

# SolveDSGE v0.3.7 — A User Guide

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## Abstract

SolveDSGE is a Julia package for solving nonlinear Dynamic Stochastic General Equilibrium models. A variety of solution methods are available, and they are interchangeable so that one solution can be used subsequently as an initialization to obtain a more accurate solution. The package can compute one- second- and third-order perturbation solutions and Chebyshev-based, Smolyak-based and piecewise linear-based projection solutions. Once a model has been solved, the package can be used to simulate data and/or compute impulse response functions.

JEL Classification: E3, E4, E5.

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# 1 Introduction

SolveDSGE is a framework for solving and analyzing Dynamic Stochastic General Equilibrium (DSGE) models that is implemented in the programming language Julia. SolveDSGE will solve nonlinear DSGE models using perturbation methods, producing solutions that are accurate to first, second, and third order, but this is not its focus. The package’s focus is on applying projection methods to obtain solutions that are globally accurate.

Obtaining globally accurate solutions to nonlinear DSGE models is notoriously difficult. Solutions are invariably slow to obtain and model-specific characteristics are often exploited to speed up the solution process. SolveDSGE does not exploit model-specific characteristics in order to solve a model. Instead, SolveDSGE applies the same general solution strategy to all models. Nonetheless, making use of Julia’s speed, SolveDSGE allows models to be solved “relatively quickly”, and it provides users with an easy, unified, way of organizing and expressing their model. At the users request, globally accurate solutions can be obtained using Chebyshev polynomials, Smolyak polynomials, or piecewise linear approximations, with the solution obtained from one approximation scheme able to be used as an initialization for the others, allowing greater speed and accuracy to be obtained via a form of homotopy.

To use SolveDSGE to solve a model, two files must be supplied. The first file (the model file) summarizes the model to be solved. The second file (the solution file) reads the model file, solves the model, and performs any post-solution analysis.

Quite a lot of time and effort has gone into writing SolveDSGE, together with the underlying modules: ChebyshevApprox, SmolyakApprox, and PiecewiseLinearApprox, but it is far from perfect. SolveDSGE may not be able to solve your model, or it may not obtain a solution quickly enough to be useful to you. You are welcome to suggest improvements to fix bugs or add functionality. At the same time, I am hopeful that you will find the package useful for your research. If it is, then please cite this User Guide and add an acknowledgement of SolveDSGE to your paper/report.

## 2 What types of models can be solved?

SolveDSGE is designed to solve models that can be written in the following standard form:

$$E_t [\mathbf{f}(\mathbf{x}_t, \mathbf{y}_t, \mathbf{x}_{t+1}, \mathbf{y}_{t+1}, \boldsymbol{\varepsilon}_{t+1})] = \mathbf{0}, \quad (1)$$

where  $\mathbf{x}_t$  is a vector of state variables,  $\mathbf{y}_t$  is a vector of jump variables, and  $\boldsymbol{\varepsilon}_{t+1}$  is a vector of shocks. The first-order conditions and constraints for the DSGE model are specified equation-by-equation. The shocks, state variables, and jump variables are defined and then SolveDSGE takes the model

and expresses it in the form of equation (1) in preparation for solution. Equation (1) covers a wide set of models, but obviously not all models. In principle SolveDSGE can handle standard business cycle models of the real and new Keynesian varieties, and it can handle models with volatility shocks, but it cannot handle heterogeneous agents models, nor models with generalized Euler equation like those that emerge from discretionary policy problems or from models with quasi-geometric discounting. Allowing for models that contain generalized Euler equations is a topic for future work. Another set of models that are not fully accommodated are those where the shocks are contemporaneously correlated. Such models can be solved via the perturbation methods, but not via the projection methods (due to the techniques used for quadrature).

### 3 The model file

SolveDSGE requires that the model that is to be solved be stored in a model file. The model file is simply a text file so there is nothing particularly special about it. Every model file must contain the following five information categories: “states:”, “jumps:”, “shocks:”, “parameters:”, and “equations:”; each category name must end with a colon. Each category will begin with its name, such as “states:” and conclude with an “end”. The model file can present these five categories in any order.

