The RBC model

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Advanced Macro
Plan of the Presentation

1. Trend and cycle
2. Introduction to RBC
3. The model
4. Steady state
5. Log-linearisation
6. Solution
7. Simulations
8. Summary
What are business cycles?

- GDP per capita in developed economies since 19th century:
  - Stable growth trend
    - Long-run growth rate approximately constant
    - Substantial deviations from the growth trend in the short run - business cycles
  - Definition of business cycles: high to medium frequency fluctuations in economic activity (usually proxied by GDP)
    - After every expansion comes a recession
    - But timing and amplitude irregular
    - Difficult to predict

- Business cycles are not restricted to GDP, they are typical for virtually all macrovariables
Extracting cyclical information from the data

- how do we define a trend?
- linear trend applied to logs (consistently with exponential growth)
  - filters operating in the frequency domain: extracting components within a given frequency range
- the most popular proxy for trend in the business cycle literature: hp filter applied to logs
  - owed to Hodrick and Prescott (1980)
  - for any time series \( \{y_t\}_{t=1}^T \), the trend component \( \{\bar{y}_t\}_{t=1}^T \) minimizes:

\[
\sum_{t=1}^{T} (y_t - \bar{y}_t)^2 + \lambda \sum_{t=2}^{T-1} [(\bar{y}_{t+1} - \bar{y}_t) - (\bar{y}_t - \bar{y}_{t-1})]^2
\]

where: \( \lambda \geq 0 \) is a smoothing parameter
- \( \lambda \) penalizes variations in the trend slope:
  - \( \lambda \to \infty \): linear trend
  - \( \lambda \to 0 \): original data
  - \( \lambda = 1600 \): standard value for quarterly data
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Origins of the RBC revolution

- 1970s: dissatisfaction with the standard Keynesian macroeconomics
- The Lucas (1976) critique:
  - Lack of microfoundations and expectations in the Keynesian model
  - In particular: if firms’ and households’ actions depend on their expectations about future policy, it is impossible to analyze the effects of this policy in a model that does not include expectations in an explicit form
  - Microfoundations and rational expectations important
- Kydland and Prescott (1982): a very stylized macromodel with microfoundations and rational expectations performs surprisingly well in terms of its fit to the data
The basic RBC model assumes an economy featuring perfectly functioning competitive markets and rational expectations. It gives primacy to technology shocks as the source of economic fluctuations. It exhibits complete monetary neutrality and Ricardian equivalence (and sets role for monetary and fiscal policy). In a nutshell - the standard Ramsey model with:

- Endogenous (but constant in the long run, i.e. $n = 0$) labour supply
- Stochastic productivity (i.e. real shocks)
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RBC model - basic features

- General equilibrium model
- No market imperfections or adjustment costs $\implies$ allocations are Pareto optimal
- The only source of uncertainty: stochastic productivity shocks
- In a nutshell - the standard Ramsey model with:
  - Endogenous (but constant in the long run, i.e. $n = 0$) labour supply
  - Stochastic productivity (i.e. real shocks)
Households - the problem

- A representative household maximises lifetime utility

\[ E_t \sum_{i=0}^{\infty} \beta^{t+i} \left[ \frac{c_{t+i}^{1-\sigma}}{1-\sigma} - \frac{l_{t+i}^{1+\varphi}}{1+\varphi} \right] \]

- subject to the budget constraint

\[ c_t + i_t = w_t l_t + R_{k,t} k_t \]

and the capital accumulation rule

\[ k_{t+1} = (1 - \delta) k_t + i_t \]

- The household rents labour and capital to firms and receives as compensation the real wage \( w_t \) and the rental rate \( R_{k,t} \).

- Note that additionally we have a transversality condition (TVC)

\[ \lim_{t \to \infty} k_t \prod_{s=0}^{\infty} \frac{1}{1 + r_s} = 0 \]
First, to simplify substitute for investment

\[ c_t + k_{t+1} = w_t l_t + (1 + R_{k,t} - \delta) k_t \]

denote \( r_t \equiv R_{k,t} - \delta \) as the real interest rate.

