_{t-1}^W + r_t^{K,h} K_t^h - I_t \right]$$

$$K_t = (1-\delta_k) K_{t-1} + [1 - \frac{\psi}{2} (I_t / I_{t-1} - 1)^2] I_t$$

$$K_t = K_t^W + K_t^h$$

Back

Housing Firms

- Rent capital from capital producer and hire labour from household
- Cobb-Douglas production technology

$$\max_{N_t^h, K_{t-1}^h} \left[q_t I_t^h - r_t^{K,h} K_{t-1}^h - w_t N_t^h \right]$$

$$I_t^h = Z_t {N_t^h}^{1-\mu_h} {K_{t-1}^h}^{\mu_h}$$

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Banks

- Follows Gertler and Kiyotaki (2010) and Gertler and Karadi (2011)

$$q_t^K S_{\tau,t} = NW_{\tau,t} + D_{i,t}$$

- Each bank has a probability σ to continue functioning until next period, and a probability to exit $1-\sigma$. This prevents the bank from overcoming its financial constraint by saving indefinitely
- Moral hazard problem to limit the bank's ability to issue deposits

$$V_{\tau,t}^B = \beta_B \mathbb{E}_t \frac{\lambda_{p,t+1}}{\lambda_{p,t}} \{(1-\sigma)NW_{\tau,t} + \sigma \max V_{\tau,t+1}^B(NW_{\tau,t+1})\}$$

subject to:

$$q_t^K S_{\tau,t} = NW_{\tau,t} + D_{\tau,t}$$

$$NW_{\tau,t+1} = \left(R_{t+1}^K - R_t^d\right) S_{\tau,t} + R_t^d NW_{\tau,t}$$

$$V_{\tau,t}^B \geq \zeta(q_{t,f}^k S_{\tau,t})$$

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Central Bank

- Follows a Taylor rule to set interest rate

$$\frac{R_t^d}{\bar{R}^d} = \left(\frac{\pi_t}{\bar{\pi}}\right)^{\omega_\pi} \left(\frac{GDP_t}{GDP_{t-1}}\right)^{\omega_y} M_t$$

- $GDP_t = C_t + I_t + \bar{q} I_t^h$
- $\bar{q}$ denotes the steady state value of real housing prices, so that short-run changes in real house prices do not affect GDP growth

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Appendix: Expectations data

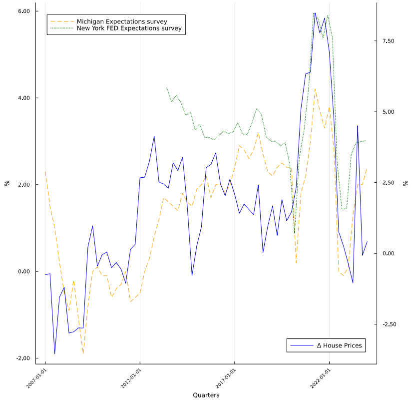

Figure: **Survey expectations and empirical data on Δ House Prices**.

Note: The orange dashed line represents the expected change in home values during the next year obtained from the University of Michigan consumer survey. The green dotted line shows home price change expectations from the survey of consumer expectations from the Federal Reserve Bank of New York. The blue line represents empirical data on the growth of quarterly house prices year over year.

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Appendix: Data

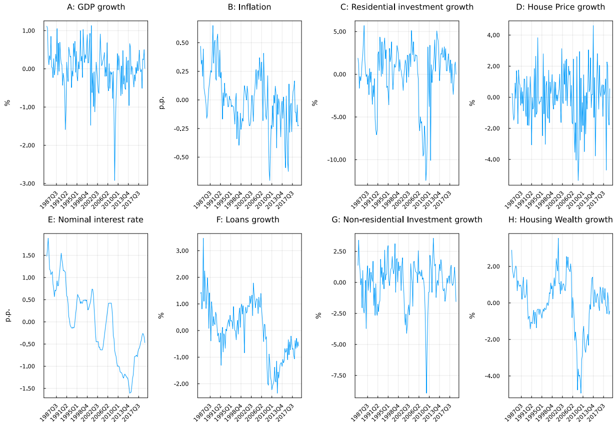

Figure: **U.S. Macroeconomic variables**.

Note: Real gross domestic product, real residential investment, real house price, real loans, real non-residential investment and real housing wealth growths are in percentages. Inflation and nominal interest rate are quarterly.