The information in each category can be presented with one element per line, or with multiple elements on each line with each element separated by either a comma or a semi-colon. So if the jump variables in the model are labor, consumption, and output, then this could be presented in a variety of ways, such as:

```
jumps:
labor
consumption
output
end
```

or:

```
jumps:
labor, consumption, output
end
```

or:

```

jumps:
labor; consumption, output
end

```

The first lag of a variable is denoted with a -1, so the lag of consumption is `consumption(-1)`. Similarly the first lead of a variable is denoted with a +1, so the lead of consumption is denoted `consumption(+1)`. The first lag of any model variable is automatically included as a state variable, second and higher lags should be given a name, defined by an equation, and included as state variables explicitly. The package may allow higher lags to be processed automatically at a later stage.

Shocks in the model refers to the innovations to the shock processes, so if the shock process is given by

$$tech(+1) = rho * tech + sd * epsilon,$$

then “*tech*” will be a state variable, “*epsilon*” will be a shock, and “*rho*” and “*sd*” will be parameters. If the model is deterministic, then it will contain no shocks.

Every element in the parameters category and the equations category must contain an “=” sign, such as “*alpha* = 0.33” in the case of the parameters category and “*output* = *exp*(*tech*) \* *capital*<sup>*alpha*</sup> \* *labor*<sup>(1.0 - *alpha*)</sup>” in the case of the equations category.

### 3.1 Example

The following is an example of a model file for the stochastic growth model:

```

states:
cap, tech
end

```

```

jumps:
cons
end

```

```

shocks:
epsilon
end

```

*parameters:*

*betta = 0.99*

*sigma = 1.1*

*delta = 0.025*

*alpha = 0.30*

*rho = 0.8*

*sd = 0.01*

*end*

*equations:*

*cap(+1) = (1.0 - delta)\*cap + exp(tech)\*cap^alpha - cons*

*cons^(-sigma) = betta\*cons(+1)^(-sigma)\*(1.0 - delta + alpha\*exp(tech(+1))\*cap(+1)^(alpha - 1.0))*

*tech(+1) = rho\*tech + sd\*epsilon*

*end*

## 4 Solving a model

Solving a model is straightforward; it consists of the following steps:

1. Read and process the model file. During the processing the order of variables in the system may be changed, typically the changes are to place the shocks at the top of the system. After processing is complete you will be told what the variable-order is.
2. Solve for the model's steady state.
3. Specify a SolutionScheme. A SolutionScheme specifies the solution method along with any parameters needed to implement that solution method.
4. Solve the model according to the chosen SolutionScheme.

### 4.1 Reading the model and solving for its steady state

To read and process a model file we simply supply the path/filename to the `get_model()` function, for example

```
dsge = get_model("c:/desktop/model.txt")
```

We can then solve for the model's steady state as follows

```
ss = compute_steady_state(dsge,tol,maxiters)
```

where *dsge* is the model whose steady state is to be computed, *tol* is a convergence tolerance, and *maxiters* is an integer specifying the maximum number of iterations before the function exits.

## 4.2 Specifying a SolutionScheme

To solve a model a SolutionScheme must be supplied. A SolutionScheme specifies the solution method and the parameters upon which this solution method relies. The solution methods in SolveDSGE are either perturbation methods or projection methods. Accordingly, the SolutionSchemes can be divided into PerturbationSchemes or ProjectionSchemes. We present each in turn.

### 4.2.1 PerturbationSchemes

To solve a model using a perturbation method requires and PerturbationScheme. Regardless of the model or the order of the perturbation, a PerturbationScheme is a structure with three fields: the point about which to perturb the model (the steady state), a cutoff parameter that separates unstable from stable eigenvalues (eigenvalues whose modulus is greater than cutoff will be placed in the model's unstable block), and the order of the perturbation. For a first-order perturbation, a typical PerturbationScheme might be the following

```
N = PerturbationScheme(ss,cutoff,"first")
```

while those for second and third order perturbations might be

```
NN = PerturbationScheme(ss,cutoff,"second")
```

and

```
NNN = PerturbationScheme(ss,cutoff,"third")
```

The method used to compute a first-order perturbation follows Klein (2000), that for a second-order perturbation follows Gomme and Klein (2011), while that for a third-order perturbation follows Binning (2013) with a refinement from Levintal (2017). At this point, perturbation solutions higher than third order are not supported.

### 4.2.2 ProjectionSchemes

ProjectionSchemes are either ChebyshevSchemes, SmolyakSchemes, or PiecewiseLinearSchemes, and for each of these there is a stochastic (for stochastic models) and a deterministic (for deterministic models) version. The SolutionScheme for the deterministic case is a special case of the stochastic one, so we focus on the stochastic case in what follows.