The household chooses \( c_t, l_t \) and \( k_{t+1} \). Write down the Lagrangean:

\[
L_t = E_t \sum_{i=0}^{\infty} \beta^{t+i} \left[ \left( \frac{c_{t+i}^{1-\sigma}}{1-\sigma} - \frac{l_{t+i}^{1+\varphi}}{1+\varphi} \right) - \lambda_{t+i}(c_{t+i} + k_{t+1+i} - w_{t+i} l_{t+i} - (1 + R_{k,t+i} - \delta) k_{t+i}) \right]
\]
Important:
- Because of uncertainty (stochastic shocks), households do not make deterministic plans for consumption and labour supply.
- Any decision at time $t$ depends on expectations concerning the relevant variables in the next periods.
- These expectations take into account all information available at the moment of decision making.
- We denote these expectations using the expectations operator $E_t$.
- Stochastic shocks make households revise their expectations every period.
- Expectations are rational, i.e. households know the structure of the economy and characteristics (but not realizations) of stochastic shocks.
Basic rules for expectations

\[ E_t(X_t + Y_t) = E_tX_t + E_tY_t \]

\[ E_t(kX_t) = kE_tX_t \]

\[ E_t(k + X_t) = k + E_tX_t \]

and, unless \( X_t \) and \( Y_t \) are independent:

\[ E_t(X_t Y_t) \neq E_tX_t E_tY_t \]
Sequence of events: at time $t$ the households, having $k_t$ units of capital, observe stochastic disturbance $\epsilon_t$ (and so productivity $z_t$), form rational expectations about future productivity levels, make optimal work, consumption and investment decisions, which determine capital stock at period $t + 1$ etc.

First order conditions:

$c_t : \text{Do it yourself :-) }$

$l_t : \text{Do it yourself :-) }$

$k_{t+1} : \text{Do it yourself :-) }$
Equilibrium conditions - Euler equation

\[ \lambda_t = \beta E_t[\lambda_{t+1}(1 + R_{k,t+1} - \delta)] \] substitute for \( \lambda_t \) to get

\[ c_t^{-\sigma} = \beta E_t[c_{t+1}^{-\sigma}(1 + R_{k,t+1} - \delta)] \]

- This is the Euler equation. It determines the household’s intertemporal choice (how much to consume today, how much to save).
- In equilibrium the disutility from one unit less consumed today equals expected discounted utility of consuming \((1 + R_{k,t+1} - \delta)\) units tomorrow.
Equilibrium conditions - consumption vs. leisure

\[ \frac{l_t^\varphi}{c_t^{-\sigma}} = w_t \]

- This equation determines the household’s intratemporal choice (how much to consume, how much to work).
- In equilibrium the utility of one unit more of work should be equal to the utility from consuming the compensation (real wage).
A representative firm uses capital and labour hired from households to produce a unique good $y_t$.

Its objective is to maximise profits:

$$\text{Div}_t = y_t - w_t l_t - r_t k_t$$

subject to technology

$$y_t = z_t k_t^\alpha l_t^{1-\alpha}$$
Substitute for production to get:

$$Div_t = z_t k_t^\alpha l_t^{1-\alpha} - w_t l_t - R_{k,t} k_t$$

First order condition for labour is:

$$l_t : \frac{\delta Div_t}{\delta l_t} = (1 - \alpha) z_t k_t^\alpha l_t^{-\alpha} - w_t = 0$$

In equilibrium the marginal product of labour equals the real wage

To simplify things substitute from production function:

$$(1 - \alpha) \frac{y_t}{l_t} = w_t$$
Firms - equilibrium condition for capital

$k_t$ : do it yourself

- In equilibrium the marginal product of capital equals the real rental rate of capital.
- To simplify things substitute from production function:

$$\alpha \frac{y_t}{k_t} = R_{k,t}$$

- In the RBC setting profits are zero (perfect competition). To see this substitute $R_{k,t}$ and $w_t$ into the profit function.
Productivity and market clearing

- It is assumed that productivity $z_t$ follows an $AR(1)$ process:

$$z_t = \exp(\epsilon_t) z_{t-1}$$
$$\hat{z}_t = \rho \hat{z}_{t-1} + \epsilon_t$$

