The Dynare Preprocessor

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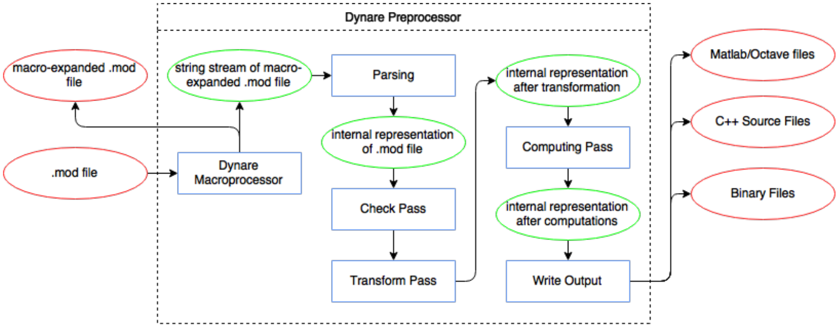
Overview



Dynare Preprocessor
macro-expanded .mod file
string stream of macro-expanded .mod file
Parsing
internal representation after transformation
Matlab/Octave files
C++ Source Files
Binary Files
internal representation of .mod file
Computing Pass
.mod file
Dynare Macroprocessor
Check Pass
internal representation after computations
Transform Pass
Write Output

Outline

Outline

Calling Dynare

- Dynare is called from the host language platform with the syntax `dynare «filename».mod`
- This call can be followed by certain options:
  - Some of these options impact host language platform functionality, *e.g.* `nograph` prevents graphs from being displayed in MATLAB
  - Some cause differences in the output created by default, *e.g.* `notmpterms` prevents temporary terms from being written to the static/dynamic files
  - While others impact the functionality of the macroprocessor or the preprocessor, *e.g.* `nostrict` shuts off certain checks that the preprocessor does by defalut

Outline

Parsing overview

- Parsing is the action of transforming an input text (a `mod` file in our case) into a data structure suitable for computation
- The parser consists of three components:
  - the lexical analyzer, which recognizes the "words" of the `mod` file (analog to the *vocabulary* of a language)
  - the syntax analyzer, which recognizes the "sentences" of the `mod` file (analog to the *grammar* of a language)
  - the parsing driver, which coordinates the whole process and constructs the data structure using the results of the lexical and syntax analyses

Lexical analysis

- The lexical analyzer recognizes the "words" (or lexemes) of the language
- Defined in `DynareFlex.ll`, it is transformed into C++ source code by the program `flex`
- This file details the list of known lexemes (described by regular expressions) and the associated token for each of them
- For punctuation (semicolon, parentheses, . . .), operators (+, -, . . .) or fixed keywords (*e.g.* `model`, `varexo`, . . .), the token is simply an integer uniquely identifying the lexeme
- For variable names or numbers, the token also contains the associated string for further processing
- When invoked, the lexical analyzer reads the next characters of the input, tries to recognize a lexeme, and either produces an error or returns the associated token

Lexical analysis

An example

- Suppose the `mod` file contains the following:

```
model;
x = log(3.5);
end;
```

- Before lexical analysis, it is only a sequence of characters
- The lexical analysis produces the following stream of tokens:

```
MODEL
SEMICOLON
NAME "x"
EQUAL
LOG
LEFT_PARENTHESIS
FLOAT_NUMBER "3.5"
RIGHT_PARENTHESIS
SEMICOLON
END
SEMICOLON
```

Syntax analysis

In Dynare

- The mod file grammar is described in DynareBison.yy, which is transformed into C++ source code by the program bison
- The grammar tells a story which looks like:
  - A mod file is a list of statements
  - A statement can be a var statement, a varexo statement, a model block, an initval block, ...
  - A var statement begins with the token VAR, then a list of NAMEs, then a semicolon
  - A model block begins with the token MODEL, then a semicolon, then a list of equations separated by semicolons, then an END token
  - An equation can be either an expression, or an expression followed by an EQUAL token and another expression
  - An expression can be a NAME, or a FLOAT_NUMBER, or an expression followed by a PLUS and another expression, ...

