MATLAB / Simulink Lab Course

Code Generation

Lehrstuhl für
Flugsystemdynamik

Objectives & Preparation “Simulink Control Design"

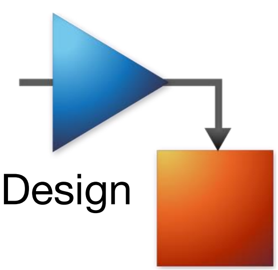
- Which MathWorks products are covered?
  - ⇨ MATLAB Coder
  - ⇨ Simulink Coder

- What skills are learnt?
  - ⇨ How to generate C/C++ code from MATLAB code
  - ⇨ MATLAB code design considerations for automatic code generation
  - ⇨ How to generate C/C++ code from Simulink models
  - ⇨ Modelling considerations for automatic code generation and Simulink Model Advisor

- How to prepare for the session?
  - ⇨ Tutorials for the MATLAB Coder:
    - https://de.mathworks.com/help/coder/getting-started-with-matlab-coder.html
  - ⇨ Tutorials for the Simulink Coder:
    - https://de.mathworks.com/help/rtw/getting-started.html

Outline

1. Introduction
2. MATLAB Code Generation & Deployment
   - MATLAB Coder GUI
   - MATLAB Coder Command Line
3. MATLAB Coder: Requirements & Best Practices
   - Supported Features and Code Design Considerations
   - Differences Between Generated Code and MATLAB Code
4. Simulink Code Generation & Deployment
   - Targets and Target Files
   - Code Generation / Build
5. Simulink Coder: Model Architecture & Design
   - Modeling Considerations
   - Model Advisor



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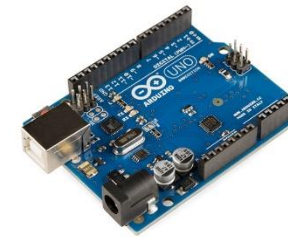

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1. Introduction

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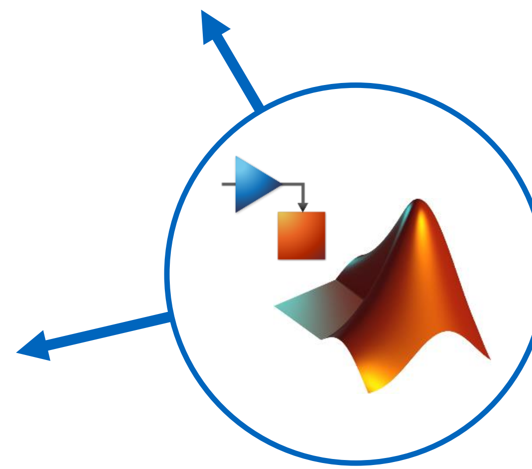
Introduction – Why Code Generation?

Why should one generate C/C++ code from MATLAB code or from Simulink models?

- To deploy algorithms developed in Simulink on embedded hardware
  - For instance, flight control laws implemented in Simulink can be deployed on a flight control computer (FCC).
  - This approach is faster than programming the control laws by hand in the embedded software language and it reduces the risk of errors and bugs.



- To accelerate the execution of a program
  - MATLAB code is generally slower than C/C++ code

- To generate production code

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Introduction – Why Code Generation?

- Terminology and some more example applications…

Application	Target Environment	
Intellectual Property Protection Accelerated Simulation Rapid Simulation System Simulation	Host Computer	The same computer that runs MATLAB. Typically a desktop PC with a non-real-time operating system.
Rapid Prototyping On-target Rapid Prototyping	Real-Time Simulator	A different computer that uses a real-time operating system.
Production Code Generation Software-in-the-loop (SIL) simulation Processor-in-the-loop (PIL) simulation Hardware-in-the-loop (HIL) testing	Embedded Microprocessor	A computer that you eventually disconnect from a host computer and run as a standalone computer as part of an electronics-based product.