- where $\epsilon_t$ is a productivity shock
- This is the only stochastic process in the basic RBC model
- Together with the internal persistence of the model it generates the business cycle
- The goods market clears:

$$c_t + i_t = y_t$$
Equilibrium conditions - summary

Now we have a system of 8 equations with 8 endogeneous variables \((c, r, l, w, k, i, y, z)\):

\[
c_t^{-\sigma} = \beta E_t[c_{t+1}^{-\sigma} (1 + R_{k,t+1} - \delta)]
\]  

\[
\frac{l_t^\phi}{c_t^{-\sigma}} = w_t
\]  

\[
k_{t+1} = (1 - \delta)k_t + i_t
\]  

\[
c_t + i_t = y_t
\]
Equilibrium conditions - cont’d

\[
y_t = z_t k_t^{\alpha} l_t^{1-\alpha} \tag{5}
\]

\[
(1 - \alpha) \frac{y_t}{l_t} = w_t \tag{6}
\]

\[
\alpha \frac{y_t}{k_t} = r_t \tag{7}
\]

\[
z_t = \exp(\epsilon_t) z_{t-1}^\rho \tag{8}
\]
Note that the system can be simplified to 3 equations

\[
c_t^{-\sigma} = \beta E_t \left\{ c_{t+1}^{-\sigma} \left( \alpha z_{t+1} k_{t+1}^{\alpha-1} l_{t+1}^{1-\alpha} + 1 - \delta \right) \right\}
\]

\[
\frac{l_t^{\varphi}}{c_t^{-\sigma}} = (1 - \alpha) z_t k_t^{\alpha} l_t^{-\alpha}
\]

\[
k_{t+1} = (1 - \delta) k_t + z_t k_t^{\alpha} L_t^{1-\alpha} - c_t
\]
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Interest rate and productivity

- In the deterministic steady state uncertainty disappears and all variables are constant, for example $c_t = c_{t+1} = c^{ss}$.
- We assume that in the steady state $z$ is constant and

$$z^{ss} = 1 \quad (9)$$

- From (1) we get

$$c_t^{-\sigma} = \beta E_t[c_{t+1}^{-\sigma}(1 + R_{k,t+1} - \delta)]$$

$$(c^{ss})^{-\sigma} = \beta (c^{ss})^{-\sigma} (1 + R_k^{ss} - \delta)$$

Simplifying

$$R_k^{ss} = \beta^{-1} - (1 - \delta) \quad (10)$$
Substituting form the production function (5) for $y_t$ into (7) we get

$$
\alpha \frac{z^t k^\alpha t^1 - \alpha}{k_t} = r_t
$$

In the steady state

$$
R_k^{ss} = \alpha (k^{ss})^{\alpha - 1} (l^{ss})^{1-\alpha} = \alpha \left( \frac{k^{ss}}{l^{ss}} \right)^{\alpha - 1}
$$

Rearranging we can obtain formula for capital-labour ratio

$$
\frac{k^{ss}}{l^{ss}} = \left( \frac{R_k^{ss}}{\alpha} \right)^{\frac{1}{\alpha - 1}}
$$

(11)

where $r^{ss}$ is given by (10).
Substituting from the production function (5) for $y_t$ into (6) we get

$$w_t = (1 - \alpha) \frac{z_t k_t^{\frac{\alpha}{1-\alpha}}}{l_t^{\frac{1}{1-\alpha}}} = (1 - \alpha) z_t \frac{k_t^\alpha}{l_t}$$

which in the steady state becomes

$$w^{ss} = (1 - \alpha) \left( \frac{k^{ss}}{l^{ss}} \right)^\alpha \quad (12)$$

where $k^{ss}/l^{ss}$ is given by (11).