Syntax analysis

Using the list of tokens produced by lexical analysis, the syntax analyzer determines which "sentences" are valid in the language, according to a grammar composed of rules.

A grammar for lists of additive and multiplicative expressions

```
%start expression_list;

expression_list := expression SEMICOLON
                 | expression_list expression SEMICOLON;

expression := expression PLUS expression
            | expression TIMES expression
            | LEFT_PAREN expression RIGHT_PAREN
            | INT_NUMBER;
```

- `(1+3)*2; 4+5;` will pass the syntax analysis without error
- `1++2;` will fail the syntax analysis, even though it has passed the lexical analysis

Semantic actions

- So far we have only described how to accept valid `mod` files and to reject others
- But validating is not enough: one needs to do something with the parsed `mod` file
- Every grammar rule can have a semantic action associated with it: C/C++ code enclosed by curly braces
- Every rule can return a semantic value (referenced by `$$` in the action)
- In the action, it is possible to refer to semantic values returned by components of the rule (using `$1`, `$2`, …)

Semantic actions

An example

A simple calculator which prints its results

```
%start expression_list
%type <int> expression

expression_list := expression SEMICOLON
                   { cout << $1 << endl; }
                 | expression_list expression SEMICOLON
                   { cout << $2 << endl; };

expression := expression PLUS expression
              { $$ = $1 + $3; }
            | expression TIMES expression
              { $$ = $1 * $3; }
            | LEFT_PAREN expression RIGHT_PAREN
              { $$ = $2; }
            | INT_NUMBER
              { $$ = $1; };
```

Parsing driver

The class `ParsingDriver` has the following roles:

- It opens the `mod` file and launches the lexical and syntaxic analyzers on it
- It implements most of the semantic actions of the grammar
- By doing so, it creates an object of type `ModFile`, which is the data structure representing the `mod` file
- Or, if there is a parsing error (unknown keyword, undeclared symbol, syntax error), it displays the line and column numbers where the error occurred and exits

Outline

The `ModFile` class

- This class is the internal data structure used to store all the information contained in a `mod` file
- One instance of the class represents one `mod` file
- The class contains the following elements (as class members):
  - a symbol table, numerical constants table, external functions table
  - trees of expressions: dynamic model, static model, original model, ramsey dynamic model, steady state model, trend dynamic model, ...
  - the list of the statements (parameter initializations, `shocks` block, `check`, `steady`, `simul`, ...)
  - model-specification and user-preference variables: `block`, `bytecode`, `use_dll`, `no_static`, ...
  - an evaluation context (containing `initval` and parameter values)
- An instance of `ModFile` is the output of the parsing process (return value of `ParsingDriver::parse()`)

The symbol table (1/3)

- A symbol is simply the name of a variable (endogenous, exogenous, local, auxiliary, etc), parameter, external function, . . . basically everything that is not recognized as a Dynare keyword
- SymbolTable is a simple class used to maintain the list of the symbols used in the `mod` file
- For each symbol, it stores:
  - its name, tex_name, and long_name (strings, some of which can be empty)
  - its type (an enumerator defined in `CodeInterpreter.hh`)
  - a unique integer identifier (also has a unique identifier by type)

The symbol table (2/3)

Existing types of symbols:

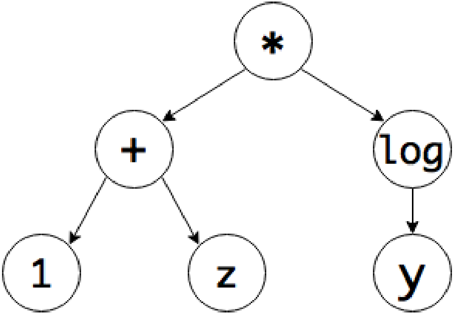
- Endogenous variables
- Exogenous variables
- Exogenous deterministic variables
- Parameters
- Local variables inside model: declared with a pound sign (#) construction
- Local variables outside model: no declaration needed (*e.g.* lhs symbols in equations from `steady_state_model` block, expression outside of model block, ...)
- External functions
- Trend variables
- Log Trend variables
- Unused Endogenous variables (created when `nostrict` option is passed)

