

Deterministic Models

Perfect foresight, nonlinearities and occasionally binding constraints

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Introduction

- Deterministic = perfect foresight
- Perfect anticipation of all shocks in the future, and therefore of all future choice variables
- Can be solved exactly (up to rounding errors)
- Full nonlinearities taken into account
- Often useful when starting study of a model, or when studying the effect of strong nonlinearities

Outline

- 1 Presentation of the problem
- 2 Solution techniques
- 3 Shocks: temporary/permanent, unexpected/pre-announced
- 4 Occasionally binding constraints
- 5 Extended path
- 6 Appendix: dealing with nonlinearities using higher order approximation of stochastic models

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The (deterministic) neoclassical growth model

$$\max_{\{c_t\}_{t=1}^{\infty}} \sum_{t=1}^{\infty} \beta^{t-1} \frac{c_t^{1-\sigma}}{1-\sigma}$$

s.t.

$$c_t + k_t = A_t k_{t-1}^{\alpha} + (1 - \delta)k_{t-1}$$

First order conditions:

$$c_t^{-\sigma} = \beta c_{t+1}^{-\sigma} (\alpha A_{t+1} k_t^{\alpha-1} + 1 - \delta)$$

$$c_t + k_t = A_t k_{t-1}^{\alpha} + (1 - \delta)k_{t-1}$$

Steady state:

$$\bar{k} = \left(\frac{1 - \beta(1 - \delta)}{\beta \alpha \bar{A}} \right)^{\frac{1}{\alpha-1}}$$

$$\bar{c} = \bar{A} \bar{k}^{\alpha} - \delta \bar{k}$$

Note the absence of stochastic elements! No expectancy term, no probability distribution

The general problem

Deterministic, perfect foresight, case:

$$f(y_{t+1}, y_t, y_{t-1}, u_t) = 0$$

y : vector of endogenous variables

u : vector of exogenous shocks

Identification rule: as many endogenous (y) as equations (f)

Steady state

- A steady state, \bar{y} , for the model satisfies

$$f(\bar{y}, \bar{y}, \bar{y}, \bar{u}) = 0$$

- Note that a steady state is conditional to:
 - ▶ The steady state values of exogenous variables \bar{u}
 - ▶ The value of parameters (implicit in the above definition)
- Even for a given set of exogenous and parameter values, some (nonlinear) models have several steady states
- The steady state is computed by Dynare with the `steady` command
- That command internally uses a nonlinear solver

What if more than one lead or one lag?

- A model with more than one lead or lag can be transformed in the form with one lead and one lag using auxiliary variables
- Transformation done automatically by Dynare
- For example, if there is a variable with two leads x_{t+2} :
 - ▶ create a new auxiliary variable a
 - ▶ replace all occurrences of x_{t+2} by a_{t+1}
 - ▶ add a new equation: $a_t = x_{t+1}$
- Symmetric process for variables with more than one lag

Return to the neoclassical growth model

$$y_t = \begin{pmatrix} c_t \\ k_t \end{pmatrix}$$

$$u_t = A_t$$

$$f(y_t) = \begin{pmatrix} c_t^{-\sigma} - \beta c_{t+1}^{-\sigma} (\alpha A_{t+1} k_t^{\alpha-1} + 1 - \delta) \\ c_t + k_t - A_t k_{t-1}^{\alpha} + (1 - \delta) k_{t-1} \end{pmatrix}$$

Solution of deterministic models

- Approximation: impose return to equilibrium in finite time instead of asymptotically
- However possible to return to another point than the steady state
- Useful to study full implications of nonlinearities
- Computes the trajectory of the variables numerically
- Uses a Newton-type method on the stacked system

A two-boundary value problem

Approximation of an infinite horizon model by a finite horizon one

The stacked system for a simulation over T periods:

$$\begin{cases} f(y_2, y_1, y_0, u_1) = 0 \\ f(y_3, y_2, y_1, u_2) = 0 \\ \vdots \\ f(y_{T+1}, y_T, y_{T-1}, u_T) = 0 \end{cases}$$

for y_0 and $y_{T+1} = \bar{y}$ given.

Compact representation:

$$F(Y) = 0$$

where $Y = \begin{bmatrix} y_1' & y_2' & \dots & y_T' \end{bmatrix}'$.