From (3) in the steady state we have

$$k^{ss} = (1 - \delta) k^{ss} + i^{ss}$$

which simplifies to

$$\frac{i^{ss}}{k^{ss}} = \delta \quad (13)$$
Consumption-labour ratio

- Substituting from (5) for $y_t$ into (4) we get

$$c_t + i_t = z_t k_t^\alpha l_t^{1-\alpha}$$

which in the steady state becomes

$$c^{ss} + i^{ss} = (k^{ss})^\alpha (l^{ss})^{1-\alpha} = \left( \frac{k^{ss}}{l^{ss}} \right)^\alpha l^{ss}$$

- Dividing by $l^{ss}$

$$\frac{c^{ss}}{l^{ss}} + \frac{i^{ss}}{l^{ss}} = \left( \frac{k^{ss}}{l^{ss}} \right)^\alpha$$

- Substituting for $i^{ss}$ from (13) and rearranging

$$\frac{c^{ss}}{l^{ss}} = \left( \frac{k^{ss}}{l^{ss}} \right)^\alpha - \delta \frac{k^{ss}}{l^{ss}}$$

(14)

where $k^{ss}/l^{ss}$ is given by (11).
From (2) we have
\[
\frac{l_t^{\varphi}}{c_t^{\sigma}} = w_t
\]
which in the steady state it becomes
\[
(l^{ss})^{\varphi}(c^{ss})^{\sigma} = w^{ss}
\]
Substituting for \(w^{ss}\) from (12) and for \(c^{ss}\) from (14)
\[
(l^{ss})^{\varphi}\left[\left(\frac{k^{ss}}{l^{ss}}\right)^{\alpha} - \delta \frac{k^{ss}}{l^{ss}}\right]^{\sigma} \cdot (l^{ss})^{\sigma} = (1 - \alpha)\left(\frac{k^{ss}}{l^{ss}}\right)^{\alpha}
\]
Solving with respect to \(l^{ss}\) we get
\[
l^{ss} = \left[\left(\frac{k^{ss}}{l^{ss}}\right)^{\alpha} - \delta \frac{k^{ss}}{l^{ss}}\right]^{\sigma} \cdot \frac{1}{\varphi + \sigma}
\]
where \(k^{ss}/l^{ss}\) is given by (11).
To obtain $c^{ss}$, note

$$c^{ss} = \frac{c^{ss}}{l^{ss}} l^{ss}$$

where $c^{ss}/l^{ss}$ is given by (14) and $l^{ss}$ is given by (15).

We can obtain capital $k^{ss}$ from

$$k^{ss} = \frac{k^{ss}}{l^{ss}} l^{ss}$$

where $k^{ss}/l^{ss}$ is given by (11) and $l^{ss}$ is given by (15).

To obtain output we use the production function

$$y^{ss} = (k^{ss})^\alpha (l^{ss})^{1-\alpha}$$

where $k^{ss}$ is given by (17) and $l^{ss}$ is given by (15).

and we can obtain investment form (13)

$$i^{ss} = \delta k^{ss}$$

where $k^{ss}$ is given by (17).
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Non-linear vs. linear models

- We have a system of non-linear difference equations
- This does not have a closed form solution
- Standard solution technique:
  - log-linear approximation of the model equations around the (non-stochastic) steady-state
  - applying an algorithm for solving linear rational expectations models (e.g. Blanchard-Kahn algorithm)
- Two options
  1. take it as it is and let your software (e.g. Dynare) linearise it
  2. linearise by hand
- Linearising on your own is tedious but has some advantages:
  1. some parameters may disappear
  2. the system is easier to understand
  3. solution easier (steady state is known)
Log-linearisation

- Log-linearisation allows to change non-linear equations into linear equations.
- This is a valid approximation in the vicinity of a given point (usually the steady state)!!!
- Two steps:
  - Express variables as log deviation from steady state using the identity:
    \[ x_t = x^{ss} \frac{x_t}{x^{ss}} = x^{ss} \exp(\ln x_t - \ln x^{ss}) = x^{ss} \exp \hat{x}_t \]
Useful tricks

- Apply first-order series expansion w.r.t. $\hat{x}_t$ around steady state, i.e. around $\hat{x}_{ss} = 0$