Introduction – Coder Overview

MATLAB Coder
Generate C and C++ code from
from MATLAB code

Simulink Coder
Generate C and C++ code from
Simulink and Stateflow model

Embedded Coder
Generate C and C++ code
optimized for embedded systems
Expands MATLAB and Simulink Coder

HDL Coder
Generate Verilog and VHDL code
for FPGA and ASIC designs

Simulink PLC Coder
Generate IEC 61131-3 Structured
Text for PLCs and PACs

Introduction – MATLAB Coder and Simulink Coder

MATLAB Coder

- Generates standalone C and C++ code, libraries, DLLs and executables (*.exe) from MATLAB code.
- The generated source code is portable and readable.
- Supports most MATLAB language features, incl. functions and matrix operations.
- Can generate MATLAB executables (*.mex)
  - ➢ Accelerate computationally intensive portions of MATLAB code.
  - ➢ Verify the behavior of the generated code.

and

Simulink Coder

- Generates and executes C and C++ code from Simulink diagrams, Stateflow charts and MATLAB functions.
- The generated source code can be used for real-time and non-real-time applications, including simulation acceleration, rapid prototyping, and hardware-in-the-loop testing.
- The generated code can be tuned and monitored using Simulink.

Introduction – Compiler Setup

- A C or C++ compiler is required for both MATLAB and Simulink Coder.

- The MATLAB help provides a full list of supported compilers.
  - Microsoft Visual C++, for example, is compatible with most coding functionalities.
  - Alternatively, to download the MATLAB Support for MinGW-w64 C/C++ Compiler Add-On, visit: `https://de.mathworks.com/matlabcentral/fileexchange/52848-matlab-support-for-mingw-w64-c-c-compiler`

- MATLAB Coder automatically locates and uses a supported installed compiler.

- To choose a default compiler yourself, type

```
mex -setup
```

or, in case you want to specify a C++ compiler,

```
mex -setup cpp
```

- Then, follow through the short configuration process.

2. MATLAB Code Generation & Deployment

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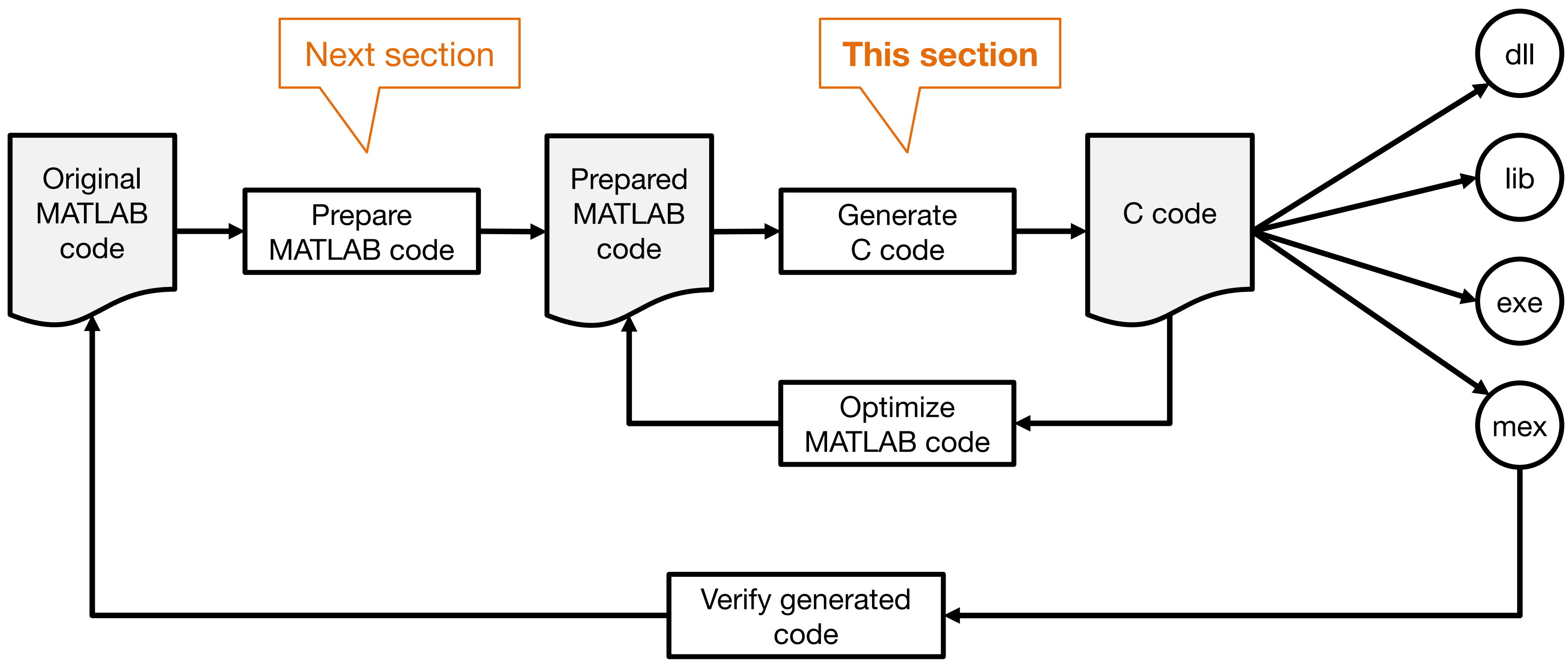
MATLAB Code Generation – Workflow