The symbol table (3/3)

- Symbol table filled in:
  - using the `var`, `varexo`, `varexo_det`, `parameter`, `external_function`, `trend_var`, and `log_trend_var` declarations
  - using pound sign (#) constructions in the model block
  - on the fly during parsing: local variables outside models or unknown functions when an undeclared symbol is encountered
  - during the creation of auxiliary variables in the transform pass
- Roles of the symbol table:
  - permits parcimonious and more efficient representation of expressions (no need to duplicate or compare strings, only handle a pair of integers)
  - ensures that a given symbol is used with only one type

Expression trees (1/3)

- The data structure used to store expressions is essentially a tree
- Graphically, the tree representation of $(1 + z) * \log(y)$ is:



- No need to store parentheses
- Each circle represents a node
- A non external function node has at most one parent and at most three children (an external function node has as many children as arguments)

Expression trees (2/3)

- A tree node is represented by an instance of the abstract class `ExprNode`
- This class has 5 sub-classes, corresponding to the 5 types of non-external-function nodes:
  - `NumConstNode` for constant nodes: contains the identifier of the numerical constants it represents
  - `VariableNode` for variable/parameters nodes: contains the identifier of the variable or parameter it represents
  - `UnaryOpNode` for unary operators (*e.g.* unary minus, log, sin): contains an enumerator representing the operator, and a pointer to its child
  - `BinaryOpNode` for binary operators (*e.g.* $+$, $*$, pow): contains an enumerator representing the operator, and pointers to its two children
  - `TrinaryOpNode` for trinary operators (*e.g.* *normcdf* , *normpdf*): contains an enumerator representing the operator and pointers to its three children

Expression trees (3/3)

- The abstract class `ExprNode` has an abstract sub-class called `AbstractExternalFunctionNode`
- This abstract sub-class has 3 sub-classes, corresponding to the 3 types of external function nodes:
  - `ExternalFunctionNode` for external functions. Contains the identifier of the external function and a vector of its arguments
  - `FirstDerivExternalFunctionNode` for the first derivative of an external function. In addition to the information contained in `ExternalFunctionNode`, contains the index w.r.t. which this node is the derivative.
  - `SecondDerivExternalFunctionNode` for the second derivative of an external function. In addition to the information contained in `FirstDerivExternalFunctionNode`, contains the index w.r.t. which this node is the second derivative.

Classes DataTree and ModelTree

- Class DataTree is a container for storing a set of expression trees
- Class ModelTree is a sub-class container of DataTree, specialized for storing a set of model equations.
- In the code, we use ModelTree-derived classes: DynamicModel (the model with lags) and StaticModel (the model without lags)
- Class ModFile contains:
  - one instance of DataTree for storing all expressions outside model block
  - several instances of DynamicModel, one each for storing the equations of the model block for the original model, modified model, original Ramsey model, the Ramsey FOCs, etc.
  - one instance of StaticModel for storing the equations of model block without lags
- Expression storage is optimized through three mechanisms:
  - symbolic simplification rules
  - sub-expression sharing
  - pre-computing of numerical constants

Constructing expression trees

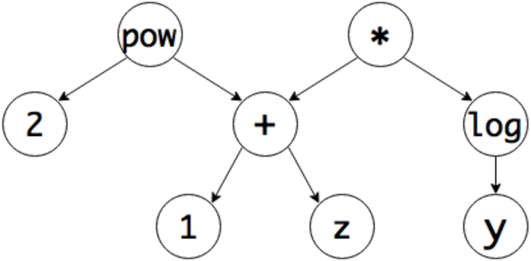
- Class `DataTree` contains a set of methods for constructing expression trees
- Construction is done bottom-up, node by node:
  - one method for adding a constant node (`AddPossiblyNegativeConstant(double)`)
  - one method for a log node (`AddLog(arg)`)
  - one method for a plus node (`AddPlus(arg1, arg2)`)
- These methods take pointers to `ExprNode`, allocate the memory for the node, construct it, and return its pointer
- These methods are called:
  - from `ParsingDriver` in the semantic actions associated to the parsing of expressions
  - during symbolic derivation, to create derivatives expressions
  - when creating the static model from the dynamic model
  - ...

