

# HANK on Speed: Robust Nonlinear Solutions using Automatic Differentiation

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## Abstract

Building on automatic differentiation, I propose a solution method for heterogeneous agents models with many aggregate equations which allows to account even for strong nonlinearities. A powerful open source reference implementation is provided which typically solves the canonical HANK model within a few seconds, including the nonlinear transition dynamics of the complete distribution. I study a permanent shift in redistribution policy in a medium-scale two-asset HANK model featuring many aggregate frictions. Since firms wish to deplete their capital stock, the transition path is characterized by a long-lasting deflationary episode, which may be intensified by the interest rate lower bound.

*Keywords:* Computational methods, General equilibrium, Heterogeneous agents, Nonlinear systems

*JEL:* C63, C32, E52, E47

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## 1 Introduction

Over the last decade, heterogeneous agent models have emerged as an important new class of macroeconomic models. They allow to account for the heterogeneity of agents in their wealth, abilities, or other characteristics, thereby permitting economists to better understand the role of different groups of agents for the economy. Heterogeneous agent models provide more accurate predictions about how different agents respond to changes in the economy, such as shifts in policy, changes in market conditions, or unexpected shocks, and in turn give insight on how these changes impact on the distribution of agents. This allows these models to capture important new economic channels, which is

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useful for designing policies that are more effective and equitable, and provide a more nuanced and realistic view of the economy, ultimately leading to a deeper understanding of how the economy works.

This paper shows how to solve and simulate heterogeneous agent models with strong nonlinearities and many aggregate equations. The current frontier of macroeconomic research assigns a pivotal role to such nonlinearities. Important examples include occasionally binding constraints such as the lower bound on nominal rates, asymmetries like downwards nominal wages or asymmetric disaggregated pricing decisions, and nonlinearities induced by severe financial frictions or labor markets with search-and-matching.<sup>1</sup> The literature stresses that such nonlinearities are likely to play a central role in the propagation of policies and economic shocks through the economy, or to different groups of economic agents. However, due to the high complexity of heterogeneous agent models – in particular if, in addition to the cross-section of agents, they also feature many aggregate equations –, current advances have focussed on methods that involve linearization techniques, thereby discarding the nonlinear features of the model. This paper fills this gap by allowing to solve heterogeneous agent models while fully accounting for the underlying nonlinearities.<sup>2</sup>

As the basis of my methodological contribution I develop a modular representation of nonlinear heterogeneous agent models. This representation allows to combine the disaggregated decisions of the cross-section of agents with an arbitrary number of – potentially highly nonlinear – aggregated equilibrium conditions. I then show that the model’s steady state and the corresponding stationary distribution can be identified by means of a robust and generic routine based on the technique of *automatic differentiation* (AD) and the Moore–Penrose inverse.<sup>3</sup> At the heart of the paper, I then provide a Newton method that, given initial conditions, solves for the perfect foresight path. The solution is represented in sequence space, i.e. represents the truncated trajectory up to a distant horizon, and fully accounts for the nonlinearity of the model. As I show, the system of linear equations associated with each Newton-step can be solved efficiently using a novel iterative procedure based on Jacobian-vector-products (JVPs). The efficiency comes from explicitly exploiting several features that are specific to economic models, and by leveraging that JVPs can be evaluated quickly using AD. The method not only allows to solve for the nonlinear aggregate dynamics, but also to obtain the full transition sequence of the cross-sectional distribution.

Along with the method, I provide a high-level reference implementation that I propose as a blueprint of best-practices for the provision of codes and numerical routines in economics: the *econpizza* package. The package consequently follows the open-source paradigm and comes with an extensive online documentation.<sup>4</sup> A core concept is the

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<sup>1</sup>E.g., see Gust et al. (2017) for the role of the interest rate lower bound on the empirical dynamics and Lindé and Trabandt (2018) for the effects of nonlinearities on fiscal multipliers. Petrosky-Nadeau et al. (2018) document that nonlinear labor search frictions can induce endogenous disasters in otherwise standard models. Klenow and Kryvtsov (2008) study the role of asymmetric state-dependent heterogeneous firms pricing on inflation dynamics.

<sup>2</sup>While this paper focuses on models with heterogeneous households, the presented methods can equally well be applied to models with heterogeneity across other types of agents, such as firms or banks.

<sup>3</sup>Automatic differentiation is a computational technique for efficiently computing the derivatives of a function without having to write out the derivative by hand or use numerical methods. Section 3 gives a short primer on AD and its virtues.

<sup>4</sup>The documentation can be found at <https://econpizza.readthedocs.io>.

strict separation of economic model (provided by the user), underlying simulation code (provided by the implementation), and the analysis of the results (left to the user). To archive this, I introduce a generic and standardized modelling syntax for the representation of heterogeneous agent models, which leveres the modular structure of these models: the aggregate equations on one side, and the disaggregated decision problem on the other. The implementation further showcases how to provide generic, reusable code and to adhere to the principles of modern software development. As I argue, this helps to make these methods accessible to a larger group of researchers while allowing and fostering continuous progress in the field.

I apply the proposed methods to a fundamental question in economics: the macroeconomic costs and benefits of redistributive policy. I propose a medium-scale heterogeneous agent model which features the full set of frictions of contemporary DSGE models. Agents may hold two classes of assets and face idiosyncratic income risk. This gives rise to a precautionary savings motive and a non-trivial distribution of assets. If government transfers are financed by labor income taxes, the distortionary effects of these taxes decreases output significantly relative to an equilibrium without transfers. My methodology allows to study the transition dynamics of the complete cross-sectional distribution between the two equilibria. As I show, these dynamics are highly deflationary in the short and medium term due to the depletion of the capital stock, and their recessionary nature may be intensified by severe nonlinearities such as a binding lower bound on the nominal interest rate or downwards nominal wage rigidity.

### *Literature*

The idea of solving *representative* agent models in sequence space dates back to the seminal paper of Fair and Taylor (1980). Building on this idea, Laffargue (1990) and Juillard et al. (1996) show that the block tridiagonal structure of the sequence space Jacobian of representative agent models can be exploited to efficiently solve the system of linear equations during each single Newton step. Juillard et al. (1998) further show that Newton-based methods are advantageous over first-order algorithms in terms of robustness and speed. This type of algorithm (but using AD to calculate the single Jacobian blocks) is also provided in the reference implementation for representative agent models. Appendix A contains details. Unfortunately, the sequence space Jacobian of *heterogeneous* agent models does not inherit such handy block tridiagonal structure, nor can we safely ex-ante assume its sparsity. For this reason I here propose a method that uses the existing knowledge about the dynamic system of heterogeneous agent models – manifested in the steady state sequence space Jacobian – to efficiently solve the system of linear equations during each Newton step iteratively.

The sequence space approach to heterogeneous agent models was introduced by Boppart et al. (2018) and further advanced by Auclert et al. (2021). Both methods focus on linearized solutions in the direct neighborhood of the steady state. Boppart et al. (2018) propose a small-scale model which features very few aggregated variables and equations. They show that the underlying heterogeneous agent model can be solved giving a guess on the trajectory of these variables without having to keep track of the disaggregated variables. The authors use the nonlinear impulse responses in the immediate neighborhood of the steady state to generate general linear impulse responses. Building on this, Auclert et al. (2021) provide an elegant and efficient method for calculating the steady state sequence space Jacobian which provides linear impulse response functions

for models with many aggregated variables. Auclert et al. (2021) also use the steady state sequence space Jacobian in the context of a Newton method to find the truly nonlinear perfect foresight solution. This approach – using the Jacobian of the initial guess for each iteration – is known as the *chord method* and usually converges only if the initial guess is sufficiently close to the solution, which in general is not the case.

An alternative approach for solving heterogeneous agent models is based on the state-space representation and goes back to Reiter (2009). This approach as well returns impulse responses to the linearized model. Since the disaggregated state spaces of heterogeneous agent models are generally very large, such state-space representation usually makes a state-space reduction necessary. Such reduction routines are given, e.g., by Algan et al. (2008), Winberry (2018) or Bayer et al. (2020), where they are also applied to the Bayesian estimation of linearized heterogeneous agent models. While these methods require the approximation or compression of the distribution, they allow for very general functional relationships between the distribution and the aggregated economy. In contrast, the sequence state approach of Auclert et al. (2021) does not require approximation or compression of distribution but requires some of these functional forms to be linear. Other than that, my method does neither require any of the functional forms of the model to be linear, nor any approximation or compression of the distribution. Centrally, the method also allows to find the fully nonlinear solution even if the trajectory is very far from the steady state, whereas the nonlinear solver is robust even to strong nonlinearities due to the use of the true Jacobian during the Newton iterations. My method further allows to fully trace the nonlinear transition of the complete cross-sectional distribution.

By applying automatic differentiation to solve economic models, this paper also adds to a very recent branch of the literature which introduces machine learning tools for quantitative economics. Examples include Scheidegger and Bionis (2019); Maliar et al. (2021); Kahou et al. (2021); Bianchi et al. (2021); Azinovic et al. (2022) and in particular Fernández-Villaverde et al. (2023). These papers use deep learning networks to solve nonlinear high-dimensional macroeconomic models including aggregate uncertainty. Notably, solving this type of models was deemed impossible only a few years ago and the current progress in this area is very impressive. The current state of this line of research documents that it is well possible to successfully apply deep learning to solve economic models, but that these methods (and their convergence properties) are not yet well understood, may take a long time to train and require additional expert knowledge. As machine learning techniques are currently very actively researched across many fields, it is highly likely that they are the path forward to circumvent the curse of dimensionality and to solve complex nonlinear models with aggregate uncertainty. This paper can be seen as an intermediary step contributing to this overarching goal.

My method is based on iteratively solving the system of linear equations of each Newton step. A class of related numerical methods are the well-known Krylov subspace methods, see e.g. the generalized minimal residual method (GMRES, Saad and Schultz, 1986) and the biconjugate gradient stabilized method (Van der Vorst, 1992, BiCGSTAB). Relative to these methods the algorithm introduced here has a considerably lower computational and memory overhead and is thus much faster.<sup>5</sup> However, while the conditions for convergence of my method are generic to the type of nonlinear systems found in

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<sup>5</sup>E.g. GMRES requires an Arnoldi iteration during each step, which can be computationally costly, and needs to store the results from previous iterations.

economic models, they are not sufficiently generic to be used for problems outside this subclass.

The rest of this paper is structured as followed. Section 2 lays out a medium-scale HANK model with two assets. Section 3 presents the main methodological contributions. Section 4 discusses details and concepts of the reference implementation with a particular focus on reproducible and extensible code. In Section 5 the method is applied to the dynamics of a change in government redistribution, whereas Section 6 gives concluding remarks.

## 2 A Class of Medium Scale Heterogeneous Agent Models

The results of this paper are based on three different models which share the same aggregate economy but differ in the degree of heterogeneity of households: a model with a single representative household (RANK), an heterogeneous agent model with one asset, and an heterogeneous agent model where households have access to a liquid and an illiquid asset (two-asset HANK). For the sake of brevity I here only sketch the setup of the two-asset HANK model and those aggregate equations that are non-standard, and redirect the exposition of the RANK and the one-asset-HANK model to Appendix B.

I combine the two-asset HANK model (e.g. Auclert et al. (2021)) with the standard medium-scale DSGE model in the tradition of Smets and Wouters (2007). This results in a rich dynamic model with many aggregate state variables that demonstrates the potential of the method. The model hence contains a disaggregated part with the households decisions and the distribution dynamics, and the aggregated part of a medium-scale DSGE model. The modular setup of the method and implementation presented in Sections 3 and 4 allows to specify both parts separately.

In the disaggregated part of the model, households can hold liquid bonds  $b_{it}$  and illiquid assets  $a_{it}$ , the latter pay higher returns but are subject to convex portfolio adjustment costs. Households face idiosyncratic labor income risk  $e_{it}$  and a borrowing constraint on both assets. They wish to accumulate net worth for the purpose of consumption smoothing and to insure against the associated idiosyncratic income risk. Their Bellman equation is given by

$$V_t(e_{it}, b_{i,t-1}, a_{i,t-1}) = \max_{c_{it}, b_{it}, a_{it}} \left\{ \frac{c_{it}^{1-\sigma_c}}{1-\sigma_c} - \chi \frac{n_t^{1+\sigma_l}}{1+\sigma_l} + \beta_t E_t V_{t+1}(e_{i,t+1}, b_{it}, a_{it}) \right\} \quad (1)$$

such that

$$c_{it} + a_{it} + b_{it} = \frac{(1-\tau_t)w_t n_t}{\int P(e_{jt})e_{jt}^{1-\Xi} dj} e_{it}^{1-\Xi} + (1+r_t^a)a_{i,t-1} + (1+r_t^b)b_{i,t-1} - \Phi_t(a_{it}, a_{i,t-1}) + T_t, \quad (2)$$

$$a_{it} \geq 0, \quad (3)$$

$$b_{it} \geq \bar{b}, \quad (4)$$

where  $n_t$  denotes labor supply,  $c_{it}$  the consumption of household  $i$ , and  $e_{it}$  is their household-specific labor productivity which follows an AR(1) process in logs,

$$\log e_{it} = \rho_e \log e_{i,t-1} + \epsilon_{it}^e. \quad (5)$$

$\Phi_t(\cdot)$  is the function specifying portfolio adjustment costs for the illiquid asset

$$\Phi_t(a_{it}, a_{i,t-1}) = \frac{\chi_1}{\chi_2} \left| \frac{a_{it} - (1 + r_t^a)a_{i,t-1}}{(1 + r_t^a)a_{i,t-1} + \chi_0} \right|^{\chi_2} [(1 + r_t^a)a_{i,t-1} + \chi_0], \quad (6)$$

with  $\chi_0, \chi_1 > 0$  and  $\chi_2 > 1$ .  $T_t$  is a government lump-sum transfer specified further below.