Common Workflow for generating C code from MATLAB



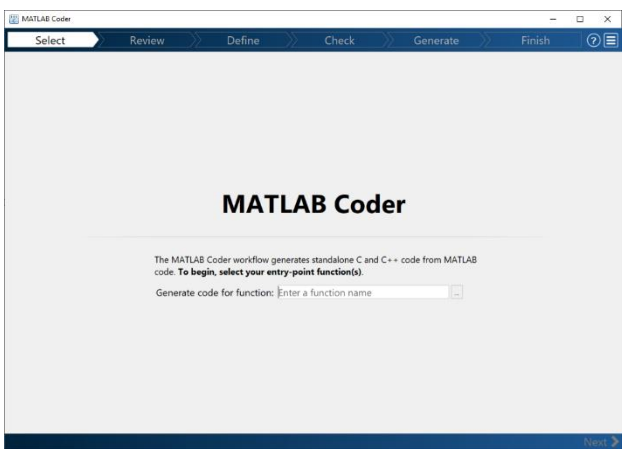
MATLAB Code Generation – MATLAB Coder GUI and Command Line

There are two ways to use the MATLAB Coder:

MATLAB Coder GUI

+ Easy to use
+ Settings stored in project file

- Not automatable



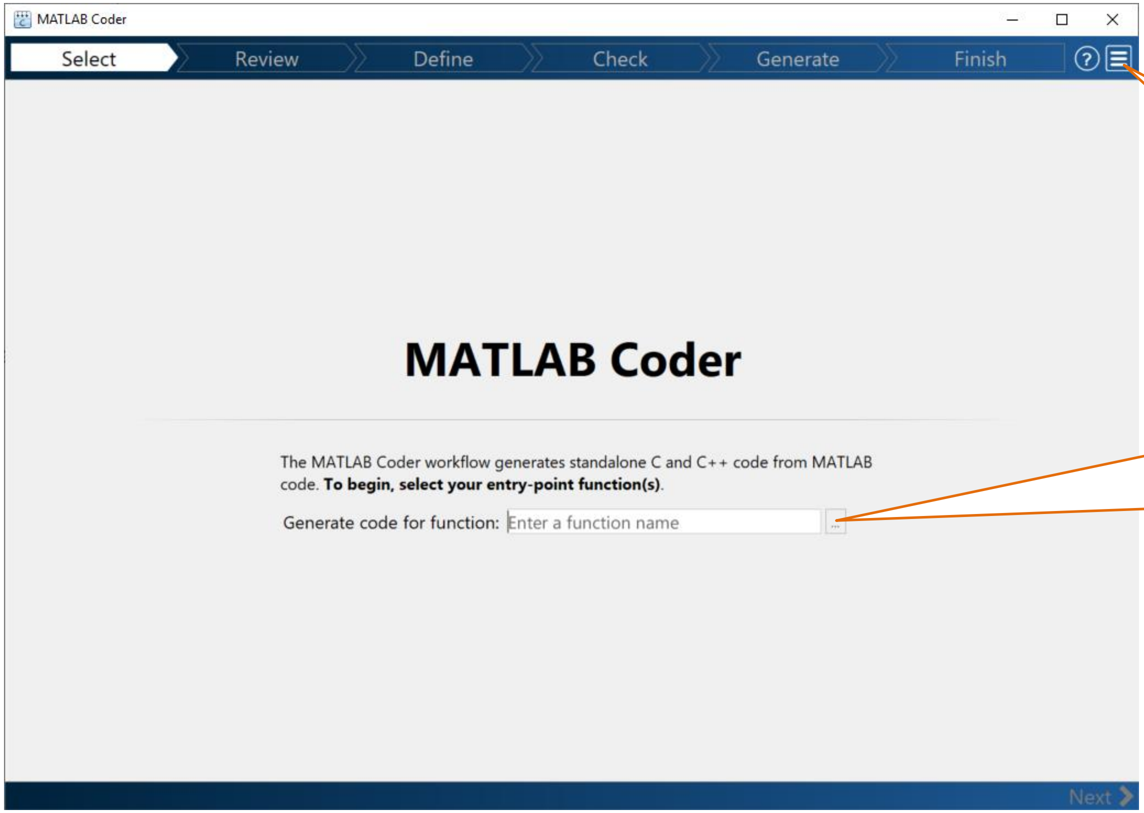
Command line: codegen

+ Faster for simple applications
+ Dynamic compilation within a MATLAB program (automatable)