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A Newton approach

- Start from an initial guess $Y^{(0)}$
- Iterate. Updated solutions $Y^{(k+1)}$ are obtained by solving:

$$F(Y^{(k)}) + \left[\frac{\partial F}{\partial Y} \right] (Y^{(k+1)} - Y^{(k)}) = 0$$

- Terminal condition:

$$\|Y^{(k+1)} - Y^{(k)}\| < \varepsilon_Y \text{ and/or } \|F(Y^{(k)})\| < \varepsilon_F$$

A practical difficulty

The size of the Jacobian is very large. For a simulation over T periods of a model with n endogenous variables, it is a matrix of order $n \times T$.

3 ways of dealing with it:

- With older computers, it was more of a problem than today: LBJ (the default method in Dynare ≤ 4.2) exploited the particular structure of this Jacobian using relaxation techniques
- Handle the Jacobian as one large, sparse, matrix (now the default method in Dynare ≥ 4.3)
- Block decomposition (divide-and-conquer methods) implemented by Mihoubi

Relaxation (2/5)

First period is special:

$$\begin{pmatrix} I & D_1 & & & & & \\ & B_2 - A_2 D_1 & C_2 & & & & \\ & A_3 & B_3 & C_3 & & & \\ & & \ddots & \ddots & \ddots & & \\ & & & A_{T-1} & B_{T-1} & C_{T-1} & \\ & & & & A_T & B_T & \end{pmatrix} \Delta Y = - \begin{pmatrix} d_1 \\ f(y_3, y_2, y_1, u_2) + A_2 d_1 \\ f(y_4, y_3, y_2, u_3) \\ \vdots \\ f(y_T, y_{T-1}, y_T, u_{T-1}) \\ f(y_{T+1}, y_T, y_{T-1}, u_T) \end{pmatrix}$$

where

- $D_1 = B_1^{-1} C_1$
- $d_1 = B_1^{-1} f(y_2, y_1, y_0, u_1)$

Relaxation (3/5)

Normal iteration:

$$\begin{pmatrix} I & D_1 & & & & & \\ & I & D_2 & & & & \\ & & B_3 - A_3 D_2 & C_3 & & & \\ & & \ddots & \ddots & \ddots & & \\ & & & A_{T-1} & B_{T-1} & C_{T-1} & \\ & & & & A_T & B_T & \end{pmatrix} \Delta Y = - \begin{pmatrix} d_1 \\ d_2 \\ f(y_4, y_3, y_2, u_3) + A_3 d_2 \\ \vdots \\ f(y_T, y_{T-1}, y_T, u_{T-1}) \\ f(y_{T+1}, y_T, y_{T-1}, u_T) \end{pmatrix}$$

where

- $D_2 = (B_2 - A_2 D_1)^{-1} C_2$
- $d_2 = (B_2 - A_2 D_1)^{-1} (f(y_3, y_2, y_1, u_2) + A_2 d_1)$

Relaxation (4/5)

Final iteration:

$$\begin{pmatrix} I & D_1 & & & & & \\ & I & D_2 & & & & \\ & & I & D_3 & & & \\ & & & \ddots & \ddots & & \\ & & & & I & D_{T-1} & \\ & & & & & I & \end{pmatrix} \Delta Y = - \begin{pmatrix} d_1 \\ d_2 \\ d_3 \\ \vdots \\ d_{T-1} \\ d_T \end{pmatrix}$$

where

$$d_T = (B_T - A_T D_{T-1})^{-1} (f(y_{T+1}, y_T, y_{T-1}, u_T) + A_T d_{T-1})$$

Relaxation (5/5)

- The system is then solved by backward iteration:

$$\begin{aligned}y_T^{k+1} &= y_T^k - d_T \\y_{T-1}^{k+1} &= y_{T-1}^k - d_{T-1} - D_{T-1}(y_T^{k+1} - y_T^k) \\&\vdots \\y_1^{k+1} &= y_1^k - d_1 - D_1(y_2^{k+1} - y_2^k)\end{aligned}$$

- No need to ever store the whole Jacobian: only the D_s and d_s have to be stored
- Relaxation was the default method in Dynare ≤ 4.2 , since it was memory efficient