The aggregate economy features all the bells and whistles of the medium-scale workhorse model of Smets and Wouters (2007). To avoid linear approximations, the design of the price and wage Phillips curves follows a Rotemberg (1982) setup as in Gust et al. (2012) rather than the Calvo (1983) price setting of Smets and Wouters (2007). The conventional parts of the model, including labor unions, the firm side and the government are presented in detail in Appendix B.1. Deviating from this, the setup of labor unions when combined with heterogeneous households gives rise to a wage Phillips curve that takes the form

$$\psi_w \left( \frac{\pi_t^w}{\tilde{\pi}_t^w} - 1 \right) \frac{\pi_t^w}{\tilde{\pi}_t^w} = \psi_w \beta_t E_t \left\{ \left( \frac{\pi_{t+1}^w}{\tilde{\pi}_{t+1}^w} - 1 \right) \frac{\pi_{t+1}^w}{\tilde{\pi}_{t+1}^w} \right\} + \frac{\mu_t^w}{\mu_t^w - 1} \left( \chi n_t^{1+\sigma_l} - \frac{w_t n_t}{\mu_t^w} \int e_{it} c_{it}^{-\sigma} di \right), \quad (7)$$

with wage indexation term  $\tilde{\pi}_t^w$  and where  $\pi_t^w = \frac{w_t^n}{w_{t-1}^n} \pi_t$  denotes wage inflation. Wages can be subject to downwards nominal wage rigidity governed by rigidity parameter  $\iota_w$ ,

$$w_t = \max \left\{ \iota_w \frac{w_{t-1}}{\pi_t}, w_t^n \right\}. \quad (8)$$

The setup of firms includes capital formation, capital adjustment costs, capital utilization costs and price indexation. Dividends are given by

$$\Pi_t = y_t - w_t n_t - i_t - \frac{\psi}{2} \left( \frac{\pi_t}{\tilde{\pi}_t} - 1 \right)^2 y_t. \quad (9)$$

No arbitrage on financial markets requires that

$$\frac{R_t}{E_t \pi_{t+1}} = \frac{E_t \{\Pi_{t+1} + s_{t+1}\}}{s_t} = E_t R_{t+1}^a = E_t R_{t+1}^b + \zeta, \quad (10)$$

where  $R_t$  is the policy rate and  $s_t$  is the stock price.  $\zeta$  parameterizes the cost for liquidity transformation charged by the financial intermediary. Ex-post returns are subject to surprise inflation,

$$R_t^b = \frac{R_{t-1}}{\pi_t} - \zeta, \quad (11)$$

and capital gains are given by

$$R_t^a = \Theta_t^s \left( \frac{\Pi_t + s_t}{s_{t-1}} \right) + (1 - \Theta_t^s) \frac{R_{t-1}}{\pi_t}, \quad (12)$$

with  $\Theta_p$  denoting the share of equity in the illiquid portfolio. A balanced government

budget requires

$$\tau_t w_t n_t = \left( \frac{R_{t-1}}{\pi_t} - 1 \right) B^g + g_t + T_t, \quad (13)$$

where  $\tau_t$  is the tax rate (rather than the tax volume), and government transfers  $T_t$  are an exogenous policy decision which is assumed to follow an AR(1) process in logs

$$\ln T_t = (1 - \rho_T) \ln \bar{T} + \rho_T T_{t-1} + \varepsilon_t^T. \quad (14)$$

Importantly, the government taxes labor only and adjusts the labor tax rate from period to period to run a balanced budget. The central bank sets the policy rate  $R_t$  following a conventional monetary policy rule with interest rate inertia.

$$\ln R_t^n = \rho \ln R_{t-1}^n + (1 - \rho) (\ln R_t^* + \phi_\pi [\ln \pi_t - \ln \bar{\pi}] + \phi_y [\ln y_t - \ln \bar{y}]) + \ln v_t, \quad (15)$$

that may be subject to the zero lower bound on nominal interest rates (ZLB)

$$R_t = \max \{1, R_t^n\}. \quad (16)$$

Market clearing requires

$$y_t = \int c_{it} di + g_t + i_t + \psi_t + \zeta b_{it} di, \quad (17)$$

$$s_t + b^g = \int a_{it} + b_{it} di. \quad (18)$$

The calibration – for the aggregate and disaggregate part of the model – is quite conventional and loosely anchored at the values reported in Boehl (2022), where a similar model is estimated under inclusion of the households' preference parameters. To allow for transition dynamics from one steady state to another, only parameters are fixed ex-ante but no steady state values. The inflation target is set to 2% annually and the initial level of transfers is zero. Appendix B contains further details on the calibration.

### 3 Solving Nonlinear Heterogeneous Agent Models

This section presents the main methodological innovations. I first provide a general aggregate representation of heterogeneous agent models. Then I review the principals of automatic differentiation (AD), which are important for understanding the innovations of the main method. I then present an iterative procedure that uses AD to find the dynamic equilibrium transition path. Finally, I show how the steady state and the steady state Jacobian, the latter being an important ingredient to the main method, can be calculated efficiently using AD.

#### 3.1 An aggregate representation of heterogeneous agent models

Let  $(x_t)_{t \geq 0} \in \mathbb{X} \subset \mathbb{R}^n$  be the *aggregated* variables in period  $t$  including aggregate shocks and denote the *disaggregated* state space of heterogeneous agents by  $\mathbb{S} \subset \mathbb{R}^{n_s}$ .<sup>6</sup>

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<sup>6</sup>Any aggregate shock  $\varepsilon_t^k$  can be included in the set of aggregate variables by shifting the timing of  $\varepsilon_t^k$  one period backwards to  $\varepsilon_{t-1}^k$  and adding an auxiliary equation  $\varepsilon_t^k = 0$ . Impulses can then be simulated

For the two-asset example from Section 2,  $\mathbb{S} \subset \mathbb{R}^3$  is the space spanning over the domains of the two types of assets  $a_{it}$  and  $b_{it}$  and the domain of the household-specific productivity level  $e_{it}$ .

A large class of heterogeneous agent models can be cast in the form

$$(a_t, w_t) = W(w_{t+1}, x_{t-1}, x_t, x_{t+1}), \quad (19)$$

$$d_t = D(a_t, d_{t-1}), \quad (20)$$

$$\mathbf{0} = f(x_{t-1}, x_t, x_{t+1}, d_t, a_t), \quad (21)$$

where  $(w_t, a_t, d_t)_{t \geq 0}$  are time- $t$  functions defined on  $\mathbb{S}$  as follows.  $w_t : \mathbb{S} \rightarrow \mathbb{W} \subset \mathbb{R}^{n_w}$  denotes recursive valuations of points in  $\mathbb{S}$ ,  $a_t : \mathbb{S} \rightarrow \mathbb{A} \subset \mathbb{R}^{n_a}$  are agents' actions (or functions thereof) for a given state, and  $d_t : \mathbb{S} \rightarrow [0, 1]$  is the distribution of agents across  $\mathbb{S}$ .<sup>7</sup> Since  $\mathbb{S}$  is of infinite dimensionality, it must be discretized on a grid  $S_g$  with suitably chosen grid size  $g$ . Thus, in practice  $(w_t, a_t, d_t)$  are grid-based representations of the underlying functions where  $w_t$  is a  $n_w \times g$  tensor,  $a_t$  is  $n_a \times g$  and  $d_t$  is the distribution over  $S_g$  represented by the  $g$ -dimensional unit hypercube  $[0, 1]^g$  with  $\sum_j^g d_{t,j} = 1$ . Notably, the only type of models not captured by this representation are models in which the agents' actions depend on the *full* distribution.

In terms of the dynamic programming problem given in Section 2,  $w_t$  would represent the value function  $V_t(e_{it}, b_{i,t-1}, a_{i,t-1})$  and  $W(\cdot)$  represents the Bellman operator over Equations (1) to (6). This takes prices such as wages and the return rates  $r_t^a$  and  $r_t^b$  as given, which, in terms of the formulation above, are part of the set of aggregate variables  $x_t$ . In practice however,  $w_t$  are often the *marginal* values as required when using variants of the endogenous grid method (EGM) of Carroll (2006), which usually are more efficient computationally.<sup>8</sup> I will therefore also refer to  $W$  as the EGM-step which maps expected marginal values into current marginal values. The above representation is without loss of generality as it also includes cases where  $W$  is a more complicated recursion, e.g. tracing default probabilities over time in models where agents can default on their debt.

The object  $a_t$  are the decisions implied by solving the Bellman equation, e.g. for the two-asset HANK the choices of  $\{a_{it}, b_{it}, c_{it}\}$  for each node on the grid  $S_g$ . Note that  $a_t$  is defined on  $S_g$  but not directly related to the distribution  $d_t$  over  $S_g$ . The role of the *evolution* of the distribution,  $D(\cdot)$  is then to map the agents' current decisions  $a_t$  and the last distribution  $d_{t-1}$  into the current distribution  $d_t$ . The function  $f(\cdot) = z_t \stackrel{!}{=} \mathbf{0}$  with  $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$  contains the  $n$  nonlinear equations describing the law-of-motion of the aggregate economy, formulated such that each equation (i.e. each residual in  $z_t$ ) must equal zero in equilibrium. For the model from Section 2 this corresponds to all equations following (7) additional to the respective aggregate relationships from Appendix B.1. Future or past aggregate variables beyond  $t + 1$  or before  $t - 1$  can easily be included by introducing auxiliary variables. In the following it is assumed that  $W$ ,  $D$ , and  $f$  are differentiable and that this property is retained throughout the discretization and

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by setting  $\varepsilon_{t-1}^t \neq 0$ . Expected shocks can be treated equivalently.

<sup>7</sup>Without loss of generality, there could be several distributions. I will here use the singular term for the sake of simplicity.

<sup>8</sup>A generalization of EGM for multiple dimensions and portfolio choice models is given by Hintermaier and Koeniger (2010). For the two-asset HANK it is necessary to track the marginal values of liquid and illiquid assets and, hence,  $w_t \in S_g^2$ .



interpolation routines.

Omitting the expectations operator on  $t + 1$ -objects implies to abstract from aggregate uncertainty and focus on the perfect foresight path. For an initial state  $(x_0, d_0) \in (\mathbb{X}, [0, 1]^g)$ , an equilibrium consists of  $(W, D, f)$  satisfied by sequences of  $\{x_t, w_t, a_t, d_t\}_{t=1}^\infty$  for all  $t = 1, 2, \dots$  periods. The above specification nests representative agent models if  $(w_t, a_t, d_t)$  are empty sets. The model then solely consist of the  $n$  aggregate variables  $x_t$  and the  $n$  aggregate equations in  $f : \mathbb{X} \rightarrow \mathbb{R}^n$

This representation generalizes the specification of Auclert et al. (2021) in two regards: first, the effect of idiosyncratic variables on the aggregated economy can take arbitrary functional forms and is not restricted to be linear in the distribution. In particular, it is not necessary to explicitly cast idiosyncratic variables into aggregate output variables before supplying them to  $f$ . Instead, the distribution and the agents' actions enter  $f$  directly and the mapping from  $(w_t, a_t, d_t)$  in  $f$  can take arbitrary functional forms. Second, the aggregate economy does not require a representation as a directed acyclic graph.

Take  $(x_0, d_0)$  as given and fix a terminal period  $T$  sufficiently large. Assume that  $(x_T, w_T)$  in period  $T$  are known (e.g. because  $T$  is very large and the economy is thus  $\epsilon$ -close to a steady state in  $T$ ). Starting with  $w_T$  and a guess for the sequence of aggregated variables  $\{x_t\}_{t=1}^{T-1}$  the function  $W(\cdot)$  can be iterated backwards in time, thereby providing the sequence of decisions  $\{a_t\}_{t=1}^{T-1}$ . Then starting with  $d_0$ , this sequence can be used to iterate the function  $D(\cdot)$  forwards in time until  $T$ , resulting in the sequence of distributions  $\{d_t\}_{t=1}^{T-1}$ . Using boldface notation for time-sequences,  $\mathbf{x} = \{x_t\}_{t=1}^{T-1}$ , let backwards and forwards iteration and aggregation be represented by the functions  $F_a$ ,  $F_d$  and  $F_x$  as

$$F_a : \mathbf{x} \xrightarrow{W} \mathbf{a}, \quad (22)$$

$$F_d : \mathbf{a} \xrightarrow{D} \mathbf{d}, \quad (23)$$

$$F_x : (\mathbf{x}, \mathbf{d}, \mathbf{a}) \xrightarrow{f} \mathbf{z}, \quad (24)$$

where  $\mathbf{z} = \{z_t\}_{t=1}^{T-1} = \{f(x_{t-1}, x_t, x_{t+1}, d_t, a_t)\}_{t=1}^{T-1}$  is the sequence of residuals from the aggregated equations. It is then straightforward to define a function  $F : \mathbb{R}^{n(T-1)} \rightarrow \mathbb{R}^{n(T-1)}$  by

$$F(\mathbf{x}) = F_x(\mathbf{x}, F_d(F_a(\mathbf{x}))) = \mathbf{z}, \quad (25)$$

which is, thus, defined in aggregate terms only.<sup>9</sup> It follows that a perfect foresight equilibrium trajectory  $\mathbf{x}^*$  is given by

$$F(\mathbf{x}^*) = \mathbf{0}, \quad (26)$$

implying that a fully nonlinear period- $T$  truncated solution to the model in Eqns. (19) to (21) can be expressed as a  $(T - 1 \times n)$ -dimensional root finding problem. A solution to this type of problems can be found using Newton's method. Starting with an initial

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<sup>9</sup>Note again that for a representative agent problem it holds simply that  $F = F_x$ .

guess on the equilibrium trajectory  $\mathbf{x}_0$ , Newton’s method is given by the iteration

$$\mathbf{x}_{i+1} = \mathbf{x}_i - J(\mathbf{x}_i)^{-1}F(\mathbf{x}_i), \quad (27)$$

until  $\|\mathbf{x}_{i+1} - \mathbf{x}_i\| < \epsilon$ , where  $J(\mathbf{x}_i)$  is the Jacobian matrix of  $F$  evaluated at  $\mathbf{x}_i$  and  $\epsilon$  is a given (very small) stopping criterion. While Newton’s method is known for its good convergence properties, applying this method directly is usually impractical (if not impossible) because the Jacobian – and its inverse – is normally very expensive to calculate. To circumvent this problem, I below present an iterative method to solve the linear system of equations associated with (27) very efficiently using automatic differentiation.

### 3.2 A primer on automatic differentiation

Automatic differentiation (AD) is a computational technique for efficiently computing derivatives of a function. AD is heavily used in machine learning, where, given a model such as, e.g., a neural network, the gradient of a loss function with respect to the model’s parameters is typically used to optimize the parameters and train the model. With AD, the gradient can be computed efficiently and accurately, even for complex models. This can be especially useful in large-scale optimization problems, where the number of variables and constraints can be very large.