Reduction of constants and symbolic simplifications

- The construction methods compute constants whenever possible
  - Suppose you ask to construct the node $1 + 1$
  - The `AddPlus()` method will return a pointer to a constant node containing 2
- The construction methods also apply a set of simplification rules, such as:
  - $0 + 0 = 0$
  - $x + 0 = x$
  - $0 - x = -x$
  - $-(-x) = x$
  - $x * 0 = 0$
  - $x/1 = x$
  - $x^0 = 1$
- When a simplification rule applies, no new node is created

Sub-expression sharing (1/2)

- Consider the two following expressions: $(1+z)*\log(y)$ and $2^{(1+z)}$
- Expressions share a common sub-expression: $1+z$
- The internal representation of these expressions is:



Sub-expression sharing (2/2)

- Construction methods implement a simple algorithm which achieves maximal expression sharing
- Algorithm uses the fact that each node has a unique memory address (pointer to the corresponding instance of `ExprNode`)
- It maintains 9 tables which keep track of the already-constructed nodes: one table by type of node (constants, variables, unary ops, binary ops, trinary ops, external functions, first deriv of external functions, second deriv of external functions, local variables)
- Suppose you want to create the node $e_1 + e_2$ (where e_1 and e_2 are sub-expressions):
  - the algorithm searches the binary ops table for the tuple equal to (address of e_1, address of e_2, op code of $+$) (it is the search key)
  - if the tuple is found in the table, the node already exists and its memory address is returned
  - otherwise, the node is created and is added to the table with its search key
- Maximum sharing is achieved because expression trees are constructed bottom-up

Final remarks about expressions

- Storage of negative constants
  - class `NumConstNode` only accepts positive constants
  - a negative constant is stored as a unary minus applied to a positive constant
  - this is a kind of identification constraint to avoid having two ways of representing negative constants: (-2) and $-(2)$
- Widely used constants
  - class `DataTree` has attributes containing pointers to constants: 0, 1, 2, -1, `NaN`, ∞, $-\infty$, and π
  - these constants are used in many places (in simplification rules, in derivation algorithm. . .)
  - sub-expression sharing algorithm ensures that these constants will never be duplicated

List of statements

- A statement is represented by an instance of a subclass of the abstract class `Statement`
- Three groups of statements:
  - initialization statements (parameter initialization with $p = \dots$, `initval`, `histval`, or `endval` block)
  - shocks blocks (`shocks`, `mshocks`, ...)
  - computing tasks (`steady`, `check`, `simul`, ...)
- Each type of statement has its own class (*e.g.* `InitValStatement`, `SimulStatement`, ...)
- The class `ModFile` stores a list of pointers of type `Statement*`, corresponding to the statements of the `mod` file, in their order of declaration
- Heavy use of polymorphism in the check pass, computing pass, and when writing outputs: abstract class `Statement` provides a virtual method for these 3 actions

Evaluation context

- The `ModFile` class contains an evaluation context
- It is a map associating a numerical value to some symbols
- Filled in with `initval` block values and parameter initializations
- Used during equation normalization (in the block decomposition), for finding non-zero entries in the jacobian
- Used in testing that trends are compatible with a balanced growth path, for finding non-zero cross partials of equations with respect to trend variables and endogenous varibales

Outline

Error checking during parsing

- Some errors in the `mod` file can be detected during parsing:
  - syntax errors
  - use of undeclared symbols in model block, initval block…
  - use of a symbol incompatible with its type (*e.g.* parameter in initval, local variable used both in model and outside model)
  - multiple shock declarations for the same variable
- But some other checks can only be done when parsing is completed…