Sparse matrix algebra

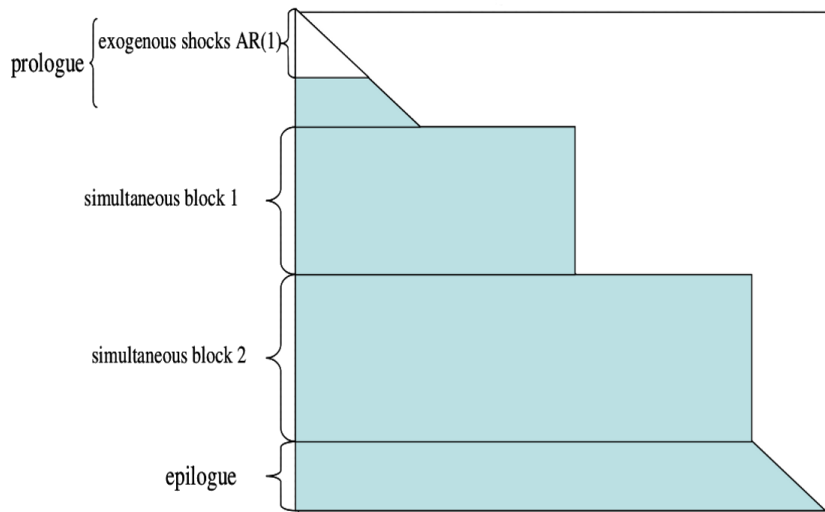
- A sparse matrix is a matrix where most entries are zero
- The Jacobian of the deterministic problem is a sparse matrix:
 - ▶ Lots of zero blocks
 - ▶ The A_s , B_s and C_s are themselves sparse
- More efficient storage possible than storing all entries
- Usually stored as a list of triplets (i, j, v) where (i, j) is a matrix coordinate and v a non-zero value
- Family of optimized algorithms for such matrices (including matrix inversion for our Newton algorithm)
- Available as native objects in MATLAB/Octave
- Works well for medium size deterministic models
- Nowadays more efficient than relaxation, even though it does not exploit the particular structure of the Jacobian \Rightarrow default method in Dynare ≥ 4.3

Block decomposition (1/3)

- Idea: apply a divide-and-conquer technique to model simulation
- Principle: identify recursive and simultaneous blocks in the model structure
- First block (prologue): equations that only involve variables determined by previous equations; example: AR(1) processes
- Last block (epilogue): pure output/reporting equations
- In between: simultaneous blocks, that depend recursively on each other
- The identification of the blocks is performed through a matching between variables and equations (normalization), then a reordering of both

Block decomposition (2/3)

Form of the reordered Jacobian



Block decomposition (3/3)

- Can provide a significant speed-up on large models
- Implemented in Dynare by Ferhat Mihoubi
- Available as option `block` to the `model` command
- Bigger gains when used in conjunction with `bytecode` options

Homotopy

- Another divide-and-conquer method, but in the shocks dimension
- Useful if shocks so large that convergence does not occur
- Idea: achieve convergence on smaller shock size, then use the result as starting point for bigger shock size
- Algorithm:
 - ① Starting point for simulation path: steady state at all t
 - ② $\lambda \leftarrow 0$: scaling factor of shocks (simulation succeeds when $\lambda = 1$)
 - ③ $s \leftarrow 1$: step size
 - ④ Try to compute simulation with shocks scaling factor equal to $\lambda + s$ (using last successful computation as starting point)
 - ★ If success: $\lambda \leftarrow \lambda + s$. Stop if $\lambda = 1$. Otherwise possibly increase s .
 - ★ If failure: diminish s .
 - ⑤ Go to 4
- Can be combined with any deterministic solver
- Used by default in deterministic simulations in Dynare ≥ 4.5

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Example: neoclassical growth model with investment

The social planner problem is as follows:

$$\max_{\{c_{t+j}, \ell_{t+j}, k_{t+j}\}_{j=0}^{\infty}} \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j u(c_{t+j}, \ell_{t+j})$$

s.t.

$$y_t = c_t + i_t$$

$$y_t = A_t f(k_{t-1}, \ell_t)$$

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

$$A_t = A^* e^{a_t}$$

$$a_t = \rho a_{t-1} + \varepsilon_t$$

where ε_t is an exogenous shock.