Many explanations of AD start by pointing out that AD works by using the chain rule of calculus to build up the derivative of a function from the derivatives of its constituent parts. While this is technically true, it is sometimes mistaken to imply that AD can magically and at almost zero computational costs provide the Jacobian of any multivariate function. This, importantly, is not the case.

AD knows two distinct modes: *forward mode* and *reverse mode*. Forward accumulation is accomplished by augmenting the algebra of real numbers and obtaining a new arithmetic: the algebra of *dual numbers*. An additional component is added to every number to represent the derivative of a function at the number, and all arithmetic operators are extended for the augmented algebra. A dual number  $x$  is given by

$$a = b + c \cdot \epsilon, \quad (28)$$

such that  $\epsilon > 0$  and  $\epsilon^2 = 0$ . The algebra of dual numbers has hence some similarities to the algebra of complex numbers, with the difference that  $\epsilon^2 = 0 \neq -1$ .

Using the vector of dual numbers  $\mathbf{a} = \mathbf{b} + \mathbf{c}\epsilon$  the algebra can be extended to multivariate analytic functions such that

$$g(\mathbf{a}) = g(\mathbf{b} + \mathbf{c}\epsilon) = g(\mathbf{b}) + J(\mathbf{b})\mathbf{c}\epsilon, \quad (29)$$

where  $g$  is a function and  $J(\mathbf{b})$  its Jacobian evaluated at  $\mathbf{b}$ . While this implies that AD – via dual numbers – is particularly efficient in calculating Jacobian-vector products (JVPs) such as  $J(\mathbf{b})\mathbf{c}$ , it does *not* mean that the Jacobian itself is cheap to obtain. To see this, denote the JVP as  $J(\mathbf{b})\mathbf{c} = \Lambda(\mathbf{b}, \mathbf{c})$ . Assuming  $g : \mathbb{R}^m \rightarrow \mathbb{R}^n$ , the Jacobian at  $\mathbf{b}$  is given by

$$J(\mathbf{y}) = J(\mathbf{y})\mathbf{I}_n = J(\mathbf{y}) \begin{bmatrix} \mathbf{e}_1^\top & \mathbf{e}_2^\top & \cdots & \mathbf{e}_n^\top \end{bmatrix} = \begin{bmatrix} \Lambda(\mathbf{y}, \mathbf{e}_1^\top) & \Lambda(\mathbf{y}, \mathbf{e}_2^\top) & \cdots & \Lambda(\mathbf{y}, \mathbf{e}_n^\top) \end{bmatrix}, \quad (30)$$

where  $\mathbf{I}_n$  is the  $n$ -dimensional identity matrix and  $\mathbf{e}_i$  is the  $i$ th vector in the standard basis of  $\mathbb{R}^n$ . This implies that calculating the Jacobian of a function with domain  $\mathbb{R}^n$  requires exactly  $n$  evaluations of  $f$ , which is only one evaluation less than needed for the one-sided finite difference approximation of the Jacobian. Notably for our application, this makes the evaluation of objects such as the Jacobian of  $f$  w.r.t.  $d_t$  (as e.g. suggested in the appendix of Auclert et al. (2021) to generalize their model specification) prohibitory expensive for many applications.<sup>10</sup> Thus and so far, the only clear advantage of AD over finite difference methods is precision.

In *reverse mode* automatic differentiation, the computational graph of the function is traversed in reverse order, and the derivative of each node is computed by using the derivatives of its outputs. The derivative of each node is then used to update the derivative of its inputs. The process continues until the derivatives of the inputs are computed. Importantly, this allows to cheaply evaluate the vector-Jacobian product (VJP)  $\mathbf{c}^\top J(\mathbf{b}) = \Gamma(\mathbf{b}, \mathbf{c})$  at a single pass of the function. Continuing to assume that the codomain of  $g$  is  $\mathbb{R}^m$ , the Jacobian can therefore also be evaluated by

$$J(\mathbf{y}) = \mathbf{I}_m J(\mathbf{y}) = \begin{bmatrix} \mathbf{e}_1 \\ \mathbf{e}_2 \\ \vdots \\ \mathbf{e}_m \end{bmatrix} J(\mathbf{y}) = \begin{bmatrix} \Gamma(\mathbf{y}, \mathbf{e}_1) \\ \Gamma(\mathbf{y}, \mathbf{e}_2) \\ \vdots \\ \Gamma(\mathbf{y}, \mathbf{e}_m) \end{bmatrix}, \quad (31)$$

which requires  $m$  evaluations. The use of reverse mode AD over finite differences is hence beneficial either for evaluating VJPs at low costs or for calculating  $J$  if  $m < n$ . The next two subsections show how to apply these insights efficiently to solve macroeconomic heterogeneous agent models.

### 3.3 An iterative method based on JVPs

Summarizing the last subsection, the particular strength of AD is to evaluate JVPs, VJPs, and Jacobians of functions with either very small domain or codomain. The latter is clearly not the case for the function  $F$  from Eqn. (25) which comprises a square Jacobian of size  $n(T-1) \times n(T-1)$ . Calculating this Jacobian for the two-asset HANK model and a truncation horizon of  $T = 300$  takes more than 5 minutes on a standard laptop, thereby rendering the calculation of a single transition path almost prohibitory costly.

Rather than actually calculating and inverting the Jacobian matrix for Newton's method in Eq. 27, we may use the solution to the system of linear equations

$$J(\mathbf{x}_i)(\mathbf{x}_{i+1} - \mathbf{x}_i) = -F(\mathbf{x}_i), \quad (32)$$

i.e. during each iteration we are looking for an  $\mathbf{y} = \mathbf{x}_i - \mathbf{x}_{i+1}$  such that  $\Lambda(\mathbf{x}_i, \mathbf{y}) = F(\mathbf{x}_i)$ . Denote by  $\bar{\mathbf{x}}$  the sequence of aggregate variables in the steady state and by  $\bar{J} = J(\bar{\mathbf{x}})$  the

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<sup>10</sup>The finite difference approximation of a JVP is given by  $\Lambda(\mathbf{y}, \mathbf{z}) \approx \frac{f(\mathbf{y} + \sigma \mathbf{z}) - f(\mathbf{y})}{\sigma}$  where  $\sigma$  is the step size. The evaluation of a JVP using dual numbers requires one evaluation of  $f$  versus two evaluations when using a finite difference approximation. Note that the dual number evaluation of  $f$  comes with a computational overhead.

steady state Jacobian. Then

$$J(\mathbf{x}_i)\mathbf{y} = F(\mathbf{x}_i), \quad (33)$$

$$(J(\mathbf{x}_i) - \alpha^{-1}\bar{J} + \alpha^{-1}\bar{J})\mathbf{y} = F(\mathbf{x}_i), \quad (34)$$

$$\alpha^{-1}\bar{J}\mathbf{y} = F(\mathbf{x}_i) - (J(\mathbf{x}_i) - \alpha^{-1}\bar{J})\mathbf{y}, \quad (35)$$

$$\mathbf{y} = \mathbf{y} + \alpha\bar{J}^{-1}(F(\mathbf{x}_i) - J(\mathbf{x}_i)\mathbf{y}), \quad (36)$$

where  $\alpha > 0$  is a scalar dampening factor to ensure convergence. Our aim is to turn this last equation into an iterative procedure. For this, the following Lemma 1 will be useful.

**Lemma 1.** *The Rayleigh quotient of a matrix  $M$  and vector  $\mathbf{c}$  is given by*

$$R(M, \mathbf{c}) = \frac{\mathbf{c}^\top M \mathbf{c}}{\mathbf{c}^\top \mathbf{c}}. \quad (37)$$

It holds that

i) *If  $\mathbf{v}$  is an eigenvector of  $M$  with associated eigenvalue  $\lambda$ , then*

$$R(M, \mathbf{v}) = \frac{\mathbf{v}^\top M \mathbf{v}}{\mathbf{v}^\top \mathbf{v}} = \frac{\mathbf{v}^\top \lambda \mathbf{v}}{\mathbf{v}^\top \mathbf{v}} = \lambda. \quad (38)$$

ii) *For any iterative procedure  $\mathbf{y}_{j+1} = \mathbf{c} + M\mathbf{y}_j$  with square matrix  $M$ ,  $\mathbf{y}_j$  grows (or shrinks) along the eigenvector associated with the eigenvalue of  $M$  with largest magnitude (Mises and Pollaczek-Geiringer, 1929). Together with i) this implies*

$$\lim_{j \rightarrow \infty} R(M, \mathbf{y}_j) = \rho(M). \quad (39)$$

iii) *The Min-max theorem states that if a square matrix  $M$  is also hermitian, then  $\lambda_{\min} \leq R(M, \mathbf{w}) \leq \lambda_{\max}$  for any  $\mathbf{w} \in \mathbb{C}^n$ , where  $(\lambda_{\min}, \lambda_{\max})$  are the smallest and largest eigenvalues of  $M$ . The singular values  $\sigma_k$  of the real square (and in general non-hermitian) matrix  $P$  are given by the square roots of the eigenvalues of  $P^\top P$ . Since  $\sqrt{R(P^\top P, \mathbf{z})} = R(P, \mathbf{z})$  we have that*

$$|R(P, \mathbf{y}_j)| \in [\sigma_{\min}, \sigma_{\max}], \quad (40)$$

where  $(\sigma_{\min}, \sigma_{\max})$  are the smallest and largest singular values of  $P$ .

Using Lemma 1 we arrive at the Proposition 1, which allows us to solve (32), and thereby nonlinear perfect foresight models with heterogeneous agents, iteratively.

**Proposition 1.** *Given an initial guess  $\mathbf{y}_0$ , a scaling parameter  $\gamma \in (0, 2)$  and initializing  $\alpha_0 = 1$ , the iterative scheme*

$$\mathbf{y}_{j+1} = \mathbf{y}_j + \alpha_j \bar{J}^{-1}(F(\mathbf{x}_i) - \Lambda(\mathbf{x}_i, \mathbf{y}_j)), \quad (41)$$

$$\alpha_j = \min \{ \alpha_{j-1}, \gamma / |R(\bar{J}^{-1}\Lambda(\mathbf{x}_i, \mathbf{y}_j), \mathbf{y}_j)| \}, \quad (42)$$

with  $R(\cdot)$  as the Rayleigh quotient, converges to

$$\lim_{j \rightarrow \infty} \mathbf{y}_j = J(\mathbf{x}_i)^{-1}F(\mathbf{x}_i) \quad (43)$$

if  $\bar{J}$  and  $J(\mathbf{x}_i)$  are invertible and all generalized eigenvalues of  $\bar{J}$  and  $J(\mathbf{x}_i)$  are positive.

*Proof.* Given invertibility of  $\bar{J}$  it is clearly the case that if  $\mathbf{y}_{j+1} = \mathbf{y}_j$ , then  $F(\mathbf{x}_i) = \Lambda(\mathbf{x}_i, \mathbf{y}_j) = J(\mathbf{x}_i)\mathbf{y}_j$ . This means we have to prove convergence of  $\mathbf{y}_j$  in (41).

Define  $B = \bar{J}^{-1}J(\mathbf{x}_i)$  and  $A_j = \mathbf{I} - \alpha_j B$  and note that the condition on the generalized eigenvalues implies that all eigenvalues of  $B$  are positive. Let  $\mathbf{c} = \alpha_j \bar{J}^{-1}F(\mathbf{x}_i)$ . It is well known that the iterative procedure

$$\mathbf{y}_{j+1} = \mathbf{c} + A_j \mathbf{y}_j \quad (44)$$

converges for a constant square matrix  $A_j$  if the spectral radius  $\rho(A_j)$  of  $A_j$  is less than unity, i.e. if all eigenvalues of  $A_j$  lie within the unit circle. Since  $A_j = \mathbf{I} - \alpha_j B$ , it is that

$$\rho(A_j) = |1 - \alpha_j \rho(B)| \implies \rho(A_j) = \alpha_j \rho(B) - 1, \quad (45)$$

which follows from the fact that  $\alpha_j > 0$  and all eigenvalues of  $B$  are assumed to be positive. Note that  $\rho(A_j)$  will thus *always* be larger than one if any of the eigenvalues of  $B$  is negative. The requirement  $\rho(A_j) < 1$  then implies that convergence requires

$$\alpha_j < 2/\rho(B), \quad (46)$$

where the spectral radius  $\rho(B)$  of  $B$  is unknown.

Eqn. (42) defines the recursion  $\alpha_j = \min \{\alpha_{j-1}, \gamma / |R(B, \mathbf{y}_j)|\}$ , which uses the Rayleigh quotient

$$R(B, \mathbf{y}_j) = \frac{\mathbf{y}_j^\top B \mathbf{y}_j}{\mathbf{y}_j^\top \mathbf{y}_j} = \frac{\mathbf{y}_j^\top \bar{J}^{-1} \Lambda(\mathbf{x}_i, \mathbf{y}_j)}{\mathbf{y}_j^\top \mathbf{y}_j}. \quad (47)$$

from Lemma 1 to approximate  $\rho(B)$  with each iteration. After also acknowledging that with Lemma 1, the magnitude of the largest eigenvalue  $|\lambda_{\max}| = |\rho(B)|$  of  $B$  is bounded by the largest singular value  $|\rho(B)| \leq \sigma_{\max}(B)$  it follows that

$$\alpha_j \in \left[ \frac{\gamma}{\sigma_{\max}}, \min \left\{ 1, \frac{\gamma}{\sigma_{\min}} \right\} \right], \quad (48)$$

i.e.,  $\alpha_j$  is bounded, and thus

$$\lim_{j \rightarrow \infty} \alpha_j \in \left[ \frac{\gamma}{\sigma_{\max}}, \min \left\{ 1, \frac{\gamma}{\rho(B)} \right\} \right], \quad (49)$$

that is,  $\alpha_j$  and thereby  $A_j = \mathbf{I} - \alpha_j B$  converges with given bounds. From that it follows that

$$\lim_{j \rightarrow \infty} \rho(A_j) \in \left\{ \begin{array}{ll} \left[ \left| \frac{\gamma}{\sigma_{\max}} - 1 \right|, \left| \frac{\gamma}{\rho(B)} - 1 \right| \right] & \text{if } \rho(B) \geq 2 \\ \left[ \left| \frac{\gamma}{\sigma_{\max}} - 1 \right|, |\rho(B) - 1| \right] & \text{if } \rho(B) < 2 \end{array} \right\} < 1, \quad (50)$$

i.e.  $\mathbf{y}_j$  also converges and is thus a solution to the linear system of equations in (32). ■

Put into a more intuitive form, we set  $\alpha_j$  to equal the inverse of the approximation of the spectral radius of  $B$  scaled by  $\gamma$  and thereby dampen the spectral radius of  $A$  to lie inside the unit circle, which guarantees convergence to a solution of the system of linear

equations. Note that  $F(\mathbf{x}_i) - \Lambda(\mathbf{x}_i, \mathbf{y}_j)$  is a vector and  $\bar{J}^{-1}(F(\mathbf{x}_i) - \Lambda(\mathbf{x}_i, \mathbf{y}_j))$  can hence be evaluated by the LU-factorization of  $\bar{J}$ , which only needs to be calculated once for a given model. All other operations are simple calculations in vector space.