**ChebyshevSchemes** Solutions based on Chebyshev polynomials rely on and make use of all of the functionality of the module ChebyshevApprox. This means that an arbitrary number of state variables can be accommodated (if you have enough time!) and both tensor-product and complete polynomials can be used. A stochastic ChebyshevScheme requires the following arguments:

- `initial_guess` — This will usually be a vector containing the model’s steady state. It is used as the initial guess at the solution for the case where an initializing solution is not provided (see the section on model solution below).
- `node_generator` — This is the name of the function used to generate the nodes for the Chebyshev polynomial. Possible options include: `chebyshev_nodes` and `chebyshev_extrema`.
- `node_number` — This gives the number of nodes to be used for each state variable. If there is only one state variables then `node_number` will be an integer. When there are two or more state variables it will be a vector of integers.
- `num_quad_nodes` — This is an integer specifying the number of quadrature points used to compute expectations.
- `order` — This defines the order of the Chebyshev polynomial to be used in the approximating functions. For a complete polynomial order will be an integer; for a tensor-product polynomial order will be a vector of integers.
- `domain` — This contains the domain for the state variables over which the solution is obtained. Domain will be a 2–element vector in the one-state-variable case and a  $2 \times n$  array in the  $n$ -state-variable case, with the first row of the array containing the upper values of the domain and the second row containing the lower values of the domain. If an initializing solution is provided, then the domain associated with that initializing solution can be used by setting domain to an empty array, `Float64[]`.
- `tol_fix_point_solver` — This specifies the tolerance to be used in the inner loop to determine convergence at each solution node.

- `tol_variables` — This specifies the tolerance to be used in the outer loop to determine convergence of the overall solution.
- `maxiters` — This is an integer specifying the maximum number of outer-loop iterations before the solution exits.

An example of a stochastic ChebyshevScheme is

```
C = ChebyshevSchemeStoch(ss,chebyshev_nodes,[21,21], 9, 4,[0.1 30.0; -0.1 20.0],1e-8,1e-6,1000)
```

In the deterministic case the number of quadrature nodes is not needed, i.e.,

```
Cdet = ChebyshevSchemeDet(ss,chebyshev_nodes,[21,21],4,[0.1 30.0; -0.1 20.0],1e-8,1e-6,1000)
```

**SmolyakSchemes** Underlying the Smolyak polynomial based solution is the module `SmolyakApprox`. This module allows for both isotropic polynomials and anisotropic polynomials and several different methods for producing nodes. `SolveDSGE` exploits all of this functionality. A stochastic `SmolyakScheme` requires the following arguments:

- `initial_guess` — This will usually be a vector containing the model’s steady state. It is used as the initial guess at the solution for the case where an initializing solution is not provided (see the section on model solution below).
- `node_generator` — This is the name of the function used to generate the nodes for the Smolyak polynomial. Possible options include: `chebyshev_gauss_lobatto` and `clenshaw_curtis_equidistant`
- `num_quad_nodes` — This is an integer specifying the number of quadrature points used to compute expectations.
- `layer` — This is an integer (isotropic case) or a vector of integers (anisotropic case) specifying the number of layers to be used in the approximation.
- `domain` — This contains the domain for the state variables over which the solution is obtained. Domain will be a 2–element vector in the one-state-variable case and a  $2 \times n$  array in the  $n$ -state-variable case, with the first row of the array containing the upper values of the domain and the second row containing the lower values of the domain. If an initializing solution is provided, then the domain associated with that initializing solution can be used by setting domain to an empty array, `Float64[]`.



- `tol_fix_point_solver` — This specifies the tolerance to be used in the inner loop to determine convergence at each solution node.
- `tol_variables` — This specifies the tolerance to be used in the outer loop to determine convergence of the overall solution.
- `maxiters` — This is an integer specifying the maximum number of outer-loop iterations before the solution exits.