Specifications

- Utility function:

$$u(c_t, l_t) = \frac{[c_t^\theta (1 - l_t)^{1-\theta}]^{1-\tau}}{1 - \tau}$$

- Production function:

$$f(k_{t-1}, l_t) = [\alpha k_{t-1}^\psi + (1 - \alpha) l_t^\psi]^{\frac{1}{\psi}}$$

First order conditions

- Euler equation:

$$u_c(c_t, l_t) = \beta \mathbb{E}_t \left[u_c(c_{t+1}, l_{t+1}) \left(A_{t+1} f_k(k_t, l_{t+1}) + 1 - \delta \right) \right]$$

- Arbitrage between consumption and leisure:

$$\frac{u_l(c_t, l_t)}{u_c(c_t, l_t)} + A_t f_l(k_{t-1}, l_t) = 0$$

- Resource constraint:

$$c_t + k_t = A_t f(k_{t-1}, l_t) + (1 - \delta)k_{t-1}$$

Calibration

Weight of consumption in utility	θ	0.357
Risk aversion	τ	2.0
Share of capital in production	α	0.45
Elasticity of substitution capital/labor (fct of...)	ψ	-0.1
Discount factor	β	0.99
Depreciation rate	δ	0.02
Autocorrelation of productivity	ρ	0.8
Steady state level of productivity	A^*	1

Scenario 1: Return to equilibrium

Return to equilibrium starting from $k_0 = 0.5\bar{k}$.

Fragment from `rbc_det1.mod`

```
...
steady;

ik = varlist_indices('Capital',M_.endo_names);
CapitalSS = oo_.steady_state(ik);

histval;
Capital(0) = CapitalSS/2;
end;

simul(periods=300);
```

Scenario 2: A temporary shock to TFP

- The economy starts from the steady state
- There is an unexpected negative shock at the beginning of period 1:
 $\varepsilon_1 = -0.1$

Fragment from `rbc_det2.mod`

```
...
steady;

shocks;
var EfficiencyInnovation;
periods 1;
values -0.1;
end;

simul(periods=100);
```


Scenario 3: Pre-announced favorable shocks in the future

- The economy starts from the steady state
- There is a sequence of positive shocks to A_t : 4% in period 5 and an additional 1% during the 4 following periods

Fragment from `rbc_det3.mod`

```
...
steady;

shocks;
var EfficiencyInnovation;
periods 4, 5:8;
values 0.04, 0.01;
end;
```

Scenario 4: A permanent shock

- The economy starts from the initial steady state ($a_0 = 0$)
- In period 1, TFP increases by 5% permanently (and this was unexpected)

Fragment from `rbc_det4.mod`

```
...
initval;
EfficiencyInnovation = 0;
end;

steady;

endval;
EfficiencyInnovation = (1-rho)*log(1.05);
end;

steady;
```

Scenario 5: A pre-announced permanent shock

- The economy starts from the initial steady state ($a_0 = 0$)
- In period 6, TFP increases by 5% permanently
- A shocks block is used to maintain TFP at its initial level during periods 1–5

Fragment from `rbc_det5.mod`

```
...  
// Same initval and endval blocks as in Scenario 4  
...  
  
shocks;  
var EfficiencyInnovation;  
periods 1:5;  
values 0;  
end;
```

Summary of commands

`initval` for the initial steady state (followed by `steady`)

`endval` for the terminal steady state (followed by `steady`)

`histval` for initial or terminal conditions out of steady state

`shocks` for shocks along the simulation path

`perfect_foresight_setup` prepare the simulation (since Dynare 4.5)

`perfect_foresight_solver` compute the simulation (since Dynare 4.5)

`simul` do both operations at the same time (alias for

`perfect_foresight_setup +`

`perfect_foresight_solver`)

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Zero nominal interest rate lower bound

- Implemented by writing the law of motion under the following form in Dynare:

$$i_t = \max \left\{ 0, (1 - \rho_i)i^* + \rho_i i_{t-1} + \rho_\pi (\pi_t - \pi^*) + \varepsilon_t^i \right\}$$

- *Warning*: this form will be accepted in a stochastic model, but the constraint will not be enforced in that case!