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Appendix: Algorithm

1. Draw initial particles from prior distribution
2. Recursively generates intermediate or “bridge” distributions
3. Each iteration refines the approximation of the posterior
4. Updating the particle weights, resampling and mutation steps
5. Final output as approximation of the posterior in the form of particles and weights

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Table: Estimation: Mean and HPDI (Continuation)

Description	Parameter	DE Ref: Q12		DE Ref: Q1		RE	
		Mean	[0.05, 0.95]	Mean	[0.05, 0.95]	Mean	[0.05, 0.95]
Structural Parameters							
Inv. adjustment cost	ψ	0.8696	[0.5039, 1.2422]	2.0600	[1.1548, 3.3689]	0.8163	[0.4974, 1.2026]
Habit formation	γ	0.7224	[0.6383, 0.7896]	0.7415	[0.6558, 0.7956]	0.7143	[0.6199, 0.7763]
Calvo parameter	ϕ	0.8485	[0.8288, 0.8637]	0.8732	[0.8604, 0.8827]	0.8593	[0.8424, 0.8718]
Taylor rule inflation	ω_π	1.6680	[1.4599, 1.8769]	1.7381	[1.4643, 2.0024]	1.7183	[1.4661, 1.9764]
Taylor rule output growth	$\omega_{\Delta y}$	0.1972	[0.1249, 0.2646]	0.1795	[0.0996, 0.2455]	0.2029	[0.1102, 0.2764]
Autoregressive Coefficients							
Goods TFP	ρ_A	0.8307	[0.7791, 0.8906]	0.8691	[0.8153, 0.9217]	0.8169	[0.7559, 0.8750]
Housing TFP	ρ_Z	0.9413	[0.9212, 0.9595]	0.9514	[0.9331, 0.9660]	0.9546	[0.9379, 0.9679]
Monetary policy	ρ_M	0.6561	[0.5444, 0.7373]	0.7625	[0.6807, 0.8115]	0.6896	[0.5965, 0.7573]
Housing demand	ρ_Γ	0.9614	[0.9400, 0.9800]	0.9445	[0.9080, 0.9715]	0.9293	[0.8876, 0.9633]

Appendix: Priors

Table 6: Prior distribution of parameters

Description	Parameter	Distribution	Mean	Std. dev
Structural Parameters				
Inv. adjustment cost	ψ	Normal	4.0	1.5
Habit formation	γ	Beta	0.667	0.05
Calvo parameter	θ	Beta	0.5	0.075
Taylor rule inflation	ω_π	Normal	1.50	0.25
Taylor rule output growth	$\omega_{\Delta y}$	Normal	0.125	0.05
Diagnostic parameters				
Diagnostic parameter	ϕ	Normal	1.0	0.3
1st quarter reference	α_1	Uniform	0.5	0.29
2nd quarter reference	α_2	Uniform	0.5	0.29
3rd quarter reference	α_3	Uniform	0.5	0.29
4th quarter reference	α_4	Uniform	0.5	0.29
5th quarter reference	α_5	Uniform	0.5	0.29
6th quarter reference	α_6	Uniform	0.5	0.29
7th quarter reference	α_7	Uniform	0.5	0.29
8th quarter reference	α_8	Uniform	0.5	0.29
9th quarter reference	α_9	Uniform	0.5	0.29
10th quarter reference	α_{10}	Uniform	0.5	0.29
11th quarter reference	α_{11}	Uniform	0.5	0.29
12th quarter reference	α_{12}	Uniform	0.5	0.29
Autoregressive coefficients				
Goods TFP	ρ_A	Beta	0.5	0.2
Housing TFP	ρ_Z	Beta	0.5	0.2
Monetary policy	ρ_M	Beta	0.5	0.2
Housing demand	ρ_Γ	Beta	0.5	0.2
Standard deviation of shocks				
Good TFP	$100^*\sigma_{\epsilon^A}$	Inverse Gamma	0.5	2.0
Housing TFP	$100^*\sigma_{\epsilon^Z}$	Inverse Gamma	0.5	2.0
Monetary policy	$100^*\sigma_{\epsilon^M}$	Inverse Gamma	0.5	2.0
Housing demand	$100^*\sigma_{\epsilon^\Gamma}$	Inverse Gamma	0.5	2.0

Note: The Inverse Gamma priors are of the form $p(\sigma|\nu, s) \propto \sigma^{-\nu-1}e^{-\frac{s}{2\sigma^2}}$. I borrow the function InverseGamma1.jl and *inverse_gamma_1_specification* from the Dynare package for Julia to obtain the parameters ν and s of and Inverse Gamma distribution characterised as in the table above.

Historical Decomposition

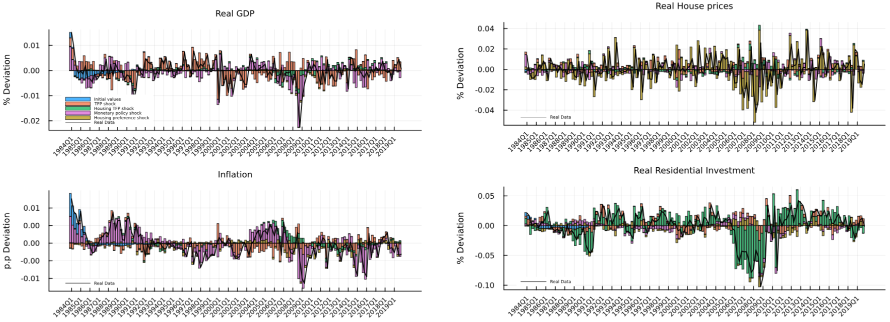

Figure: Historical shock decomposition under DE model with 1-quarter reference.