- Syntax needs to be learned
- Complex function calls may be required for specific problems

MATLAB Code Generation – MATLAB Coder GUI

- On the MATLAB toolstrip tab *Apps*, under *Code Generation*, click the *MATLAB Coder* app icon.



This button leads to a menu that lets you open an existing project.

To create a new project, specify the entry-point function here. (This is the function that you call from MATLAB.) Then click *Next*.

File names may not contain spaces!

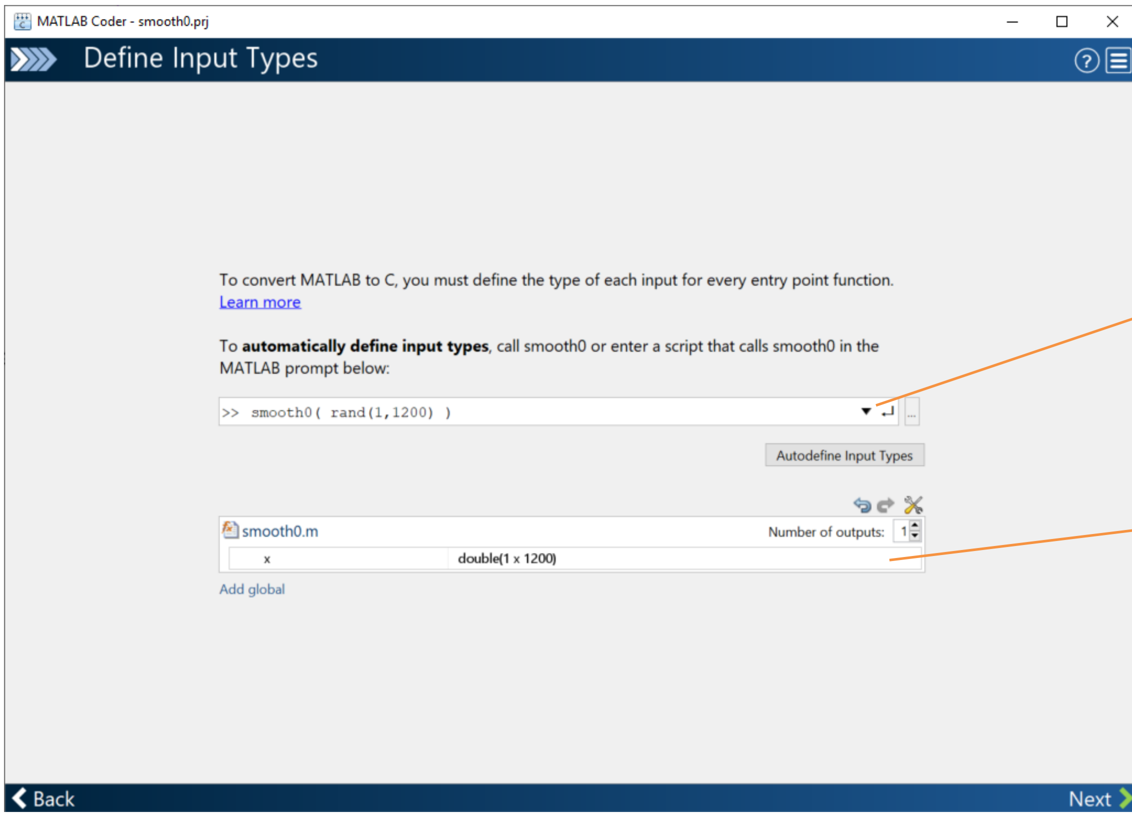
MATLAB Code Generation – MATLAB Coder GUI

- Suppose you want to create code from a MATLAB function `smooth0.m`, which implements a simple moving average filter (see right side).
  This is the following window of the MATLAB Coder GUI:

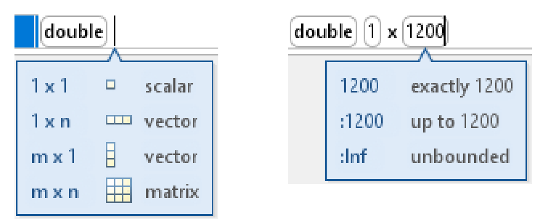
```matlab
function y = smooth0(x) %#codegen

y = zeros(1,length(x)-16);

% Calculate matrix multiplication
for iter = 1:length(x)-16
    y(iter) = mean(x(iter:iter+16));
end
```

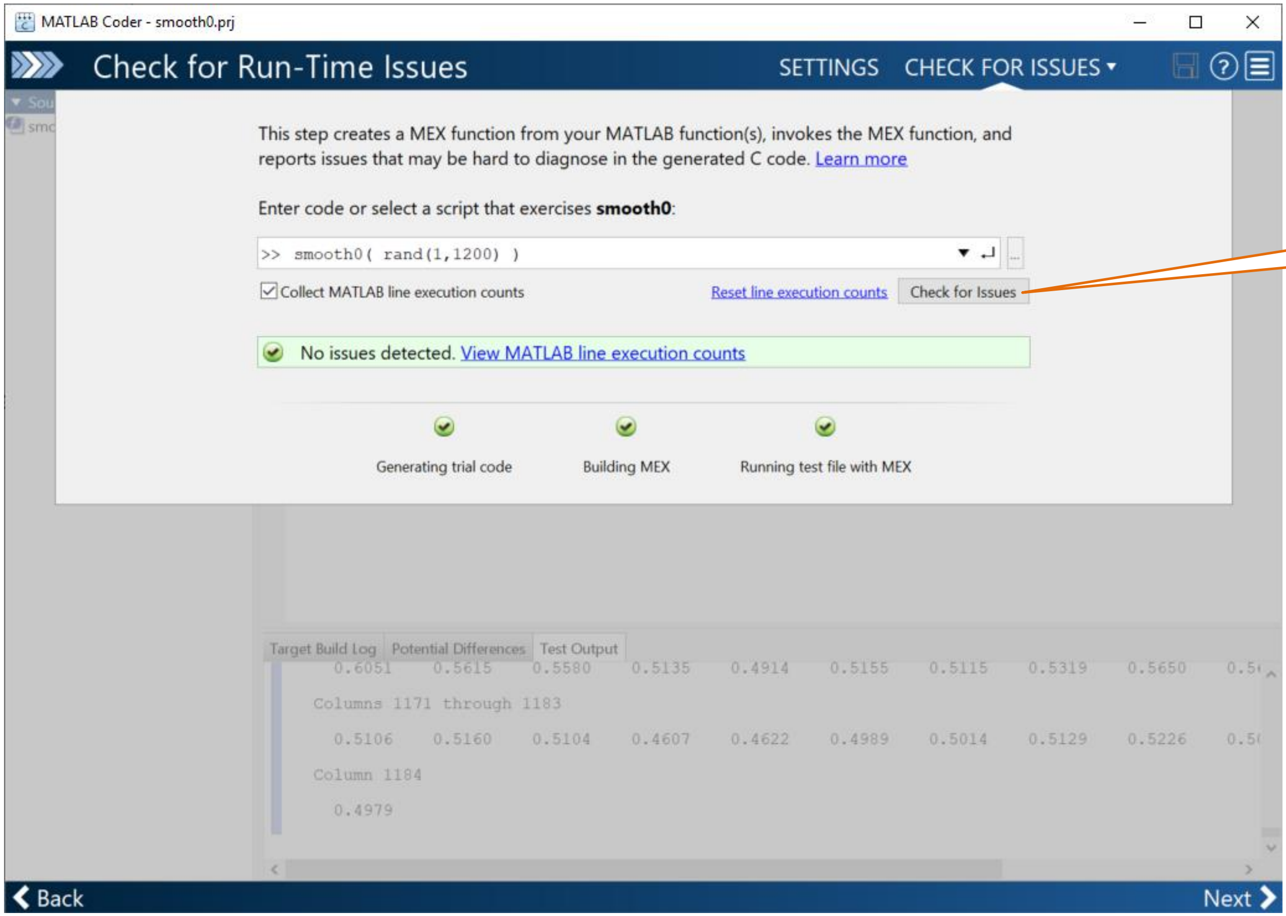


- You can either have the input types defined automatically by calling the function, or
- you can manually specify all inputs:



MATLAB Code Generation – MATLAB Coder GUI

- In the following step, you can check for run-time issues.