Check pass

- The check pass is implemented through the method `ModFile::checkPass()`
- Performs many checks. Examples include:
  - check there is at least one equation in the model (except if doing a standalone BVAR estimation)
  - checks for coherence in statements (*e.g.* options passed to statements do not conflict with each other, required options have been passed)
  - checks for coherence among statements (*e.g.* if `osr` statement is present, ensure `osr_params` and `optim_weights` statements are present)
  - checks for coherence between statements and attributes of `mod` file (*e.g.* `use_dll` is not used with `block` or `bytecode`)

Outline

Transform pass (1/2)

- The transform pass is implemented through the method `ModFile::transformPass(bool nostrict)`
- It makes necessary transformations (notably to the dynamic model, symbol table, and statements list) preparing the `ModFile` object for the computing pass. Examples of transformations include:
  - creation of auxiliary variables and equations for leads, lags, expectation operator, differentiated forward variables, etc.
  - detrending of model equations if nonstationary variables are present
  - decreasing leads/lags of predetermined variables by one period
  - addition of FOCs of Langrangian for Ramsey problem
  - addition of `dsge_prior_weight` initialization before all other statements if estimating a DSGE-VAR where the weight of the DSGE prior of the VAR is calibrated

Transform pass (2/2)

- It then freezes the symbol table, meaning that no more symbols can be created on the `ModFile` object
- Finally checks are performed on the transformed model. Examples include:
  - same number of endogenous varibables as equations (not done in certain situations, *e.g.* Ramsey, discretionary policy, etc.)
  - correspondence among variables and statements, *e.g.* Ramsey policy, identification, perfect foresight solver, and simul are incompatible with deterministic exogenous variables
  - correspondence among statements, *e.g.* for DSGE-VAR without `bayesian_irf` option, the number of shocks must be greater than or equal to the number of observed variables

Outline

Overview of the computing pass

- Computing pass implemented in `ModFile::computingPass()`
- Creates Static model from Dynamic (by removing leads/lags)
- Determines which derivatives to compute
- Then calls `DynamicModel::computingPass()` which computes:
  - leag/lag variable incidence matrix
  - symbolic derivatives w.r.t. endogenous, exogenous, and parameters, if needed
  - equation normalization + block decomposition
  - temporary terms
  - computes equation cross references, if desired
- NB: analagous operations for Static model are performed by `StaticModel::computingPass()`
- Asserts that equations declared linear are indeed linear (by checking that Hessian $==0$)
- Finally, calls `Statement::computingPass()` on all statements

Model Variables

- In the context of class `ModelTree`, a variable is a pair (symbol, lag)
- The symbol must correspond to a variable of type endogenous, exogenous, deterministic exogenous variable, or parameter
- The `SymbolTable` class keeps track of valid symbols while the `variable_node_map` keeps track of model variables (symbol, lag pairs stored in `VariableNode` objects)
- After the computing pass, the `DynamicModel` class writes the leag/lag incidence matrix:
  - three rows: the first row indicates $t-1$, the second row t, and the third row $t+1$
  - one column for every endogenous symbol in order of declaration; NB: includes endogenous auxiliary variables created during the transform pass
  - elements of the matrix are either 0 (if the variable does not appear in the model) or correspond to the variable's column in the Jacobian of the dynamic model

Static versus dynamic model

- The static model is simply the dynamic model without leads and lags
- Static model used to characterize the steady state
- The jacobian of the static model is used in the (MATLAB) solver for determining the steady state

Example

- suppose dynamic model is $2x_t \cdot x_{t-1} = 0$
- static model is $2x^2 = 0$, whose derivative w.r.t. x is $4x$
- dynamic derivative w.r.t. x_t is $2x_{t-1}$, and w.r.t. x_{t-1} is $2x_t$
- removing leads/lags from dynamic derivatives and summing over the two partial derivatives w.r.t. x_t and x_{t-1} gives $4x$

Which derivatives to compute?