The value of  $\gamma \in (0, 2)$  determines the speed of convergence and can be chosen freely within the given bounds: a value close to 2 will shift the largest eigenvalue of  $B$  close to 2, resulting in a spectral radius  $\rho(A)$  of  $A$  close to one. A value of  $\alpha$  close to 0 will shift the *smallest* eigenvalue of  $B$  close to 0, which also results in  $\rho(A)$  close to one. Since convergence speed depends on the magnitude of  $\rho(A)$  (smaller in magnitude is better) an optimal value will lie somewhere in the mid-range.

Appendix C discusses the eigenvalue condition further and provides intuition why this condition is satisfied in a very large class of economic models. Additionally, note that the eigenvalue condition in Proposition 1 is only a sufficient, but not a necessary condition. Importantly, this implies that the Newton procedure may converge even if the condition is not satisfied.

### 3.4 Finding the steady state and its Jacobian

Continue to denote steady state objects by a bar, i.e.  $\bar{x}$ ,  $\bar{d}$ ,  $\bar{a}$  and  $\bar{w}$ . In the common cases when the steady state is not unique some variables must be fixed ex-ante via an additional set of restrictions  $x = b(\mathfrak{r})$ , where  $\mathfrak{r}$  is the subset of  $x$  necessary to evaluate  $\bar{x}$ .<sup>11</sup> The steady state must satisfy

$$\bar{x} = b(\bar{\mathfrak{r}}), \quad (51)$$

$$(\bar{a}, \bar{w}) = W(\bar{w}, \bar{x}, \bar{x}, \bar{x}), \quad (52)$$

$$\bar{d} = D(\bar{a}, \bar{d}), \quad (53)$$

$$\mathbf{0} = f(\bar{x}, \bar{x}, \bar{x}, \bar{d}, \bar{a}). \quad (54)$$

For a given guess on  $\mathfrak{r}$  calculate the corresponding guess on  $\bar{x}$  using  $b(\cdot)$ .  $\bar{w}$  can then be found by iterating on Eqn. (52) until it converges. Denote the function that does so as  $\bar{w} = \bar{W}(\bar{x})$ . Given  $\bar{x}$  and  $\bar{w}$ , the steady-state distribution  $\bar{d}$  can also be found by iterating on Eqn. (53) until convergence (or, alternatively, via the unit-eigenvector). Denote this solver as  $\bar{d} = \bar{D}(\bar{a})$  and define  $\bar{f}$  equivalently for  $f(\cdot)$ . Combining those three,  $\bar{\mathfrak{r}}$  must satisfy  $H(\bar{\mathfrak{r}}) = \mathbf{0}$  with  $H$  defined as

$$H(\bar{\mathfrak{r}}) = \bar{f}(b(\bar{\mathfrak{r}}), \bar{D}(b(\bar{\mathfrak{r}}), \bar{W}(b(\bar{\mathfrak{r}}))), \bar{W}(b(\bar{\mathfrak{r}}))). \quad (55)$$

Since  $\mathfrak{r} \in \mathbb{R}^m$  with  $m$  small we can this time calculate the complete Jacobian of  $H$  using forward mode automatic differentiation and, starting with some guess  $\mathfrak{r}_i$  on  $\bar{\mathfrak{r}}$ , the root of  $H$  can be found using a modified Newton's method

$$\mathfrak{r}_{i+1} = \mathfrak{r}_i - J_H(\mathfrak{r}_i)^+ H(\mathfrak{r}_i), \quad (56)$$

where  $J_H(\mathfrak{r}_i)^+$  denotes the Moore–Penrose inverse. Using the latter is necessary because  $J_H(\mathfrak{r}_i)$  typically does not have full rank since the codomain of  $f$  is  $\mathbb{R}^n$  and  $n \leq m$ .

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<sup>11</sup>A typical example for New-Keynesian models is that the steady state inflation needs to be fixed ex-ante since it is a policy choice variable of the central bank.

The modified Newton procedure is very robust and does not require any manual input. In particular, it is usually not necessary to manually provide some of the steady state relationships as an additional input to the dynamic system of the economic model.

Given  $\bar{x}$ , the steady state Jacobian  $\bar{J} = J(\bar{x}) = J(\{\bar{x}\}_0^T)$  of  $F$  can also be found using AD. To be clear on notation, let  $J_{x \rightarrow y}$  be the matrix whose  $(i, j)$ th entry is  $J_{ij} = \frac{\partial y_i}{\partial x_j}$ . The  $(i, j)$ th entry of the steady state Jacobian is then for  $i > 1$  given by

$$\bar{J}_{ij} = \frac{\partial z_i}{\partial x_j} = \frac{\partial f_i}{\partial x_j} + \frac{\partial f_i}{\partial d_i} \frac{\partial d_i}{\partial x_j} = \frac{\partial f_i}{\partial x_j} + \frac{\partial f_i}{\partial d_i} \left( \frac{\partial d_i}{\partial a_i} \frac{\partial a_i}{\partial x_j} + \frac{\partial d_i}{\partial d_{i-1}} \frac{\partial d_{i-1}}{\partial x_j} \right) \quad (57)$$

$$= \frac{\partial f_i}{\partial x_j} + \frac{\partial f_i}{\partial d_i} \sum_k^{T-j} \frac{\partial d_i}{\partial d_k} \frac{\partial d_k}{\partial a_k} \frac{\partial a_k}{\partial x_j} = \frac{\partial f_i}{\partial x_j} + \sum_k^{T-j} \frac{\partial f_i}{\partial a_k} \frac{\partial a_k}{\partial x_j}, \quad (58)$$

which is a  $n$ -by- $n$  matrix.

Recall that the function  $F_a(\cdot)$  from Eqn. (22) is defined on the complete sequence  $\mathbf{x}$ . We can calculate the Jacobian with respect to  $x_{T-1}$  by stacking the JVPs of the transpose of the last  $n$  vectors of the standard basis of  $\mathbb{R}^{(T-1)n}$ :

$$\bar{J}_{x_{t-1} \rightarrow \mathbf{a}} = \begin{bmatrix} \Lambda_{F_a}(\bar{\mathbf{x}}, \mathbf{e}_{(T-1)}^\top)^\top \\ \Lambda_{F_a}(\bar{\mathbf{x}}, \mathbf{e}_{(T-1)2}^\top)^\top \\ \vdots \\ \Lambda_{F_a}(\bar{\mathbf{x}}, \mathbf{e}_{(T-1)(n-1)}^\top)^\top \\ \Lambda_{F_a}(\bar{\mathbf{x}}, \mathbf{e}_{(T-1)n}^\top)^\top \end{bmatrix}^\top = \begin{bmatrix} \frac{\partial a_0}{\partial x_{T-1}} \\ \frac{\partial a_1}{\partial x_{T-1}} \\ \vdots \\ \frac{\partial a_{T-2}}{\partial x_{T-1}} \\ \frac{\partial a_{T-1}}{\partial x_{T-1}} \end{bmatrix}^\top = \begin{bmatrix} \frac{\partial a_0}{\partial x_{T-1}} \\ \frac{\partial a_0}{\partial x_{T-2}} \\ \vdots \\ \frac{\partial a_0}{\partial x_1} \\ \frac{\partial a_0}{\partial x_0} \end{bmatrix}^\top = \bar{J}_{\mathbf{x} \rightarrow a_0}, \quad (59)$$

where the equivalence in the second step holds because in the steady state we have  $\frac{\partial a_0}{\partial x_k} = \frac{\partial a_l}{\partial x_{k+l}}$  for any  $l$ . Note that the calculation of this object requires only  $n$  evaluations of  $F_a(\cdot)$ .

Similarly, the Jacobian  $\bar{J}_{\mathbf{a} \rightarrow z_{T-1}}$  of  $z_{T-1}$  (i.e. the last output element of  $F_x$ ) w.r.t. the sequence  $\mathbf{a}$  can be evaluated by using reverse mode automatic differentiation:

$$\bar{J}_{\mathbf{a} \rightarrow z_{T-1}} = \begin{bmatrix} \Gamma_{F_x \circ F_d}(\bar{\mathbf{x}}, \mathbf{e}_{(T-1)}) \\ \Gamma_{F_x \circ F_d}(\bar{\mathbf{x}}, \mathbf{e}_{(T-1)2}) \\ \vdots \\ \Gamma_{F_x \circ F_d}(\bar{\mathbf{x}}, \mathbf{e}_{(T-1)(n-1)}) \\ \Gamma_{F_x \circ F_d}(\bar{\mathbf{x}}, \mathbf{e}_{(T-1)n}) \end{bmatrix} = \begin{bmatrix} \frac{\partial z_{T-1}}{\partial a_0} \\ \frac{\partial z_{T-1}}{\partial a_1} \\ \vdots \\ \frac{\partial z_{T-1}}{\partial a_{T-2}} \\ \frac{\partial z_{T-1}}{\partial a_{T-1}} \end{bmatrix}^\top = \begin{bmatrix} \frac{\partial z_{T-1}}{\partial a_0} \\ \frac{\partial z_{T-2}}{\partial a_0} \\ \vdots \\ \frac{\partial z_1}{\partial a_0} \\ \frac{\partial z_0}{\partial a_0} \end{bmatrix}^\top = \bar{J}_{a_0 \rightarrow \mathbf{y}}, \quad (60)$$

which, as above, uses the fact that  $\frac{\partial z_k}{\partial a_0} = \frac{\partial z_{k+l}}{\partial a_l}$  in steady state. Note again that independently of the complexity of the functions  $F_x$  and  $F_d$  this requires only  $n$  evaluations of  $F_x \circ F_d$ .

Finally, initialize a helper matrix  $\hat{J}$  with the tensor (outer) product  $J(\bar{\mathbf{x}})_{\mathbf{a} \rightarrow z_{T-1}} \otimes$

$J(\bar{\mathbf{x}})_{x_{t-1} \rightarrow \mathbf{a}}$  and add  $\frac{\partial f}{\partial x_t}$  to  $\hat{J}_{T-1, T-1}$ ,  $\frac{\partial f}{\partial x_{t+1}}$  to  $\hat{J}_{T-1, T-2}$  and  $\frac{\partial f}{\partial x_{t-1}}$  to  $\hat{J}_{T-2, T-1}$ . Then

$$\hat{J} = \begin{bmatrix} \frac{\partial z_{T-1}}{\partial a_0} \frac{\partial a_0}{\partial x_{T-1}} & \dots & \frac{\partial z_{T-1}}{\partial a_0} \frac{\partial a_0}{\partial x_1} & \frac{\partial z_{T-1}}{\partial a_0} \frac{\partial a_0}{\partial x_0} \\ \vdots & \ddots & \vdots & \vdots \\ \frac{\partial z_1}{\partial a_0} \frac{\partial a_0}{\partial x_{T-1}} & \dots & \frac{\partial z_1}{\partial a_0} \frac{\partial a_0}{\partial x_1} & \frac{\partial f}{\partial x_{t-1}} + \frac{\partial z_1}{\partial a_0} \frac{\partial a_0}{\partial x_0} \\ \frac{\partial z_0}{\partial a_0} \frac{\partial a_0}{\partial x_{T-1}} & \dots & \frac{\partial f}{\partial x_{t+1}} + \frac{\partial z_0}{\partial a_0} \frac{\partial a_0}{\partial x_1} & \frac{\partial f}{\partial x_t} + \frac{\partial z_0}{\partial a_0} \frac{\partial a_0}{\partial x_0} \end{bmatrix} = \begin{bmatrix} \frac{\partial z_{T-1}}{\partial x_{T-1}} & \dots & \frac{\partial z_{T-1}}{\partial x_0} \\ \vdots & \ddots & \vdots \\ \frac{\partial z_1}{\partial x_{T-1}} & \dots & \frac{\partial f}{\partial x_t} + \frac{\partial z_0}{\partial x_0} \end{bmatrix}, \quad (61)$$

and  $\bar{J}$  can be expressed as the recursion over its block components

$$\bar{J}_{ij} = \bar{J}_{i-1, j-1} + \hat{J}_{T-i, T-j} = \sum_{k=0}^{\min\{i, j\}} \hat{J}_{T-i+k, T-j+k}, \quad (62)$$

which corresponds to the expression in Eqn. (57) and therefore yields  $\bar{J}$  for only  $n$  evaluations of  $F_a$ ,  $F_d$  and  $F_x$  each.

## 4 Conceptual Approach and Implementation

The methods used in macroeconomics in general, and in particular the methods presented in this paper, have reached a degree of complexity that not only requires expert knowledge on numerical methods but also on computational and programming tools. Two implications follow from this insight: First, for a methodological contribution to be useful for the general economics community it is important to provide high-level reference implementations that do not require expert computational knowledge. Such a high-level implementation is a program with strong abstraction from the computational details of the implementation. Second, it calls for a design of software that is comprehensible and extensible, but yet allows for reproducible research that can be conducted efficiently.

This section discusses these design and implementation requirements in detail. The methodological contributions of this paper are implemented in the *econpizza* software package, which I propose as a blueprint to address these issues. Together with the package, I suggest a generic high-level syntax to express heterogeneous agent models, which is presented thereafter. I then give speed benchmarks for the reference implementation. Concrete details on the *econpizza* software – including guides and tutorials – are redirected to the extensive online documentation of the package.<sup>12</sup>

### 4.1 Design choices, open-source software, and the importance of reusable code

The reference implementation addresses five requirements, which I regard as central for the future progress of macroeconomic research:

- i.) Strict separation between the input representing the economic model, the code of the solution routines, and routines for economic analysis.
- ii.) Adherence to the open-source paradigm.
- iii.) Integration in a modern software development workflow.

<sup>12</sup>The online documentation can be found at <https://econpizza.readthedocs.io>.