- This yields

  - $x_t = x^{ss} \exp(\hat{x}_t) \approx x^{ss} \exp(\hat{x}_{ss}) + x^{ss} \exp(\hat{x}_{ss})(\hat{x}_t - \hat{x}_{ss}) = x^{ss}(1 + \hat{x}_t)$
  - $x_t y_t = x^{ss} \exp(\hat{x}_t) y^{ss} \exp(\hat{y}_t) \approx x^{ss} y^{ss}(1 + \hat{x}_t + \hat{y}_t)$
  - $x_t^a \approx (x^{ss})^a (1 + a\hat{x}_t)$
  - $x_t^a y_t^b \approx (x^{ss})^a (y^{ss})^b (1 + a\hat{x}_t + b\hat{y}_t)$
Log-linearise labour - consumption choice

\[ \frac{l_t^\varphi}{c_t^{-\sigma}} = w_t \]

In the steady state:

\[ \frac{(l^{ss})^\varphi}{(c^{ss})^{-\sigma}} = w^{ss} \]

Let’s log-linearise:

\[ \frac{(l^{ss})^\varphi}{(c^{ss})^{-\sigma}} (1 + \varphi \hat{l}_t + \sigma \hat{c}_t) = w^{ss} (1 + \hat{w}_t) \]

Divide by steady state:

\[ \varphi \hat{l}_t + \sigma \hat{c}_t = \hat{w}_t \]
Log-linearise Euler

\[ c_t^{-\sigma} = \beta E_t [c_{t+1}^{-\sigma} (1 + R_k, t+1 - \delta)] \]

In the steady state:

\[ 1 = \beta (1 + R_k^{ss} - \delta) \]

So let’s linearise:

\[ (c^{ss})^{-\sigma} (1 - \sigma \hat{c}_t) = \beta (c^{ss})^{-\sigma} E_t \left[ (1 - \sigma \hat{c}_{t+1})(1 - \delta + R_k^{ss} (1 + \hat{R}_k, t+1)) \right] \]
Log-linearise Euler cont’d

Substitute for $R_{k}^{ss}$:

$1 - \sigma \hat{c}_t = \beta E_t \left[(1 - \sigma \hat{c}_{t+1})(1 - \delta + \left(\frac{1}{\beta} - 1 + \delta\right)(1 + \hat{R}_{k,t+1})\right]$ 

$1 - \sigma \hat{c}_t = E_t \left[(1 - \sigma \hat{c}_{t+1})(\beta - \beta \delta + (1 - \beta + \beta \delta)(1 + \hat{R}_{k,t+1})\right]$ 

$1 - \sigma \hat{c}_t = E_t \left[(1 - \sigma \hat{c}_{t+1})(1 + (1 - \beta(1 - \delta))\hat{R}_{k,t+1})\right]$ 

Multiply and drop higher order terms:

$1 - \sigma \hat{c}_t = 1 - \sigma E_t \hat{c}_{t+1} + (1 - \beta(1 - \delta))E_t \hat{R}_{k,t+1}$

Rearrange terms:

$\sigma(E_t \hat{c}_{t+1} - \hat{c}_t) = (1 - \beta(1 - \delta))E_t \hat{R}_{k,t+1}$
Log-linearise market clearing condition

\[ c_t + i_t = y_t \]

Do it yourself :-)
Log-linearise firm’s equilibrium conditions

- For labour
  \[(1 - \alpha) \frac{y_t}{l_t} = w_t\]
  Do it yourself :-)

- For capital
  \[\alpha \frac{y_t}{k_t} = r_t\]
  Do it yourself :-)

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Log-linearise production function

\[ y_t = z_t k_t^\alpha l_t^{1-\alpha} \]

Do it yourself :-)

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Log-linearise capital accumulation equation

$$k_{t+1} = (1 - \delta)k_t + i_t$$

Do it yourself :-)}
Log-linearise shock process

\[ z_t = \exp(\epsilon_t) z_{t-1}^\rho \]
\[ \hat{z}_t = \rho \hat{z}_{t-1} + \epsilon_t \]
Our equations contain steady state ratio \( \frac{i^{ss}}{y^{ss}} \). These are determined by our parameters.