An example of a stochastic SmolyakScheme is

```
S = SmolyakSchemeStoch(ss,chebyshev_gauss_lobatto,9,3,[0.1 30.0; -0.1 20.0],1e-8,1e-6,1000)
```

In the deterministic case the number of quadrature nodes is not needed, i.e.,

```
Sdet = SmolyakSchemeDet(ss,chebyshev_gauss_lobatto,3,[0.1 30.0; -0.1 20.0],1e-8,1e-6,1000)
```

**PiecewiseLinearSchemes** To obtain piecewise linear solutions, SolveDSGE employs the module PiecewiseLinearApprox, which allows approximations over an arbitrary number of state variables. A stochastic PiecewiseLinearScheme requires the following arguments:

- `initial_guess` — This will usually be a vector containing the model's steady state. It is used as the initial guess at the solution for the case where an initializing solution is not provided (see the section on model solution below).
- `node_number` — This gives the number of nodes to be used for each state variable. If there is only one state variables then `node_number` will be an integer. When there are two of more state variables it will be a vector of integers.
- `num_quad_nodes` — This is an integer specifying the number of quadrature points used to compute expectations.
- `domain` — This contains the domain for the state variables over which the solution is obtained. Domain will be a 2–element vector in the one-state-variable case and a  $2 \times n$  array in the  $n$ -state-variable case, with the first row of the array containing the upper values of the domain and the second row containing the lower values of the domain. If an initializing solution is provided, then the domain associated with that initializing solution can be used by setting domain to an empty array, `Float64[]`.

- `tol_fix_point_solver` — This specifies the tolerance to be used in the inner loop to determine convergence at each solution node.
- `tol_variables` — This specifies the tolerance to be used in the outer loop to determine convergence of the overall solution.
- `maxiters` — This is an integer specifying the maximum number of outer-loop iterations before the solution exits.

An example of a stochastic `PiecewiseLinearScheme` is

```
P = PiecewiseLinearStoch(ss,[21,21],9,[0.1 30.0; -0.1 20.0],1e-8,1e-6,1000)
```

In the deterministic case the number of quadrature nodes is not needed, i.e.,

```
Pdet = PiecewiseLinearDet(ss,[21,21],9,[0.1 30.0; -0.1 20.0],1e-8,1e-6,1000)
```

### 4.3 Model solution

Once a `SolutionScheme` is specified we are in a position to solve the model. In order to do so we use the `solve_model()` function, which takes either two or three arguments. For a perturbation solution `solve_model()` requires two arguments: the model to be solved and the `SolutionScheme`, as follows:

```
soln_first_order = solve_model(dsge,N)
```

```
soln_second_order = solve_model(dsge,NN)
```

```
soln_third_order = solve_model(dsge,NNN)
```

Alternatively, for a projection solution `solve_model()` takes either two or three arguments. To provide a concrete example, suppose we wish to solve our model using Chebyshev polynomials. If we want the projection solution to be initialized using the steady state, then `solve_model()` requires only two arguments: the model to be solved and the `SolutionScheme`:

```
soln_chebyshev = solve_model(dsge,C)
```

If we want the projection solution to be initialized using the third order perturbation solution, then `solve_model()` requires three arguments: the model to be solved, the initializing solution, and the `SolutionScheme`:

`soln_chebyshev = solve_model(dsge,soln_third_order,C)`

Although this example uses a third order perturbation as the initializing solution, any solution (first order, second order, third order, Chebyshev, Smolyak, or piecewise linear) can be used.

#### 4.3.1 A comment on third-order perturbation

Sometimes it can be useful to add skewness to the shocks, but this is not easy to do through the model file. If you want your shocks to be skewed, then you can access the third order perturbation solution by calling

`soln_third_order = solve_third_order(dsge,NNN,skewness)`

where skewness is a 2D array containing the skewness coefficients. If there is only one shock, then the skewness array is

$$skewness = E[\epsilon_1 \epsilon_1 \epsilon_1].$$

If there are two shocks, then the skewness array is

$$skewness = E \begin{bmatrix} \epsilon_1 \epsilon_1 \epsilon_1 & \epsilon_1 \epsilon_1 \epsilon_2 & \epsilon_1 \epsilon_2 \epsilon_1 & \epsilon_1 \epsilon_2 \epsilon_2 \\ \epsilon_2 \epsilon_1 \epsilon_1 & \epsilon_2 \epsilon_1 \epsilon_2 & \epsilon_2 \epsilon_2 \epsilon_1 & \epsilon_2 \epsilon_2 \epsilon_2 \end{bmatrix}.$$

Etc.

#### 4.3.2 Solution structures

When a model is solved the solution is returned in the form of a structure. The exact structure returned depends on the solution method.