- iv.) Maintenance of a high-level information flow between the user and the software.
- v.) Use of a module-oriented programming language that fully supports the functional programming paradigm.

Point i.) is consequential because the reusability of code is only given if numerical solution routines can be separated from the model, so that these routines can be used as a software library *across* models easily. Macroeconomic research is currently struggling with issues of insufficient replicability of numerical work. It can not be assumed that journal referees have the time budgeted or the ability to check and verify the large amounts of codes that are necessary for a single contemporary research project. A path to mitigate this problem is to use standardized and reusable code and software packages instead of relying on large blobs of user-written routines. To this end, the *econpizza* package not only provides a high-level library for solving heterogeneous agent models, but also implements a syntax to generically represent heterogeneous agent models, which is discussed further below.

Point ii.) is important because with the increase of complexity of numerical methods, their performance more and more also depends on their implementation. This means that implementations should improve over time, must allow for corrections or usability enhancements, and should benefit from external computational advances. Although tempting, it is not a fruitful approach for PhD students and young scholars to write simulation programs from scratch. Rather, it makes sense to build and elaborate on an existing codebase. To allow this, the reference implementation is publicly developed on the version control platform GitHub, which allow users to suggest changes to the code, point out potential bugs, or to propose new functionalities. This is the fundamental concept behind open-source software.<sup>13</sup> Version control systems play a central role in modern software development and their use is widespread in other disciplines that rely on computationally intensive methods to an equal extend, such as physics and engineering.

Point iii.) is desirable because it helps to maintain a clean, working, and well-documented code base. To respect these requirements, the reference implementation employs tools for versioning (see above), automated unit testing, automatic code linting, and automated module documentations. Automated unit tests ensure that, after any changes, the publicly available code produces economically correct results.<sup>14</sup> Linting is an automated procedure to format code such that it adheres to official coding style guidelines. This greatly improves readability of code and thus supports extensibility and reproducibility.<sup>15</sup> Automated module documentation are webpages that are automatically generated from the documentation strings of classes and functions, which help to increase the transparency and traceability of the software.<sup>16</sup>

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<sup>13</sup>It is hence somewhat counterproductive, in the sense of points i and ii, to publish a blob of inseparable model, simulation, and analysis codes on a private website where they can not evolve over time.

<sup>14</sup>Unit testing is implemented through *pytest*, a widely used testing framework in Python, running in GitHub Actions. The latter is a free GitHub service that automatically employs the tests on a remote server whenever updates are pushed to the GitHub repository.

<sup>15</sup>In *econpizza*, automated linting is implemented through the *autopep8* package (which enforces the PEP 8 style guide) and pre-commit hooks. Such hooks are running automatically before code is uploaded to GitHub.

<sup>16</sup>Automated documentation for *econpizza* is implemented through *Sphinx*, a documentation generator widely used by the Python community, and employed on Read the Docs, which is an open-sourced free software documentation hosting platform used by many open-source projects.

Point iv.) is particularly important whenever some underlying low-level routines do not provide the expected results. As only a cursory understanding of the underlying implementation can be expected from the user, an insufficient information flow bears the risk of unintentional misuse and false results. This is in especially fatal if internal errors are not sufficiently propagated and communicated. For this reason it is crucial to implement reliable checks and informative warning and error messages for the underlying routines and potential pitfalls, as it is covered in the reference implementation.

Point v.) is crucial because it is very challenging to write (and maintain) code libraries written in languages with limited support for functional programming. For example, the Matlab software widely used in economics restricts the number of function definition per file to one, and function definitions do not allow for default arguments.<sup>17</sup> This complicates writing and sharing function libraries that are reusable across frameworks and models because the libraries quickly becomes intractable in size and functions are inflexible. Furthermore, a programming language should integrate well with versioning systems (such as, e.g., GitHub) and feature a straightforward packaging system.<sup>18</sup> For these reasons, the community has recently started to adapt free and open-source languages such as Python and Julia. In particular, Python is highly flexible, simple to use, and is well integrated into modern development workflows.<sup>19</sup> The reference implementation is written in Python using the JAX framework, which provides just-in-time compilation and automatic differentiation. Additional details on JAX are given further below.

#### 4.2 *A generic syntax to express heterogeneous agent models*

A fundamental design principle (cf. Point i.) above) of the econpizza package is to separate the input of the economic model (provided by the user), the underlying solution routines (the software package), and the economic analysis of the simulation outcomes. Using the formalization from Section 3, the necessary user input to describe a heterogeneous agent model can be reduced to two elements: the EGM step manifesting in the function  $W(\cdot)$  from Equation (19) and the  $n$  aggregate equations in  $f(\cdot)$  from Equation (21). In contrast, it is typically not necessary to explicitly specify the mapping from agents' decisions to the distribution,  $D(\cdot)$ , from (20) since this function is generic and standard routines such as, e.g., the lottery method of Young (2010) can be used.

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<sup>17</sup>A default argument is an argument to a function that a programmer is not required to specify because a default value is provided.

<sup>18</sup>A packaging system allows to easily install additional modules/packages which provide specific functions and classes. Python and R, and more recently also Julia, have very rich ecosystem of packages for a large variety of applications, the large majority of which are well-tested and developed in the public domain. The econpizza package can be directly installed via the official Python repositories.

<sup>19</sup>Python is an object-oriented general purpose language used in a large field of applications. It is the de-facto industry standard in data science and machine learning and supported by mayor big-tech firms. Python is free and open source with no limiting licences or additional costs, has a huge active user base and its design simplicity allows for a high code quality.

---

```

# EGM stage: marginal values & decisions
decisions:
  inputs: [WaPrime,WbPrime]
  calls: |
    z_grid = income(skills_grid, tax, w, n, transfers)
    Psi = marginal_cost_grid(a_grid, Ra-1, psi_a0, psi_a1, psi_a2)
    WaPrimeExp = expect_transition(skills_transition, WaPrime)
    WbPrimeExp = expect_transition(skills_transition, WbPrime)
    Wa, Wb, a, b, c, uce = egm_step(WaPrimeExp, WbPrimeExp, a_grid, b_grid, z_grid, skills_grid, kappa_grid, \
      beta, sigma_c, Rb-1, Ra-1, psi_a0, psi_a1, psi_a2, Psi)
  outputs: [a,b,c,uce]

# intermediate stage: aggregation
aux.equations: |
  # calculate asset share of top-10%
  top10a = 1 - percentile(a, dist, .9)
  # aggregation
  UCE = sum(dist*uce, axis=(0,1,2))
  ...

# main stage: aggregate equations
equations:
  ~ psi_w*(piwn/piwntilde - 1)*piwn/piwntilde = wage_markup/(wage_markup-1)*chi*n**(1+sigma_l) + \
    1/(1-wage_markup)*(1 - tax)*w*n*UCE + \
    psi_w*beta*(piwnPrime/piwntildePrime - 1)*piwnPrime/piwntildePrime # wage Phillips curve
  ~ piwn = wn/wnLag*pi # wage inflation
  ~ w = max(iota*wLag/pi, wn) # downwards nominal wage rigidity

  ~ div = (1 - psi_p/2*(pi/pitilde - 1)**2)*y - w * n - i # dividends
  ~ Rb = Rr - zeta # real bond returns
  ~ Ra = assetshareLag * (div + equity) / equityLag + (1 - assetshareLag) * Rr # real asset returns
  ...

```

---

Figure 1: Part of the YAML-file which specifies the two-asset HANK from 2. The block `decisions` represents the function  $W(\cdot)$  which depends on  $w_{t+1}$  (here: `WaPrime` and `WbPrime`) and aggregate variables such as wages `w`, labor hours `n`, and parameters such as  $\sigma_c$  (here `sigma_c`). The outputs are disaggregated savings  $a_{it}$  and  $b_{it}$ , consumption  $c_{it}$  and marginal utilities. The equations block shows the first aggregate equations starting with Equation (7).

The reference implementation provides a simple syntax for expressing heterogeneous agent models, which is based on the widely used YAML format.<sup>20</sup> Similar as the mod-file in Dynare, the YAML allows to specify variables and parameters as well as meta-parameters such as, e.g., the grids used to represent the distribution of idiosyncratic states across agents. Importantly, the YAML permits a standardized way to specify the function  $W(\cdot)$  including its inputs and outputs. This is illustrated in Figure 1 (key: “`decisions`”) for a part of the specification of the one-asset-HANK model from Appendix B. Subfunctions of  $W(\cdot)$  (e.g. the function `egm_step`) can be described as a conventional Python function that is defined in an external functions file and referenced in the YAML. In the example, `Wa` and `Wb` are the recursive decision object  $w_t$  from Section 3.1 while `a,b,c,uce` are the agents actions in  $a_t$ .

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<sup>20</sup>YAML stands for “Yet Another Markup Language” and is a human-readable data-serialization language. YAML is similar to the Extensible Markup Language (XML) but has a minimal syntax in order to be easily usable. It is useful to provide data input in a clear and simple way.

The figure further shows a part of the system of aggregate equations (“equations”), which constitute the function  $f(\cdot)$ .<sup>21</sup> Together with the specification of  $W(\cdot)$ , this allows the combination of the disaggregated parts of various heterogeneous agents models with arbitrary systems of aggregate equations. Additionally, the file further allows to stage parameter values and the inputs required for the steady state search (not shown in the figure).

### 4.3 Speed benchmarks

The implementation in the econpizza package heavily leverages on just-in-time (“jit”) compilation via the Python framework JAX. JAX is an open-source machine learning framework developed by Google which supports high-level automatic differentiation and jitting while providing the same syntax as NumPy, which is the primary Python library for numerical computing. The execution speed of JAX-jitted functions is en-par with execution speed of compiled code from languages as Fortran or C.

| Model              | tentative |            | full   |            |
|--------------------|-----------|------------|--------|------------|
|                    | once      | subsequent | once   | subsequent |
| RANK               | 2.289     | 0.104      | 2.392  | 0.160      |
| HANK1              | 13.408    | 1.020      | 17.494 | 3.0678     |
| HANK2 (no capital) | 30.722    | 1.435      | 62.120 | 8.927      |
| HANK2              | 33.881    | 1.177      | 79.496 | 6.836      |

Table 1: Speed benchmarks for the three models provided in Appendix B. All numbers are in seconds. The HANK2 model without capital is the small-scale HANK model with two assets as described in Section 5.3.

Table 1 provides speed benchmarks for the four baseline models presented in Appendix B.<sup>22</sup> Note that RANK models are not solved using the method from Section 3 but rely on a simpler procedure that exploits the block tridiagonal structure of the sequence space Jacobian, which is outlined in Appendix A. The simulations listed under “tentative” use a truncation horizon of 150 (vs. 300 for “full”) and a slightly smaller grid (50 grid points for the asset grid of the HANK1 model and 10 and 20 grid points for the liquid and illiquid assets in the HANK2 models) than reported in Appendix B. The simulation results from these tentative simulations are very similar to the results obtained when using the full grid as specified in Appendix B.

The table documents a large speed difference between the first simulation (“once”) and each successive simulation (“subsequent”). Subsequent simulations allow to use different shocks, initial conditions, or parameters that do not alter the steady state. These simulations are much faster for two reasons. First, for each new steady state the steady state sequence space Jacobian must be recomputed including its LU decomposition. The computational load of the Jacobian and the LU decomposition vary substantially with the length of the truncation horizon. Second, the model functions must be compiled

<sup>21</sup>For example, expressing the aggregate relationships in  $f(\cdot)$  is, in its core, what the “model” block in Dynare’s mod-file does.

<sup>22</sup>All benchmarks are done on a laptop with 8 Intel(R) Core(TM) i7-8650U CPUs (1.90GHz). The package does not make explicit use of parallel computing.

(which is done automatically by JAX). Both steps are not necessary if the steady state remains unaltered when the objects can simply be reused.

Runtimes of the RANK model are much faster since solving the RANK model does not require the calculation of the steady state Jacobian and its LU decomposition. Additionally, automatic differentiation does not have to traverse through the distribution and value functions. Comparing the HANK1 model to the HANK2 model, calculation and compilation times roughly double while the number of grid points remains roughly the same. This hints that the setup of the two-asset model is per-se more complicated to calculate and hence obtaining the derivatives is more challenging. Further, calculation and compilation times of the medium-scale HANK2 model with capital compared to the small-scale HANK2 model without capital are only marginally larger although the complexity of the aggregate system of equations of the medium-scale model is considerably larger than the complexity of the small scale model. Since the disaggregated problem is exactly the same for both models, this suggests that the complexity of the aggregated system of equations is of second order importance for the computational complexity.

## 5 Nonlinear Transition Dynamics

A key feature of models with heterogeneous households is that they allow to study the dynamic effects of government transfers, taxes, and redistribution over the cross-sectional distribution of households and business cycle aggregates. This section applies the proposed methodology to study the nonlinear transition dynamics of a permanent change in government redistribution policy. I first discuss the dynamic responses of a change in steady state transfers. I then study the effects of two severe nonlinearities on the transition dynamics, the first being downwards nominal wage rigidity and the second being the zero lower bound on nominal interest rates. Finally, I analyse the role of the distribution of wealth for the transmission of policy shocks. To allow for a realistic account of the distribution of assets while being en-par with the business cycle literature, simulations in this section are based on the two-asset HANK model from Section 2.

### 5.1 *A permanent increase in government redistribution*

Assume a permanent increase in government transfers from zero to 10% of GDP. After announcement, the government gradually increases the volume of transfers with an autocorrelation of  $\rho_T = 0.8$ . Since the government is running a balanced budget, the labor tax rate must adjust simultaneously and the policy thus redistributes income of high labor income earners to those with low labor income. Importantly, this permanent shift in transfers and taxes implies the transition from one steady state to another.

Before looking at the dynamics it is useful to study and compare the two steady states in detail. Figure 2 shows the stationary distribution of assets in the steady state without redistribution. The distribution is bimodal: the majority of agents holds a fair amount of assets and bonds, where agents with many bonds tend to hold fewer assets and vice versa. Roughly one-third (34.3%) of all agents do not hold any bonds but yet a considerable volume of assets. These are the famous wealthy hand-to-mouth households of Kaplan et al. (2018). These households have experienced a series of negative income shocks and thus depleted their stock of liquid bonds. Since they only hold illiquid bonds and liquidations of these bonds are subject to portfolio adjustment cost, they face limited insurance and have a higher marginal propensity to consume out of income.