- In deterministic mode:
  - static jacobian w.r.t. endogenous variables only
  - dynamic jacobian w.r.t. endogenous variables only
- In stochastic mode:
  - static jacobian w.r.t. endogenous variables only
  - dynamic jacobian w.r.t. endogenous, exogenous, and deterministic exogenous variables
  - dynamic hessian w.r.t. endogenous, exogenous, and deterministic exogenous variables
  - possibly dynamic 3rd derivatives (if `order` option ≥ 3)
  - possibly dynamic jacobian and/or hessian w.r.t. parameters (if `identification` or analytic derivs needed for `estimation` and `params_derivs_order` > 0)
- For Ramsey policy: the same as above, but with one further order of derivation than declared by the user with `order` option (the derivation order is determined in the check pass, see `RamseyPolicyStatement::checkPass()`)

Derivation algorithm (1/2)

- Derivation of the model implemented in `ModelTree::computeJacobian()`, `ModelTree::computeHessian()`, `ModelTree::computeThirdDerivatives()`, and `ModelTree::computeParamsDerivatives()`
- Simply call `ExprNode::getDerivative(deriv_id)` on each equation node
- Use of polymorphism:
  - for a constant or variable node, derivative is straightforward (0 or 1)
  - for a unary, binary, trinary op nodes and external function nodes, recursively calls method `computeDerivative()` on children to construct derivative

Derivation algorithm (2/2)

Optimizations

- Caching of derivation results
  - method `ExprNode::getDerivative(deriv_id)` memorizes its result in a member attribute (`derivatives`) the first time it is called
  - the second time it is called (with the same argument), it simply returns the cached value without recomputation
  - caching is useful because of sub-expression sharing
- Efficiently finds symbolic derivatives equal to 0
  - consider the expression $x + y^2$
  - without any computation, you know its derivative w.r.t. z is zero
  - each node stores in an attribute (`non_null_derivatives`) the set of variables which appear in the expression it represents ($\{x, y\}$ in the example)
  - this set is computed in `prepareForDerivation()`
  - when `getDerivative(deriv_id)` is called, immediately returns zero if `deriv_id` is not in that set

Temporary terms (1/2)

- When the preprocessor writes equations and derivatives in its outputs, it takes advantage of sub-expression sharing
- In MATLAB static and dynamic output files, equations are preceded by a list of temporary terms
- These terms are variables containing expressions shared by several equations or derivatives
- Using these terms greatly enhances the computing speed of the model residual, jacobian, hessian, or third derivative

Example

The equations:

```
residual(0)=x+y^2-z^3;
residual(1)=3*(x+y^2)+1;
```

Can be optimized in:

```
T1=x+y^2;
residual(0)=T1-z^3;
residual(1)=3*T1+1;
```

Temporary terms (2/2)

- Expression storage in the preprocessor implements maximal sharing but this is not optimal for the MATLAB output files, because creating a temporary variable also has a cost (in terms of CPU and of memory)
- Computation of temporary terms implements a trade-off between:
  - cost of duplicating sub-expressions
  - cost of creating new variables
- Algorithm uses a recursive cost calculation, which marks some nodes as being "temporary"
- *Problem*: redundant with optimizations done by the C/C++ compiler (when Dynare is in DLL mode) ⇒ compilation very slow on big models

The special case of Ramsey policy

- For most statements, the method `computingPass()` is a no-op...
- ...except for `planner_objective` statement, which serves to declare planner objective when doing optimal policy under commitment
- Class `PlannerObjectiveStatement` contains an instance of `ModelTree`, which stores the objective function (`i.e.` only one equation in the tree)
- During the computing pass, triggers the computation of the first and second order (static) derivatives of the objective

Outline

Output overview

- Implemented in `ModFile::writeOutputFiles()`
- If `mod` file is `model.mod`, all created filenames will begin with `model`
- Main output file is `model.m`, containing:
  - general initialization commands
  - symbol table output (from `SymbolTable::writeOutput()`)
  - lead/lag incidence matrix (from `DynamicModel::writeDynamicMFile()`)
  - call to MATLAB functions corresponding to the statements of the `mod` file (written by calling `Statement::writeOutput()` on all statements through polymorphism)
- Subsidiary output files:
  - one for the static model
  - one for the dynamic model
  - one for the auxiliary variables
  - one for the steady state file (if relevant)
  - one for the planner objective (if relevant)