From the Euler equation:

\[
R_k^{ss} = \beta^{-1} - (1 - \delta)
\]

and from the equilibrium condition for capital:

\[
\begin{align*}
R_k^{ss} k^{ss} &= \alpha y^{ss} \\
k^{ss} &= \frac{\alpha}{R_k^{ss}} = \frac{\alpha}{\beta^{-1} - (1 - \delta)}
\end{align*}
\]
From the capital accumulation equation:

\[ \delta k^{ss} = i^{ss} \]

thus

\[ \frac{i^{ss}}{y^{ss}} = \delta \frac{k^{ss}}{y^{ss}} = \frac{\alpha \delta}{\beta^{-1} - (1 - \delta)} \]
Log-linearised system

- We now have a system of 8 linear (difference) equations and 8 variables
- Have to solve it
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Solving linear DSGE models

- Solving a DSGE model means changing the system of forward looking difference equations that we have ...
- ... into a VAR system
- There are several techniques for solving such systems
One very important thing is the stability condition.

Write the system in state space form:

$$A_1 \begin{bmatrix} X_{t+1} \\ E_tP_{t+1} \end{bmatrix} = A_0 \begin{bmatrix} X_t \\ P_t \end{bmatrix} + \gamma Z_{t+1}$$

where:

- $X_t$: vector $n \times 1$ of state variables (backward-looking)
- $P_t$: vector $m \times 1$ of jumpers (forward-looking)
- $Z_t$: wektor $k \times 1$ of shocks (with mean equal to 0 every period)
- $A_1, A_0$: $(n + m) \times (n + m)$ matrices
- $\gamma$: $(n + m) \times k$ matrix
Assume $A_1$ is invertible and rewrite the system as:

$$
\begin{bmatrix}
X_{t+1} \\
E_t P_{t+1}
\end{bmatrix} = A \begin{bmatrix}
X_t \\
P_t
\end{bmatrix} + RZ_{t+1}
$$

where:

- $A \equiv A_1^{-1} A_0$
- $R \equiv A_1^{-1} \gamma$

and apply Jordan decomposition $A = C \Lambda C^{-1}$ where $\Lambda$ is a diagonal matrix of eigenvalues and $C$ is matrix of eigenvectors.
Blanchard & Kahn solution method cont’d

- Then (under some conditions stated below)

\[
P_t = -C_{22}^{-1}C_{21}X_t
\]

\[
X_{t+1} = (A_{11} - A_{12}C_{22}^{-1}C_{21})X_t + R_1Z_{t+1}
\]

- Where the matrices $A$, $C$ and $R$ have been divided into blocks whose size is determined by the number of stable eigenvalues $\Lambda$ (lying within the unit circle).
- This is the recursive solution of the DSGE model.
- Alternative solution method is based on the $QZ$ decomposition of $A_0$ and $A_1$. Does not require invertibility of $A_1$ (Sims 2002).
Blanchard & Kahn stability conditions

- Blanchard & Kahn stated two necessary conditions for obtaining a unique solution:
  - $C_{22}$ is of full rank
  - the number of eigenvalues of $A$ lying outside the unit circle (unstable roots) must equal the number of forward looking variables (jumpers)

- If too many unstable roots - no solution
- If too few - infinite number of solutions
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Convergence

Notes: grey line - exogenous labour (Ramsey model); black line - endogenous labour choice (RBC model); time unit - quarters; all variables expressed as percentage deviations from their steady-state values.
Impulse responses - technology shock

Notes: black line - baseline ($\rho = 0.976$); dark grey line - permanent productivity shock ($\rho = 1$); light grey line - no productivity shock inertia ($\rho = 0$); time unit - quarters; all variables expressed as percentage deviations from their steady-state values.
## Moments

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<tr>
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<th>Std. deviation Data</th>
<th>Std. deviation Model</th>
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Notes: Calculations based on HP-detrended variables
RBC model - summary

- Very simple dynamic stochastic general equilibrium model (DSGE)
- Fluctuations driven by productivity shocks only
  - No market imperfections or adjustment costs \( \implies \) decentralized allocations Pareto optimal, attempts to smooth business cycles harmful
- Remarkable success:
  - Surprisingly good fit to the data (in terms of moment matching)
  - Methodological approach adopted by the New Keynesian school - "great neoclassical synthesis"
- Criticism:
  - Estimation rather than moment matching
  - Other shocks
  - Some counterfactual implications or questionable calibration choices
- Response to criticism and extensions:
  - Unprecedented development program - numerous refinements and extensions
  - Important extension: monopolistic competition and sticky prices (the New Keynesian school)