Irreversible investment

Same model than above, but the social planner is constrained to positive investment paths:

$$\max_{\{c_{t+j}, \ell_{t+j}, k_{t+j}\}_{j=0}^{\infty}} \sum_{j=0}^{\infty} \beta^j u(c_{t+j}, \ell_{t+j})$$

s.t.

$$y_t = c_t + i_t$$

$$y_t = A_t f(k_{t-1}, \ell_t)$$

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

$$i_t \geq 0$$

$$A_t = A^* e^{a_t}$$

$$a_t = \rho a_{t-1} + \varepsilon_t$$

where the technology (f) and the preferences (u) are as above.

First order conditions

$$u_c(c_t, l_t) - \mu_t = \beta \mathbb{E}_t [u_c(c_{t+1}, l_{t+1}) (A_{t+1} f_k(k_t, l_{t+1}) + 1 - \delta) - \mu_{t+1}(1 - \delta)]$$

$$\frac{u_\ell(c_t, l_t)}{u_c(c_t, l_t)} + A_t f_l(k_{t-1}, l_t) = 0$$
$$c_t + k_t = A_t f(k_{t-1}, l_t) + (1 - \delta)k_{t-1}$$

Slackness condition:

$$\mu_t = 0 \text{ and } i_t \geq 0$$

or

$$\mu_t > 0 \text{ and } i_t = 0$$

where $\mu_t \geq 0$ is the Lagrange multiplier associated to the non-negativity constraint for investment.

Writing this model in Dynare

- Slackness condition defined by equation tag `mcp`
- Mixed-complementarity problem (MCP) solver triggered with `lmmcp` option of `simul`.

Fragment from `rbcii.mod`

```
((c^theta)*((1-l)^(1-theta)))^(1-tau))/c - mu
= expterm(1)-beta*mu(1)*(1-delta);
expterm = beta*(((c^theta)*((1-l)^(1-theta)))^(1-tau))/c
*(alpha*((y/k(-1))^(1-psi))+1-delta);
...
[ mcp = 'i > 0' ]
mu = 0;
...
simul(periods=400,lmmcp);
```

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Extended path (EP) algorithm

- Algorithm for creating a stochastic simulated series
- At every period, compute endogenous variables by running a *deterministic* simulation with:
 - ▶ the previous period as initial condition
 - ▶ the steady state as terminal condition
 - ▶ a random shock drawn for the current period
 - ▶ but no shock in the future
- Advantages:
 - ▶ shocks are unexpected *at every period*
 - ▶ nonlinearities fully taken into account
- Inconvenient: solution under certainty equivalence (Jensen inequality is violated)
- Method introduced by Fair and Taylor (1983)
- Implemented by Stéphane Adjemian under the command `extended_path` (with option `order = 0`, which is the default)

k -step ahead EP

- Accuracy can be improved by computing conditional expectation by quadrature, computing next period endogenous variables with the previous algorithm
- Approximation: at date t , agents assume that there will be no more shocks after period $t + k$ (hence k measures the degree of future uncertainty taken into account)
- If $k = 1$: one-step ahead EP; no more certainty equivalence
- By recurrence, one can compute a k -step ahead EP: even more uncertainty taken into account
- Difficulty: computing complexity grows exponentially with k
- k -step ahead EP triggered with option order = k of `extended_path` command

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Local approximation of stochastic models

The general problem:

$$\mathbb{E}_t f(y_{t+1}, y_t, y_{t-1}, u_t) = 0$$

y : vector of endogenous variables

u : vector of exogenous shocks

with:

$$\mathbb{E}(u_t) = 0$$

$$\mathbb{E}(u_t u_t') = \Sigma_u$$

$$\mathbb{E}(u_t u_s') = 0 \text{ for } t \neq s$$

What is a solution to this problem?