**First-order perturbation** The first-order perturbation solution takes the following form:

$$\begin{aligned} \mathbf{x}_{t+1} &= \mathbf{h}_x \mathbf{x}_t + \mathbf{k} \epsilon_{t+1}, \\ \mathbf{y}_t &= \mathbf{g}_x \mathbf{x}_t. \end{aligned}$$

The solution structure for a stochastic first-order perturbation has the following fields:

- `hbar` — The steady state of the state variables
- `hx` — The first-order coefficients in the state-transition equation
- `k` — The loading matrix on the shocks in the state-transition equation.
- `gbar` — The steady state of the jump variables

- $\mathbf{g}_x$  — The first-order coefficients in the jump's equation
- $\mathbf{\sigma}$  — An identity matrix
- $\mathbf{grc}$  — The number of eigenvalues with modulus greater than cutoff.
- $\mathbf{Soln\_type}$  — Either “determinate”, “indeterminate”, or “unstable”.

The solution to a deterministic model has the same fields as the stochastic solution with the exceptions of  $\mathbf{k}$  and  $\mathbf{\sigma}$ .

**Second-order perturbation** The second-order perturbation solution takes the following form:

$$\begin{aligned}\mathbf{x}_{t+1} &= \mathbf{h}_x \mathbf{x}_t + \frac{1}{2} \mathbf{h}_{ss} + \frac{1}{2} (\mathbf{I} \otimes \mathbf{x}_t) \mathbf{h}_{xx} (\mathbf{I} \otimes \mathbf{x}_t) + \mathbf{k} \boldsymbol{\epsilon}_{t+1}, \\ \mathbf{y}_t &= \mathbf{g}_x \mathbf{x}_t + \frac{1}{2} \mathbf{g}_{ss} + \frac{1}{2} (\mathbf{I} \otimes \mathbf{x}_t) \mathbf{g}_{xx} (\mathbf{I} \otimes \mathbf{x}_t).\end{aligned}$$

The solution structure for a stochastic second-order perturbation has the following fields:

- $\mathbf{hbar}$  — The steady state of the state variables
- $\mathbf{h}_x$  — The first-order coefficients in the state-transition equation
- $\mathbf{hss}$  — The second-order stochastic adjustment to the mean in the state-transition equation
- $\mathbf{hxx}$  — The second-order coefficients in the state-transition equation
- $\mathbf{k}$  — The loading matrix on the shocks in the state-transition equation.
- $\mathbf{gbar}$  — The steady state of the jump variables
- $\mathbf{g}_x$  — The first-order coefficients in the jump's equation
- $\mathbf{gss}$  — The second-order stochastic adjustment to the mean in the jump's equation
- $\mathbf{gxx}$  — The second-order coefficients in the jump's equation
- $\mathbf{\sigma}$  — An identity matrix
- $\mathbf{grc}$  — The number of eigenvalues with modulus greater than cutoff.
- $\mathbf{Soln\_type}$  — Either “determinate”, “indeterminate”, or “unstable”.

The solution to a deterministic model has the same fields as the stochastic solution with the exceptions of  $\mathbf{h}_{ss}$ ,  $\mathbf{k}$ ,  $\mathbf{g}_{ss}$ , and  $\mathbf{\sigma}$ .

**Third-order perturbation** The third-order perturbation solution takes the following form:

$$\begin{aligned}\mathbf{x}_{t+1} &= \mathbf{h}_x \mathbf{x}_t + \frac{1}{2} \mathbf{h}_{ss} + \frac{1}{2} \mathbf{h}_{xx} (\mathbf{x}_t \otimes \mathbf{x}_t) + \frac{1}{6} \mathbf{h}_{sss} + \frac{1}{6} \mathbf{h}_{ssx} \mathbf{x}_t + \frac{1}{6} \mathbf{h}_{xxx} (\mathbf{x}_t \otimes \mathbf{x}_t \otimes \mathbf{x}_t) + \mathbf{k} \epsilon_{t+1}, \\ \mathbf{y}_t &= \mathbf{g}_x \mathbf{x}_t + \frac{1}{2} \mathbf{g}_{ss} + \frac{1}{2} \mathbf{g}_{xx} (\mathbf{x}_t \otimes \mathbf{x}_t) + \frac{1}{6} \mathbf{g}_{sss} + \frac{1}{6} \mathbf{g}_{ssx} \mathbf{x}_t + \frac{1}{6} \mathbf{g}_{xxx} (\mathbf{x}_t \otimes \mathbf{x}_t \otimes \mathbf{x}_t).\end{aligned}$$