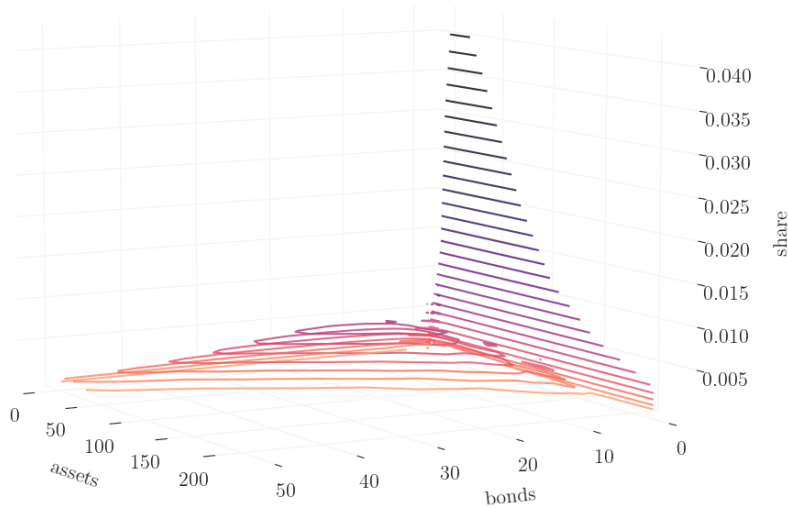


Figure 2: The stationary distribution of the heterogeneous agent New Keynesian model with two-assets. Note that for the sake of clearer display, quantities are given as shares of nodes on a log-grid (rather than true densities), meaning that shares for larger values on the grid are overrepresented.

Table 2 presents the redistributive steady state relative to the steady state without redistribution. Clearly, the distorting effect of the necessary additional 20% in labor tax rate is massive. Production in the new steady state is more than ten percent below the old level, with the capital stock almost 20% below the previous level and an accompanying decline in real wages. The fall in output reflects in lower dividends and an associated drop in equity. Since households are better insured through the new system of government transfers, the demand for liquid bonds falls by almost 50%. Since poor households wish to insure less, inequality as measured by top-10-percentiles increases for both types of assets while it falls slightly for consumption.

|                | relative change |                           | relative change |
|----------------|-----------------|---------------------------|-----------------|
| output         | -11.1%          | top-10% share assets      | +8.1%           |
| wages          | -1.8%           | top-10% share bonds       | +11.8%          |
| labor hours    | -9.4%           | top-10% share consumption | -3.7%           |
| capital        | -17.5%          | assets                    | -21.6%          |
| consumption    | -11.6%          | bonds                     | -43.5%          |
| interest rates | +0.27%          | equity                    | -26.8%          |
| dividends      | -7.6%           | tax rate                  | +20.2%          |

Table 2: Difference of the steady states with redistribution relative to the old steady state without redistribution.

Turn next to the aggregate dynamic effects of such policy. As we have seen in Table 2, the new steady state comes with a higher real interest rate because with higher lump-sum transfers, the households wish less insurance and thus demand higher bond and asset returns. The central bank leaves the inflation target unchanged but immediately adjusts

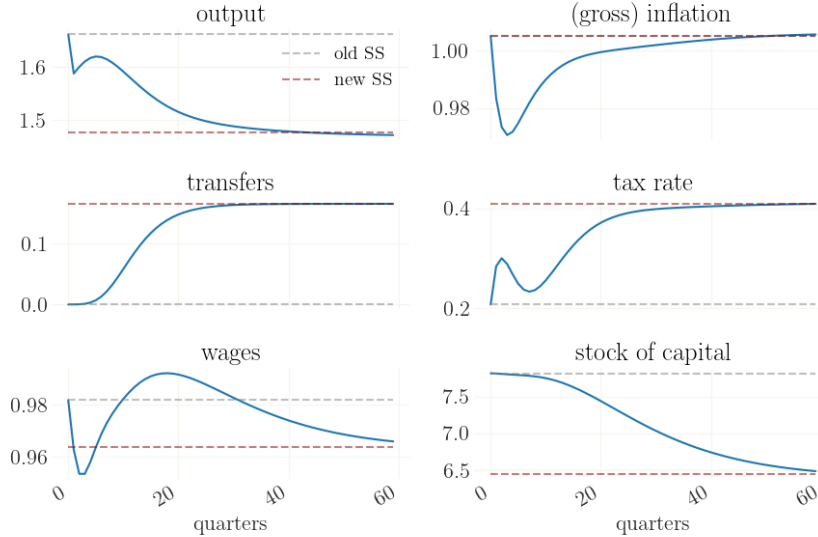


Figure 3: Nonlinear transition dynamics for a permanent increase in government transfers. All measures are given in levels. Interest and inflation rates are given in quarterly gross-rates. The dashed gray and red lines represent the old steady state without and with redistribution, respectively.

its target rate to the new steady state real rate. Yet, the adjustment of the nominal rate is gradual due to interest rate smoothing.

Figures 3 and 4 show the aggregate dynamics. Most centrally, after the announcement of the new policy firms strive to downsize their capital stock. They wish to do so smoothly due to the presence of capital adjustment costs, resulting in a relatively high ratio of capital to output and a fall of the marginal productivity of capital. The firms' new choice of optimal factor inputs then leads to a dampening of labor demand and causes wages to decrease, leading to a decline in marginal costs and inflation. Monetary policy responds with lowering the nominal interest rate to stimulate consumption. When the increase in transfers gains momentum, so does the surge in the labor tax rate. Consequently, pre-tax wages increase which, in turn, stimulates inflation. This effect is, however, dampened by price and wage inertia.

Firms reduce their capital stock by distributing disproportionately large dividends and, consequently, dividends fluctuate around their old level for an extended period of time. However, the anticipation of lower dividends in the future causes a large contraction in the volume of equity which leads to a crash in the asset market that is reflected by a massive one-time devaluation of assets. While the transition to the new system of transfers is by large completed after 20 quarters (i.e. five years), the response of the economy shows a high degree of persistence. As such, the new level of the capital stock and the new wage rate is only reached after about 60 quarters or, respectively, 15 years.

Figure 5 shows the transition dynamics of the distribution of assets. Wealthy households experience the announcement of the new policy as a strong negative news shock. The large change in the expected flow of future dividends triggers an ample change in

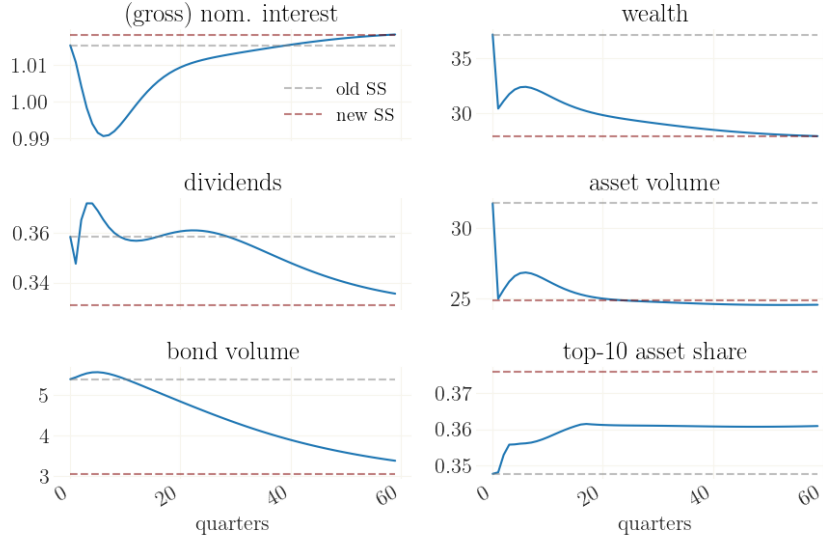


Figure 4: Nonlinear transition dynamics for a permanent increase in government transfers. All measures are given in levels. Interest and inflation rates are given in quarterly gross-rates. The dashed gray and red lines represent the old steady state without and with redistribution, respectively.

the volume of equity, which causes assets to devalue heavily. This destroys a considerable amount of wealth in the economy and the weak positive effect of a larger return to assets due to higher dividend payments can not offset this effect. Consequently, the finding that the new steady state supply of assets is significantly below the old steady state (c.f. Table 2) reflects in a shrinkage of the tail-mass of the distribution over time, as documented in Figure 5. This effect – the convergence of the distribution – is considerably slower than the convergence of aggregate variables. This can also be seen when converging the convergence speed of inequality dynamics in asset holdings as measured in top-10-percentiles in Figure 4.

## 5.2 The role of DNWR and the ZLB during transition

The presence of strong nonlinearities such as the zero lower bound (ZLB) on nominal interest rate and downwards nominal wage rigidity (DNWR) can have large effects on the transition dynamics. At the ZLB, the central bank is reluctant to set the nominal rate below zero to avoid that households start hoarding cash. DNWR implies that, either due to regulatory reasons or for incentive considerations, firms are unable to lower *nominal* wages below a certain threshold. Both are known to pose severe challenges to numerical solution techniques.

Figure 6 again shows the transition dynamics after the announced gradual and permanent increase in transfers from the previous subsection. The gray dashed line is the same as in Figures 3 and 4 where I abstract from the ZLB and DNWR. The blue line shows responses where the ZLB is present and active. The dynamic effects of the ZLB are qualitatively quite similar to those implied by a representative agent model with the



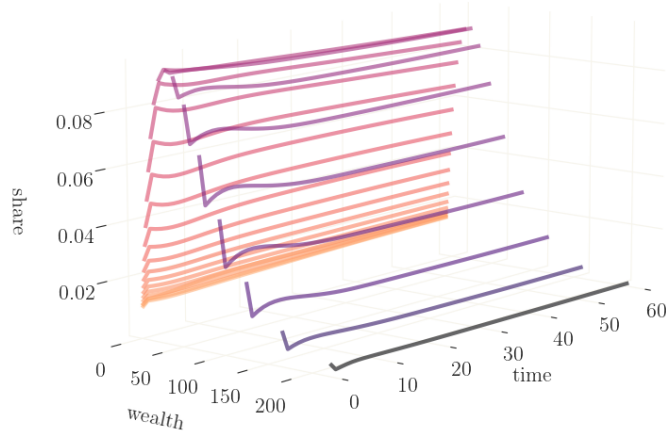


Figure 5: Nonlinear transition dynamics of the distribution of illiquid asset for a permanent increase in government transfers. Each line presents the transition over time of the share associated with one grid node, meaning that the shares of larger grid values are overrepresented.

ZLB: since the central bank can no longer respond and stimulate the economy by decreasing the real rate, consumption falls. Households are willing to accept lower wages because the marginal utility of consumption increases. The associated fall in marginal costs leads to an additional drop in inflation which causes a further increase in the real rate. The response of inequality – as measured by top percentiles – is striking: both measures double in the initial spike relative to the scenario without the ZLB. Clearly, only the wealthy benefit from relatively higher interest rates while the lack of an additional monetary stimulus harms those households with low net worth.

The orange line in Figure 6 shows simulations where nominal wages are downward-rigid (DNWR). The setup is calibrated to allow wages to fall by a maximum of 2% quarterly, which corresponds to realistic estimates. The constraint keeps wages from falling in the beginning of the transition period, which in turn dampens the response of inflation. While this has some negative impact on output during the transition phase, the overall effects are rather moderate compared to the simulations with ZLB.

### 5.3 The role of the distribution for the transition of shocks

As a final exercise, let me focus on the role of the distribution of wealth for the transmission of transitory shocks, i.e. to one-time shocks without any persistence. For this purpose, let me simplify the setup considerably by abstracting from capital (i.e.,  $\alpha = 0$ ), labor unions ( $\psi_w = 0$ ) and price and wage indexation ( $\omega_p = \omega_w = 0$ ). Additionally, I set the interest rate smoothing parameter  $\rho$  to zero. The model then collapses to the two-asset HANK pendant of the canonical 3-equation model and all persistence in response to economic shocks comes from temporary shifts in the distribution of wealth.

Consider again a one-time transfer of the size of 10% of GDP. As before, the government runs a balanced budget and the increase in transfers must be compensated by an increase in taxes. By assumption, all taxes in the model are labor taxes and the shock can thus right away be interpreted as a redistribution shock. Figure 7 shows the impulse

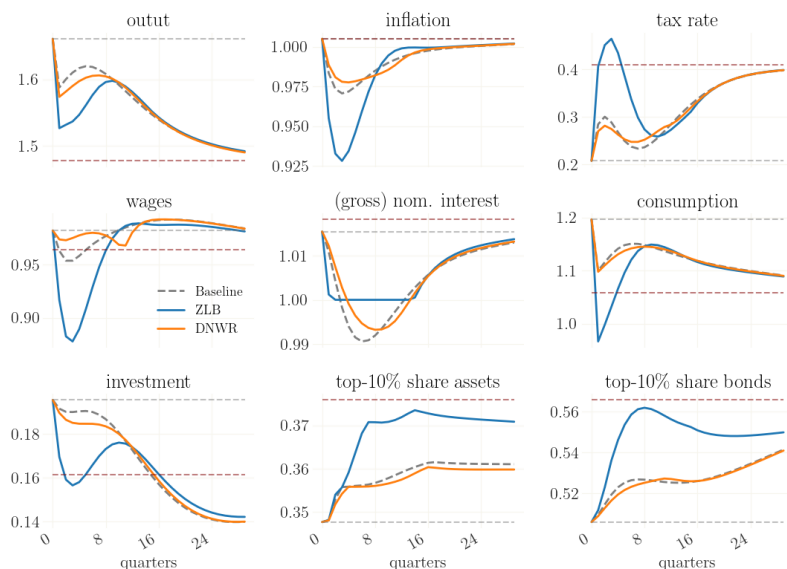


Figure 6: Nonlinear transition dynamics for a permanent increase in government transfers. The blue and orange lines show the transition dynamics with an active ZLB and DNWR, respectively. Both are inactive for the dashed black line. All measures are given in levels. Interest and inflation rates are given in quarterly gross-rates. The dashed gray and red lines represent the old steady state without and with redistribution, respectively.

responses to such redistributive shock. When taxes increase, households see their after-tax income decreasing and respond by lowering their labor supply. To counteract this, firms have to increase pre-tax wages. The increase in the tax rate thus acts like a classic distortionary wedge between supply and demand, causing hours worked and output to decline.