- A solution is a policy function of the form:

$$y_t = g(y_{t-1}, u_t, \sigma)$$

where σ is the *stochastic scale* of the problem and:

$$u_{t+1} = \sigma \varepsilon_{t+1}$$

- The policy function must satisfy:

$$\mathbb{E}_t f(g(g(y_{t-1}, u_t, \sigma), u_{t+1}, \sigma), g(y_{t-1}, u_t, \sigma), y_{t-1}, u_t) = 0$$

Local approximations

$$\hat{g}^{(1)}(y_{t+1}, u_t, \sigma) = \bar{y} + g_y \hat{y}_{t-1} + g_u u_t$$

$$\begin{aligned}\hat{g}^{(2)}(y_{t+1}, u_t, \sigma) &= \bar{y} + \frac{1}{2} g_{\sigma\sigma} + g_y \hat{y}_{t-1} + g_u u_t \\ &\quad + \frac{1}{2} (g_{yy} (\hat{y}_{t-1} \otimes \hat{y}_{t-1}) + g_{uu} (u_t \otimes u_t)) \\ &\quad + g_{yu} (\hat{y}_{t-1} \otimes u_t)\end{aligned}$$

$$\begin{aligned}\hat{g}^{(3)}(y_{t+1}, u_t, \sigma) &= \bar{y} + \frac{1}{2} g_{\sigma\sigma} + \frac{1}{6} g_{\sigma\sigma\sigma} + \frac{1}{2} g_{\sigma\sigma y} \hat{y}_{t-1} + \frac{1}{2} g_{\sigma\sigma u} u_t \\ &\quad + g_y \hat{y}_{t-1} + g_u u_t + \dots\end{aligned}$$

Breaking certainty equivalence (1/2)

The combination of future uncertainty (future shocks) and nonlinear relationships makes for precautionary motives or risk premia.

- 1st order: certainty equivalence; today's decisions don't depend on future uncertainty
- 2nd order:

$$\begin{aligned}\hat{g}^{(2)}(y_{t+1}, u_t, \sigma) &= \bar{y} + \frac{1}{2}g_{\sigma\sigma} + g_y\hat{y}_{t-1} + g_u u_t \\ &\quad + \frac{1}{2}(g_{yy}(\hat{y}_{t-1} \otimes \hat{y}_{t-1}) + g_{uu}(u_t \otimes u_t)) \\ &\quad + g_{yu}(\hat{y}_{t-1} \otimes u_t)\end{aligned}$$

Risk premium is a constant: $\frac{1}{2}g_{\sigma\sigma}$

Breaking certainty equivalence (2/2)

- 3rd order:

$$\hat{g}^{(3)}(y_{t+1}, u_t, \sigma) = \bar{y} + \frac{1}{2}g_{\sigma\sigma} + \frac{1}{6}g_{\sigma\sigma\sigma} + \frac{1}{2}g_{\sigma\sigma y}\hat{y}_{t-1} + \frac{1}{2}g_{\sigma\sigma u}u_t \\ + g_y\hat{y}_{t-1} + g_u u_t + \dots$$

Risk premium is linear in the state variables:

$$\frac{1}{2}g_{\sigma\sigma} + \frac{1}{6}g_{\sigma\sigma\sigma} + \frac{1}{2}g_{\sigma\sigma y}\hat{y}_{t-1} + \frac{1}{2}g_{\sigma\sigma u}u_t$$

The cost of local approximations

- 1 High order approximations are accurate around the steady state, and more so than lower order approximations
- 2 But can be totally wrong far from the steady state (and may be more so than lower order approximations)
- 3 Error of approximation of a solution \hat{g} , at a given point of the state space (y_{t-1}, u_t) :

$$\mathcal{E}(y_{t-1}, u_t) = \mathbb{E}_t f(\hat{g}(\hat{g}(y_{t-1}, u_t, \sigma), u_{t+1}, \sigma), \hat{g}(y_{t-1}, u_t, \sigma), y_{t-1}, u_t)$$

- 4 Necessity for pruning

Approximation of occasionally binding constraints with penalty functions

The investment positivity constraint is translated into a penalty on the welfare:

$$\max_{\{c_{t+j}, l_{t+j}, k_{t+j}\}_{j=0}^{\infty}} \sum_{j=0}^{\infty} \beta^j u(c_{t+j}, l_{t+j}) + h \cdot \log(i_{t+j})$$

s.t.

$$y_t = c_t + i_t$$

$$y_t = A_t f(k_{t-1}, l_t)$$

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

$$A_t = A^* e^{a_t}$$

$$a_t = \rho a_{t-1} + \varepsilon_t$$

where the technology (f) and the preferences (u) are as before, and h governs the strength of the penalty (*barrier parameter*)

Thanks for your attention!

Questions?



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