The solution structure for a stochastic third-order perturbation has the following fields:

- `hbar` — The steady state of the state variables
- `hx` — The first-order coefficients in the state-transition equation
- `hss` — The second-order stochastic adjustment to the mean in the state-transition equation
- `hxx` — The second-order coefficients in the state-transition equation
- `hsss` — The third-order stochastic adjustment to the mean in the state-transition equation
- `hssx` — The skewness adjustment to the state-transition equation
- `hxxx` — The third-order coefficients in the state-transition equation
- `k` — The loading matrix on the shocks in the state-transition equation.
- `gbar` — The steady state of the jump variables
- `gx` — The first-order coefficients in the jump's equation
- `gss` — The second-order stochastic adjustment to the mean in the jump's equation
- `gxx` — The second-order coefficients in the jump's equation
- `gsss` — The third-order stochastic adjustment to the mean in the jump's equation
- `gssx` — The skewness adjustment in the jump's equation
- `gxxx` — The third-order coefficients in the jump's equation
- `sigma` — An identity matrix
- `grc` — The number of eigenvalues with modulus greater than cutoff.
- `Soln_type` — Either “determinate”, “indeterminate”, or “unstable”.

The solution to a deterministic model has the same fields as the stochastic solution with the exceptions of `hss`, `hsss`, `hssx`, `k`, `gss`, `gsss`, `gssx`, and `sigma`.

**Chebyshev solution** The solution structure for the Chebyshev solution has the following fields:

- `variables` — A vector of arrays containing the solution for each variable
- `weights` — A vector of arrays containing the weights for the Chebyshev polynomials
- `nodes` — A vector of vectors containing the Chebyshev nodes
- `order` — The order of the Chebyshev polynomials
- `domain` — The domain for the state variables
- `sigma` — The variance-covariance matrix for the shocks
- `iteration_count` — The number of iterations needed to achieve convergence

The solution to a deterministic model has the same fields with the exception of `sigma`.

**Smolyak solution** The solution structure for the Smolyak solution has the following fields:

- `variables` — A vector of arrays containing the solution for each variable
- `weights` — A vector of vectors containing the weights for the Chebyshev polynomials
- `grid` — A matrix containing the Smolyak grid
- `multi_index` — A matrix containing the multi-index underlying the polynomials
- `layer` — The number of layers in the approximation
- `domain` — The domain for the state variables
- `sigma` — The variance-covariance matrix for the shocks
- `iteration_count` — The number of iterations needed to achieve convergence

The solution to a deterministic model has the same fields with the exception of `sigma`.

**Piecewise linear solution** The solution structure for the piecewise linear solution has the following fields:

- `variables` — A vector of arrays containing the solution for each variable
- `nodes` — A vector of vectors containing the Chebyshev nodes
- `domain` — The domain for the state variables
- `sigma` — The variance-covariance matrix for the shocks
- `iteration_count` — The number of iterations needed to achieve convergence

The solution to a deterministic model has the same fields with the exception of `sigma`.

## 5 Post-solution analysis

Once you have solved your model there are many things that you might want to use the solution for. Some of the more obvious things, such as simulating data from the solution and computing impulse response functions have been built into SolveDSGE to make things easier for you.

### 5.1 Simulation

To simulate data from the solution to a model the function to use is `simulate()`, whose arguments are a model solution, an initial state, and the number of observations to simulate. An optional final argument is the seed for the random number generator. An example of `simulate()` in action might be

```
data_states, data_jumps = simulate(soln,[0.0, 25.0],100000)
```

As this example makes clear, the `simulate` function returns two 2D arrays. The first array contains simulated data for the state variables, the second array contains simulated data for the jump variables. The `simulate` function can be applied to both stochastic and deterministic models.

### 5.2 Impulse response functions

Impulse responses are obtained using the `impulses()` function, which takes three arguments: the model solution, the length of the impulse response function (number of periods), the number of the shock to apply the impulse to, and the number of repetitions to use for the Monte Carlo integration.

Responses to both a positive and a negative innovation are generated. An optimal final argument is the seed for the random number generator. An example of `impulses()` in use might be

```
pos_responses, neg_responses = impulses(soln, 50, 1, 10000)
```

For the nonlinear solutions (second-order perturbation, third-order perturbation, and the projection-based solutions) the initial state is “integrated-out” via a Monte Carlo that averages over draws taken from the unconditional distribution of the state variables. At this stage in the package’s development, the impulses need to be computed one shock at a time; this will probably change at some point.