Additionally, the increase in real wages triggers an increase in prices, thereby causing inflation. This is different to the previous results since the effect coming from the depletion of the capital stock is absent in this model. The central bank reacts instantaneously by raising the nominal (and real) interest rate, which in turn causes two effects. First, the government has to further increase taxes to finance the higher interest payments on government debt. Second, the increase in the real rate triggers an increase in savings. Since dividends are falling due to lower revenues and higher costs, the return on assets falls and bonds become relatively more attractive than assets. Correspondingly the total volume of bonds increases while asset demand falls. However, the effect of lower dividends on equity causes aggregate wealth to decline overall.

Since the effect of the shock is short lived, the inequality effects of this measure are of second order. Households with a larger share of assets lose a small fraction of their wealth due to the fall in dividends. Since the transfer is only transitory, less productive households with no liquid assets save parts of their transfer. Overall, this causes a slight increase in inequality in asset holdings (top-10% hold more) and a slight decrease in inequality in bond holdings (top-10% hold less). Households are slowly melting off their

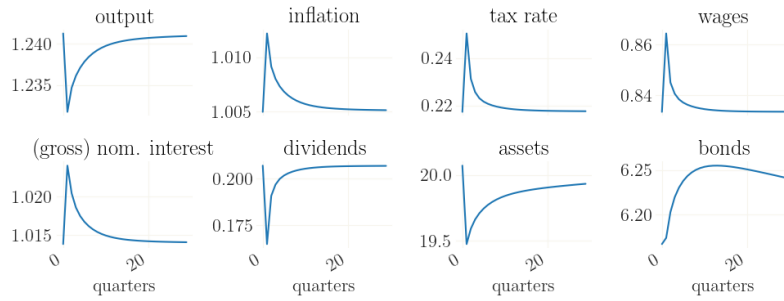


Figure 7: Nonlinear impulse responses to a one-time increase in government transfers. All measures are given in levels. Interest and inflation rates are given in quarterly gross-rates.

excess savings after the one-time transfer.

## 6 Conclusion

This paper introduces an iterative method to find nonlinear solutions to macroeconomic models with heterogeneous agents. The method is based on Newton iterations and leverages the technique of automatic differentiation. I provide an easy-to-use reference implementation and suggest a series of central requirements of such an implementation. These are, among others, the consequent separation of economic model, solution code, and analysis, the generation of reusable code (across models), and adherence to the open-source philosophy.

The solution method is applied to study the nonlinear transition dynamics of a gradual but permanent change in government redistribution. The overall effects of such policy, both in the short and in the long run, are contractionary and can be aggravated by strong nonlinearities such as a lower bound on interest rates or downwards nominal wage rigidity.

The method draws two potential paths for future research: first, further advancements in the standardization of representing economic models are desirable. Second, the application of techniques from machine learning – such as automatic differentiation and deep learning – is a promising path forward to solve nonlinear heterogeneous agent models with *aggregate* uncertainty and while avoiding the curse of dimensionality.

## References

- Algan, Y., Allais, O., Den Haan, W.J., 2008. Solving heterogeneous-agent models with parameterized cross-sectional distributions. *Journal of Economic Dynamics and Control* 32, 875–908.
- Auclert, A., Bardóczy, B., Rognlie, M., Straub, L., 2021. Using the sequence-space jacobian to solve and estimate heterogeneous-agent models. *Econometrica* 89, 2375–2408.
- Azinovic, M., Gaegauf, L., Scheidegger, S., 2022. Deep equilibrium nets. *International Economic Review* 63, 1471–1525.
- Bayer, C., Born, B., Luetticke, R., 2020. Shocks, Frictions, and Inequality in US Business Cycles. CEPR Discussion Papers 14364.
- Bianchi, F., Melosi, L., Rottner, M., 2021. Hitting the elusive inflation target. *Journal of Monetary Economics* 124, 107–122.
- Boehl, G., 2022. An Ensemble MCMC Sampler for Robust Bayesian Inference. Available at SSRN 4250395.
- Boppart, T., Krusell, P., Mitman, K., 2018. Exploiting mit shocks in heterogeneous-agent economies: the impulse response as a numerical derivative. *Journal of Economic Dynamics and Control* 89, 68–92.
- Calvo, G.A., 1983. Staggered prices in a utility-maximizing framework. *Journal of Monetary Economics* 12, 383–398.
- Carroll, C.D., 2006. The method of endogenous gridpoints for solving dynamic stochastic optimization problems. *Economics letters* 91, 312–320.
- Fair, R.C., Taylor, J.B., 1980. Solution and Maximum Likelihood Estimation of Dynamic Nonlinear Rational Expectations Models. Technical Report. National Bureau of Economic Research.
- Fernández-Villaverde, J., Hurtado, S., Nuno, G., 2023. Financial frictions and the wealth distribution. *Econometrica* 91, 869–901.
- Gust, C., Herbst, E., López-Salido, D., Smith, M.E., 2017. The empirical implications of the interest-rate lower bound. *American Economic Review* 107, 1971–2006.
- Gust, C.J., Herbst, E.P., López-Salido, J.D., Smith, M.E., 2012. The Empirical Implications of the Interest-Rate Lower Bound. Technical Report. Board of Governors of the Federal Reserve System (US).
- Hintermaier, T., Koeniger, W., 2010. The method of endogenous gridpoints with occasionally binding constraints among endogenous variables. *Journal of Economic Dynamics and Control* 34, 2074–2088.
- Juillard, M., Laxton, D., McAdam, P., Pioro, H., 1998. An algorithm competition: First-order iterations versus newton-based techniques. *Journal of Economic Dynamics and Control* 22, 1291–1318.

- Juillard, M., et al., 1996. Dynare: A program for the resolution and simulation of dynamic models with forward variables through the use of a relaxation algorithm. volume 9602. Citeseer.
- Kahou, M.E., Fernández-Villaverde, J., Perla, J., Sood, A., 2021. Exploiting symmetry in high-dimensional dynamic programming. Technical Report. National Bureau of Economic Research.
- Kaplan, G., Moll, B., Violante, G.L., 2018. Monetary policy according to HANK. NBER Working Papers 3. National Bureau of Economic Research, Inc. URL: <https://ideas.repec.org/p/nbr/nberwo/21897.html>.
- Klenow, P.J., Kryvtsov, O., 2008. State-dependent or time-dependent pricing: Does it matter for recent us inflation? *The Quarterly Journal of Economics* 123, 863–904.
- Laffargue, J.P., 1990. Résolution d’un modèle macroéconomique avec anticipations rationnelles. *Annales d’Economie et de Statistique*, 97–119.
- Lindé, J., Trabandt, M., 2018. Should we use linearized models to calculate fiscal multipliers? *Journal of Applied Econometrics* 33, 937–965.
- Maliar, L., Maliar, S., Winant, P., 2021. Deep learning for solving dynamic economic models. *Journal of Monetary Economics* 122, 76–101.
- Mises, R., Pollaczek-Geiringer, H., 1929. Praktische verfahren der gleichungsauflösung. *ZAMM-Journal of Applied Mathematics and Mechanics/Zeitschrift für Angewandte Mathematik und Mechanik* 9, 58–77.
- Petrosky-Nadeau, N., Zhang, L., Kuehn, L.A., 2018. Endogenous disasters. *American Economic Review* 108, 2212–45.
- Reiter, M., 2009. Solving heterogeneous-agent models by projection and perturbation. *Journal of Economic Dynamics and Control* 33, 649–665.
- Rotemberg, J.J., 1982. Monopolistic price adjustment and aggregate output. *The Review of Economic Studies* 49, 517–531.
- Saad, Y., Schultz, M.H., 1986. Gmres: A generalized minimal residual algorithm for solving nonsymmetric linear systems. *SIAM Journal on scientific and statistical computing* 7, 856–869.
- Scheidegger, S., Bilonis, I., 2019. Machine learning for high-dimensional dynamic stochastic economies. *Journal of Computational Science* 33, 68–82.
- Smets, F., Wouters, R., 2007. Shocks and frictions in us business cycles: A bayesian dsge approach. *American Economic Review* 97, 586–606.
- Trimborn, T., Koch, K.J., Steger, T.M., 2008. Multidimensional transitional dynamics: a simple numerical procedure. *Macroeconomic Dynamics* 12, 301–319.
- Van der Vorst, H.A., 1992. Bi-cgstab: A fast and smoothly converging variant of bi-cg for the solution of nonsymmetric linear systems. *SIAM Journal on scientific and Statistical Computing* 13, 631–644.
- Winberry, T., 2018. A method for solving and estimating heterogeneous agent macro models. *Quantitative Economics* 9, 1123–1151.
- Young, E.R., 2010. Solving the incomplete markets model with aggregate uncertainty using the krusell-smith algorithm and non-stochastic simulations. *Journal of Economic Dynamics and Control* 34, 36–41.

## Appendix A Representative agent models and automatic differentiation

Analog to the representation in Section 3 for heterogeneous agent models, a representative agent model can simply be written as

$$\mathbf{0} = f(x_{t-1}, x_t, x_{t+1}). \quad (\text{A.1})$$

For simplicity, denote the three Jacobians of this function as

$$f_A(x) = \partial f / \partial x_{t-1}, \quad (\text{A.2})$$

$$f_B(x) = \partial f / \partial x_t, \quad (\text{A.3})$$

$$f_C(x) = \partial f / \partial x_{t+1}. \quad (\text{A.4})$$

For each  $f(x_{t-1}, x_t, x_{t+1}) = z_t$ , these three Jacobians can be obtained at low costs via backwards propagation with only  $n$  evaluations of  $f$ . Since  $\dim(z_t) = n \ll \dim(\mathbf{z}) =$



growth in steady state. The model features all the bells and whistles of the medium-scale workhorse model of Smets and Wouters (2007) but uses Rotemberg pricing instead of Calvo pricing. This model also forms the basis for the aggregate equations for the two HANK models.

#### *Households*

$$\Lambda_t = \frac{1}{c_t - hc_{t-1}} - \frac{h\beta_t}{E_t c_{t+1} - hc_t} \quad (\text{B.1})$$

$$\Lambda_t = \beta_t \epsilon_t^\Lambda E_t \left\{ \Lambda_{t+1} \frac{R_t}{\pi_{t+1}} \right\} \quad (\text{B.2})$$

$$d_t + c_t + \tau_t + \frac{\psi_w}{2} \left( \frac{\pi_t^w}{\tilde{\pi}_t^w} - 1 \right)^2 = w_t n_t + R_{t-1} / \pi_t d_{t-1} + \Pi_t + \Pi_t^b \quad (\text{B.3})$$

The last equation is the households budget constraint which not necessary for the aggregate dynamics due to Walras' law.

#### *Labor Unions*

$$\psi_w \left( \frac{\pi_t^w}{\tilde{\pi}_t^w} - 1 \right) \frac{\pi_t^w}{\tilde{\pi}_t^w} = \psi_w \beta_t E_t \left\{ \left( \frac{\pi_{t+1}^w}{\tilde{\pi}_{t+1}^w} - 1 \right) \frac{\pi_{t+1}^w}{\tilde{\pi}_{t+1}^w} \right\} + n_t \frac{\mu_t^w}{\mu_t^w - 1} (\chi n_t^{\sigma_l} - \Lambda_t w_t / \mu_t^w) \quad (\text{B.4})$$

$$\pi_t^w = \frac{w_t^n}{w_{t-1}^n} \pi_t \quad (\text{B.5})$$

$$\ln \tilde{\pi}_t^w = \omega_w \ln \bar{\pi}^w + (1 - \omega_w) \ln \pi_{t-1}^w \quad (\text{B.6})$$

$$w_t = \max \left\{ \iota_w \frac{w_{t-1}}{\pi_t}, w_t^n \right\} \quad (\text{B.7})$$

*Firms*

$$\psi \left( \frac{\pi_t}{\tilde{\pi}_t} - 1 \right) \frac{\pi_t}{\tilde{\pi}_t} = \frac{1}{1 - \mu_t} + \frac{\mu_t}{\mu_t - 1} mc_t + \psi E_t \left\{ \beta_{t+1} \frac{\Lambda_{t+1}}{\Lambda_t} \left( \frac{\pi_{t+1}}{\tilde{\pi}_t} - 1 \right) \frac{\pi_{t+1}}{\tilde{\pi}_t} \frac{y_{t+1}^f}{y_t^f} \right\} \quad (\text{B.8})$$

$$\ln \tilde{\pi}_t = \omega \ln \bar{\pi} + (1 - \omega) \ln \pi_{t-1} \quad (\text{B.9})$$

$$y_t^f = (u_t k_{t-1})^\alpha (z_t n_t)^{1-\alpha} \quad (\text{B.10})$$

$$k_t = (1 - \delta)k_{t-1} + \epsilon_t^i \left( 1 - \frac{\psi_i}{2} \left( \frac{i_t}{i_{t-1}} - 1 \right)^2 \right) i_t \quad (\text{B.11})$$

$$1 = q_t \epsilon_t^i \left( 1 - \frac{\psi_i}{2} \left( \frac{i_t}{i_{t-1}} - 1 \right)^2 - \psi_i \left( \frac{i_t}{i_{t-1}} - 1 \right) \frac{i_t}{i_{t-1}} \right) + \beta_t \epsilon_{t+1}^i \frac{\Lambda_{t+1}}{\Lambda_t} q_{t+1} \psi_i \left( \frac{i_{t+1}}{i_t} - 1 \right) \left( \frac{i_{t+1}}{i_t} \right)^2 \quad (\text{B.12})$$

$$q_{t-1} \frac{R_t}{\pi_{t+1}} = MPK_t u_t + (1 - \delta)q_t - C(u_{t-1}) \quad (\text{B.13})$$

$$w_t = (1 - \alpha) mc_t \frac{y_t^f}{n_t} \quad (\text{B.14})$$

$$MPK_t = \alpha mc_t \frac{y_t^f}{(u_t k_{t-1})} \quad (\text{B.15})$$

$$C(u_t) = M\bar{P}K(u_t - 1) + \frac{1}{2} \frac{\psi_u}{1 - \psi_u} (u_t - 1)^2 \quad (\text{B.16})$$

$$\psi_u (u_t - 1) = (1 - \psi_u)(MPK_t - M\bar{P}K) \quad (\text{B.17})$$

$$\Pi_t = \left( 1 - mc_t - \frac{\psi_p}{2} \left( \frac{\pi_t}{\tilde{\pi}_t} - 1 \right)^2 \right) y_t^f - \left( 1 - q_t \left( 1 - \frac{\psi_i}{2} \left( \frac{i_t}{i_{t-1}} - 1 \right)^2 \right) \right) i_t \quad (\text{B.18})$$