Model output files

Three possible output types:

- MATLAB/Octave mode: static and dynamic files in MATLAB
- Julia mode: static and dynamic files in Julia
- DLL mode:
  - static and dynamic files in C++ source code (with corresponding headers)
  - compiled through `mex` to allow execution from within MATLAB
- Sparse DLL mode:
  - static file in MATLAB
  - two possibilities for dynamic file:
    - by default, a C++ source file (with header) and a binary file, to be read from the C++ code
    - or, with `no_compiler` option, a binary file in custom format, executed from MATLAB through `simulate` DLL
    - the second option serves to bypass compilation of C++ file which can be very slow

Outline

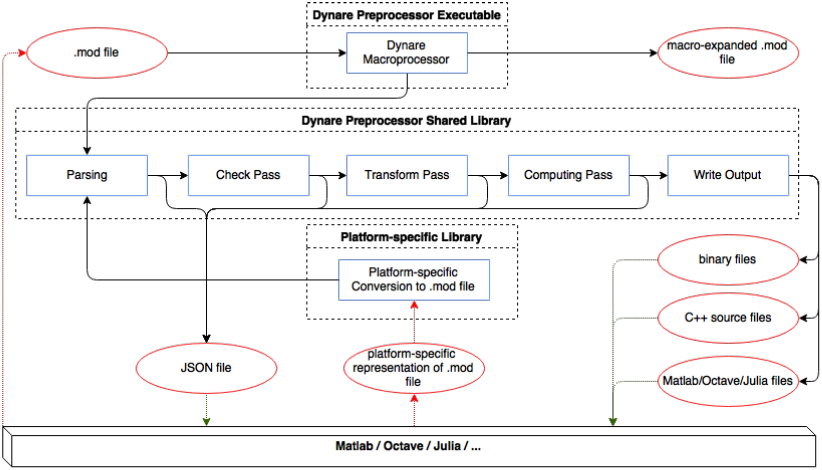
Proposed changes with addition of Julia support (1/2)

1. Julia output is provided upon parsing of `mod` file, everything else done in Julia
   - Pros: very few changes to the preprocessor
   - Cons: repeated code (same checks, transformations, computations done in preprocessor and Julia); potential code divergence/two parallel projects
2. Dump preprocessor altogether: do everything with Julia
   - Pros: simple to distribute, move away from C++ (no contributions, requires more expertise)
   - Cons: MATLAB/Octave users must also download Julia, a big project, speed (?)

Proposed changes with addition of Julia support (2/2)

3. Create libraries out of the preprocessor
   - Pros: Dynare interaction similar across HLPs, preprocessor used as is
   - Cons: difficult for outsiders to contribute, big project, not much benefit in speed when compared to…
4. Write `mod` file from HLP then call preprocessor; option to output JSON file representing `ModFile` object at every step of the preprocessor
   - Pros: Dynare interaction similar across HLPs, preprocessor used as is, minimal amount of work, easy incremental step, allows users to support any given HPL given the JSON output
   - Cons: unnecessary processing when certain changes made in host language, keeps defaults of current preprocessor, speed (?)
5. Other ideas?

Using HLP mod file objects (1/2)



Using HLP `mod` file objects (2/2)

- Allows interactivity for all HLPs; requires only
  - A definition of a mod file class in the HLP
  - A library function that converts an HLP mod file object to a `mod` file
- Allows users to use Dynare with any HPL. Standard JSON output can be read in any HPL; user can use it construct desired HPL objects and work with model in their language of preference
- Easy first step
- No divergence of codebase: don't need to repeat code (checks, transformations, etc.) across platforms
- Creates `mod` files that can be used on other host language platforms
- Adds one more HLP library to distribute
- Need to design/implement classes that will store processed dynare `mod` file in various HLPs