### 5.3 PDFs and CDFs

SolveDSGE contains functions for approximating the probability density function and the cumulative distribution function of a variable, where the approximation is based on Fourier series (Kronmal and Tarter, 1968). Most of the functionality relates to the univariate case, but some functionality is included to approximate and evaluate the PDF in the multivariate case.

#### 5.3.1 Univariate

To approximate the probability density function and evaluate the approximated function at a point the function is

```
f = approximate_density(sample, point, order, lower_bound, upper_bound)
```

where *sample* is a vector of data, *point* is the value at which the PDF is evaluated, *order* is the order of the Fourier series approximation, and *lower\_bound* and *upper\_bound* specify the support over which the PDF is constructed. If an approximation of the entire PDF is sought, then the function is

```
nodesf, f = approximate_density(sample, order, lower_bound, upper_bound)
```

Similarly, the cumulative distribution function is approximated and evaluated at a point using the function

```
F = approximate_distribution(sample, point, order, lower_bound, upper_bound)
```

where *sample* is a vector of data, *point* is the value at which the CDF is evaluated, *order* is the order of the Fourier series approximation, and *lower\_bound* and *upper\_bound* specify the support



over which the CDF is constructed. If an approximation of the entire CDF is sought, then the function is

$$nodesF, F = \text{approximate\_distribution}(sample, order, lower\_bound, upper\_bound)$$

### 5.3.2 Multivariate

In the multivariate case the PDF can be approximated and evaluated at a point using the function

$$f = \text{approximate\_density}(sample, point, order, lower\_bound, upper\_bound)$$

where *sample* is a 2D array of data, *point* is a vector, *order* is a vector of integers, and *lower\_bound* and *upper\_bound* are vectors. From this function, marginal densities and conditional densities can be computed. Similarly, the CDF can be approximated and evaluated at a point using the function

$$F = \text{approximate\_distribution}(sample, point, order, lower\_bound, upper\_bound)$$

where *sample* is a 2D array of data, *point* is a vector, *order* is a vector of integers, and *lower\_bound* and *upper\_bound* are vectors.

## References

- [1] Andreasen, M., Fernández-Villaverde, J., and J. Rubio-Ramirez, (2017), “The Pruned State-Space System for Non-Linear DSGE Models: Theory and Empirical Applications”, *Review of Economic Studies*, 0, pp. 1—49.
- [2] Binning, A., (2013), “Third-order approximation of dynamic models without the use of tensors”, *Norges Bank Working Paper* 2013–13.
- [3] Gomme, P., and P. Klein, (2011), “Second-Order Approximation of Dynamic Models Without the Use of Tensors”, *Journal of Economic Dynamics and Control*, 35, pp. 604—615.
- [4] Judd, K. (1992), “Projection Methods for Solving Aggregate Growth Models”, *Journal of Economic Theory*, 58, pp.410—452.
- [5] Judd, K., Maliar, L., Maliar, S., and R. Valero, (2014), “Smolyak Method for Solving Dynamic Economic Models: Lagrange Interpolation, Anisotropic Grid and Adaptive Domain”, *Journal of Economic Dynamics and Control*, 44, pp. 92—123.

- [6] Judd, K., Maliar, L., Maliar, S., and I. Tsener, (2017), “How to Solve Dynamic Stochastic Models Computing Expectations just Once”, *Quantitative Economics*, 8, pp.851—893.
- [7] Klein, P., (2000), “Using the Generalized Schur Form to Solve a Multivariate Linear Rational Expectations Model”, *Journal of Economic Dynamics and Control*, 24, pp. 1405—1423.
- [8] Kronmal, R., and M. Tarter, (1968), “The Estimation of Probability Densities and Cumulatives by Fourier Series Methods”, *Journal of the American Statistical Association*, 63, 323, pp.925—952.
- [9] Levintal, O., (2017), “Fifth-Order Perturbation Solution to DSGE models”, *Journal of Economic Dynamics and Control*, 80, pp. 1–16.
- [10] Potter, S., (2000), “Nonlinear Impulse Response Functions”, *Journal of Economic Dynamics and Control*, 24, pp. 1425—1446.