*Financial sector*

$$d_t = q_t^b b_t + q_t k_t \quad (\text{B.19})$$

$$R_t = \frac{(1 + \kappa q_{t+1}^b)}{q_t^b} \quad (\text{B.20})$$

$$\Pi_t^b = ((1 + \kappa q_t^b) b_{t-1} + R_{t-1} q_{t-1} k_{t-1} - R_{t-1} d_{t-1}) / \pi_t \quad (\text{B.21})$$



*Government*

$$q_t^b b_t + \tau_t = g_t + \frac{(1 + \kappa q_t^b)}{\pi_t} b_{t-1} \quad (\text{B.22})$$

$$b_t = \frac{\bar{y}}{\bar{q}^b} \quad (\text{B.23})$$

$$\ln R_t^n = \rho \ln R_{t-1}^n + (1 - \rho) (\ln R_t^* + \phi_\pi [\ln \pi_t - \ln \bar{\pi}] + \phi_y [\ln y_t - \ln \bar{y}]) + \ln v_t \quad (\text{B.24})$$

$$R_t = \max \{1, R_t^n\} \quad (\text{B.25})$$

*Clearing conditions*

$$c_t + i_t + g_t + u_t k_{t-1} + \frac{\psi_w}{2} \left( \frac{\pi_t^w}{\bar{\pi}_t^w} - 1 \right)^2 = \left( 1 - \frac{\psi}{2} \left( \frac{\pi_t}{\pi_{ss}} - 1 \right)^2 \right) y_t^f \quad (\text{B.26})$$

$$c_t + i_t + g_t = y_t \quad (\text{B.27})$$

*Exogenous processes*

$$\ln \beta_t = (1 - \rho_\beta) \ln \bar{\beta} + \rho_\beta \ln \beta_{t-1} + \varepsilon_t^\beta \quad (\text{B.28})$$

$$\ln z_t = (1 - \rho_z) \ln \bar{z} + \rho_z \ln z_{t-1} + \varepsilon_t^z \quad (\text{B.29})$$

$$\ln \mu_t^w = (1 - \rho_w) \ln \bar{\mu}^w + \rho_w \ln \mu_{t-1}^w + \varepsilon_t^w \quad (\text{B.30})$$

$$\ln \mu_t = (1 - \rho_p) \ln \bar{\mu} + \rho_p \ln \mu_{t-1} + \varepsilon_t^p \quad (\text{B.31})$$

$$\ln g_t = (1 - \rho_g) \ln(0.2\bar{y}) + \rho_g \ln g_{t-1} + \varepsilon_t^g \quad (\text{B.32})$$

$$\ln \epsilon_t^i = \rho_i \ln \epsilon_{t-1}^i + \varepsilon_t^i \quad (\text{B.33})$$

$$\ln \epsilon_t^\Lambda = \rho_\Lambda \ln \epsilon_{t-1}^\Lambda + \varepsilon_t^\Lambda \quad (\text{B.34})$$

$$\ln R_t^* = (1 - \rho_r) \ln \bar{R} + \rho_r \ln R_{t-1}^* + \varepsilon_t^r \quad (\text{B.35})$$

$$(\text{B.36})$$

*Parameters*

The parameters are set as in Table B.3.

*Appendix B.2 A small scale HANK model with one asset*

Households can hold one type of assets  $a_{it}$  and face idiosyncratic income risk and a borrowing constraint. They have GHH preferences with the composite good  $x_{i,t}$ , and the

| Parameter    |   | Value                | Target           |
|--------------|---|----------------------|------------------|
| $\sigma_l$   | inverse Frisch elasticity of labour supply                    | 2                    |                  |
| $\chi$       | weight on the disutility of labour                            | –                    | $\bar{n} = 0.33$ |
| $\beta$      | steady state discount factor                                  | 0.995                |                  |
| $\theta$     | elasticity of substitution                                    | 6                    |                  |
| $\theta_w$   | elasticity of substitution for wages                          | 11                   |                  |
| $\kappa$     | decay parameter for coupon payments of perpetual bonds        | 0.975                |                  |
| $\delta$     | depreciation rate   | 0.025                |                  |
| $h$          | habit formation parameter                                     | 0.74                 |                  |
| $\psi_i$     | parameter on the costs of investment adjustment               | 5.6                  |                  |
| $\psi_p$     | parameter on the costs of price adjustment                    | 60.                  |                  |
| $\psi_w$     | parameter on the costs of wage adjustment                     | 96.                  |                  |
| $\psi_u$     | parameter on the capital utilisation costs                    | 0.8                  |                  |
| $\alpha$     | capital income share  | 0.33                 |                  |
| $\pi^*$      | inflation target  | $1.02^{\frac{1}{4}}$ |                  |
| $\phi_{pi}$  | Monetary policy rule coefficient on inflation                 | 1.5                  |                  |
| $\phi_y$     | Monetary policy rule coefficient on output                    | 0.1                  |                  |
| $\rho$       | persistence in (notional) nominal interest rate               | 0.8                  |                  |
| $\omega_p$   | coefficient on steady state inflation in price indexation     | 0.44                 |                  |
| $\omega_w$   | coefficient on steady state wage inflation in wage indexation | 0.66                 |                  |
| $\iota_w$    | degree of downwards nominal wage rigidity                     | 1.                   |                  |
| $\rho_\beta$ | persistence of discount factor shock                          | 0.9                  |                  |
| $\rho_z$     | persistence of technology shocks                              | 0.9                  |                  |
| $\rho_p$     | persistence of price MU shock                                 | 0.9                  |                  |
| $\rho_w$     | persistence of wage MU shock                                  | 0.9                  |                  |
| $\rho_g$     | persistence of government spending shock                      | 0.9                  |                  |
| $\rho_i$     | persistence of MEI shock                                      | 0.9                  |                  |
| $\rho_r$     | persistence of MP shock                                       | 0.9                  |                  |
| $\rho_u$     | persistence of wage MU shock                                  | 0.9                  |                  |

Table B.3: Joint parameters

Bellman equation is given by

$$V_t(e_{it}, a_{i,t-1}) = \max_{c_{it}, n_{it}, a_{it}} \left\{ \frac{x_{it}^{1-\sigma_c}}{1-\sigma_c} + \beta \mathbb{E}_t [V_{t+1}(e_{i,t+1}, a_{it}) | e] \right\} \quad (\text{B.37})$$

$$x_{it} = c_{it} - e_{it} \frac{n_{it}^{1+\sigma_l}}{1+\sigma_l} \quad (\text{B.38})$$

$$c_{it} + a_{it} = \frac{R_{t-1}}{\pi_t} a_{i,t-1} + w_t e_{it} n_{it} - \tau_t \bar{\tau}(e_{it}) + \Pi_t \bar{\Pi}(e_{it}) \quad (\text{B.39})$$

$$a_{it} \geq 0 \quad (\text{B.40})$$

where  $e_{it}$  is  $i$ 's household-specific productivity which follows an AR(1) process in logs as in (5).  $\bar{\tau}(e)$  and  $\bar{\Pi}(e)$  are skill-specific incidence rules for taxes and dividends.

The aggregate model is as in Appendix B.1 but parameters are chosen such that

labor is the only production factor (i.e. no capital accumulation with  $\alpha = 0$ ) and such that there are no price inertia in the Phillips curve ( $\omega = 0$ ). Dividends are given by (9). The government is running a balanced budget with

$$\tau_t = \left( \frac{R_{t-1}}{\pi_t} - 1 \right) \bar{B} + g_t. \quad (\text{B.41})$$

I further abstract from labor unions and thus, due to GHH preferences, labor supply simplifies to

$$n_t^{\sigma_l} = w_t. \quad (\text{B.42})$$

Markets clear with

$$\int c_{it} di = C_t = \left( 1 - \frac{\psi}{2} \left( \frac{\pi_t}{\bar{\pi}} - 1 \right)^2 \right) y_t, \quad (\text{B.43})$$

$$\int a_{it} di = \bar{B}, \quad (\text{B.44})$$

and the parameters specific to this model are given in Table B.4.

| Parameter     |   | Value |
|---------------|---|-------|
| $\sigma_c$    | intertemporal elasticity of substitution                  | 2     |
| $\bar{\beta}$ | discount factor   | 0.98  |
| $\bar{B}$     | bond supply   | 5.6   |
| $\alpha$      | capital factor share                                      | 0     |
| $\omega_p$    | coefficient on steady state inflation in price indexation | 1     |
| $\bar{a}$     | borrowing constraint                                      | 0     |
| $\sigma_e$    | standard error of earnings                                | 0.6   |
| $\rho_e$      | autocorrelation of earnings                               | 0.966 |
| $n_e$         | points for Markov chain of $e$                            | 4     |
| $n_a$         | points for asset grid                                     | 50    |

Table B.4: Parameters specific to the one-asset-HANK model.

### Appendix B.3 A medium scale HANK model with two assets

The two-asset HANK model shares many of the aggregate features with the representative agent model in Appendix B.1 and is presented in Section 2. A central difference is the setup of households. Based on the endogenous grid method of Carroll (2006), the appendix of Auclert et al. (2021) describes an efficient algorithm to solve the two-asset household problem with convex adjustment costs. All equations that are not stated in 2 are as in the RANK model, including the exogenous processes from Equations (B.28)-(B.35). Parameters specific to the two-asset HANK model are given in Table B.5.

| Parameter     |  | Value |
|---------------|--|-------|
| $\sigma_c$    | intertemporal elasticity of substitution   | 2     |
| $\sigma_l$    | inverse Frisch elasticity of labour supply | 2.9   |
| $\chi$        | weight on the disutility of labour         | 0.5   |
| $\psi_p$      | parameter on the costs of price adjustment | 60    |
| $\psi_w$      | parameter on the costs of price adjustment | 96    |
| $\psi_a0$     | parameter on portfolio adjustment no.1     | 0.25  |
| $\psi_a1$     | parameter on portfolio adjustment no.2     | 15    |
| $\psi_a2$     | parameter on portfolio adjustment no.3     | 2     |
| $\zeta$       | liquidity premium                          | 0.005 |
| $B_G$         | government bond supply                     | 2.8   |
| $\bar{\beta}$ | discount factor                            | 0.98  |
| $\bar{T}$     | steady state government transfers          | 1e-5  |
| $\rho_T$      | autocorrelation government transfers       | 0.8   |
| $\bar{b}$     | borrowing constraint                       | 0     |
| $\sigma_e$    | standard error of earnings                 | 0.92  |
| $\rho_e$      | autocorrelation of earnings                | 0.966 |
| $\zeta$       | steady state liquidity premium             | 0.1   |
| $n_e$         | points for Markov chain of $e$             | 3     |
| $n_b$         | points for liquid asset grid               | 20    |
| $n_a$         | points for illiquid asset grid             | 25    |

Table B.5: Parameters specific to the two-asset HANK model.

## Appendix C A discussion of the eigenvalue condition

This section discusses why the eigenvalue condition in Proposition 1 is likely to be satisfied in a very large class of economic models. The condition that all generalized eigenvalues of  $\bar{J}$  and  $J(\mathbf{x}_i)$  are positive implies that for any  $\lambda$  and  $v$  satisfying

$$J(\mathbf{x}_i)v = \lambda\bar{J}v, \quad (\text{C.1})$$

all entries of  $\lambda$  are positive, which, given that  $\bar{J}$  is invertible, is equivalent to all regular eigenvalues of  $\bar{J}^{-1}J(\mathbf{x}_i)$  being positive. While it cannot be shown in general that this is *always* the case, we can provide general arguments why this is likely the case for most economic models.

The Jacobian is the sequence of partial derivatives over the full truncated horizon with respect to the sequence of aggregate variables over the truncated horizon. Recall from (57) in Section 3.4 that

$$\bar{J}_{ij} = \frac{\partial z_i}{\partial x_j} = \frac{\partial f_i}{\partial x_j} + \frac{\partial f_i}{\partial d_i} \frac{\partial d_i}{\partial x_j}, \quad (\text{C.2})$$

where  $\bar{J}_{ij}$  again is a  $n$ -by- $n$  matrix, and let us for simplicity abstract from the second term in (C.2), for which the following arguments will hold nevertheless. Then, each row in the Jacobian corresponds to the partial derivatives of one aggregate equation in  $f$  w.r.t. the aggregate variables. Note that in a RANK model, these will be zero for

$j < i - 1$  and  $j > i + 1$ .

In economic models nearly all objects of interest – prices, levels, volumes, (gross) interest and growth rates, probabilities – are defined to be larger than zero. Relationships between these objects are usually linear, quadratic or exponential. This means that under very general conditions, the partial derivatives of  $f$  (and, more generally, of  $z$ ) do not change the sign for different aggregate variable inputs  $\mathbf{x}$ . For example, the derivative of the production function in (B.10) below,

$$y_t^f = (u_t k_{t-1})^\alpha (z_t n_t)^{1-\alpha}, \quad (\text{C.3})$$

with respect to any of the variables is always positive given that capital utilisation, capital stock as well as productivity and labor hours are all positive. This holds true for most economic models (see, e.g., the aggregate equations in Appendix B) and a large range of realistic variable values.

Take  $\bar{J}_k$  as a single row  $k$  from  $\bar{J}$ , and  $\bar{J}_k v$  as the inner product with an arbitrary vector  $v$ . If  $\frac{J(\mathbf{x}_i)_k v}{\bar{J}_k v} < 0$ , this may either be because one (or several) partial derivatives in  $J(\mathbf{x}_i)_k$  change sign relative to  $\bar{J}_k$ , or because  $v$  is such that negative partial derivatives have more weight. The above example with the production function suggests that the former may not be very likely. If the eigenvalue requirement is not satisfied, i.e. where one or more generalized eigenvalues of  $\bar{J}$  and  $J(\mathbf{x}_i)$  is negative, this would imply that  $\frac{J(\mathbf{x}_i)_k v}{\bar{J}_k v} < 0$  for *all*  $k$  and a  $v$  that is a generalized eigenvector satisfying (C.1). For this eigenvector *all* entries in  $J(\mathbf{x}_i)v$  must switch sign relative to  $\bar{J}v$ . While it is possible to construct a nonlinear system where this is the case, such system is rather improbable to encounter in practice.