Starts the check

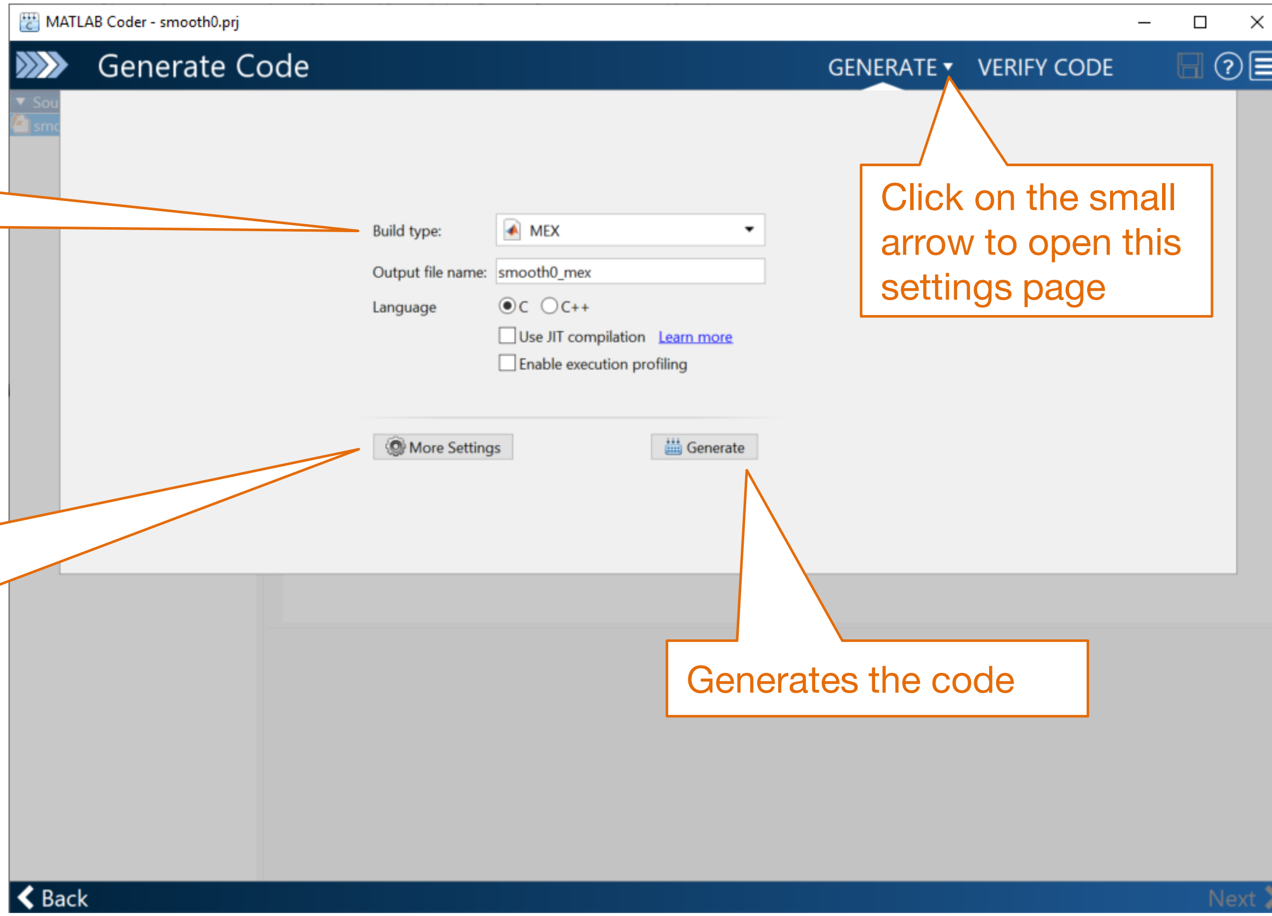
This check is optional, so you may skip it by clicking *Next*.

MATLAB Code Generation – MATLAB Coder GUI

- Configuring settings is possible before actual code generation

Type of build to be generated. Here: MATLAB executable

Opens more settings for fine tuning of generated code in a new window
→ see next slide

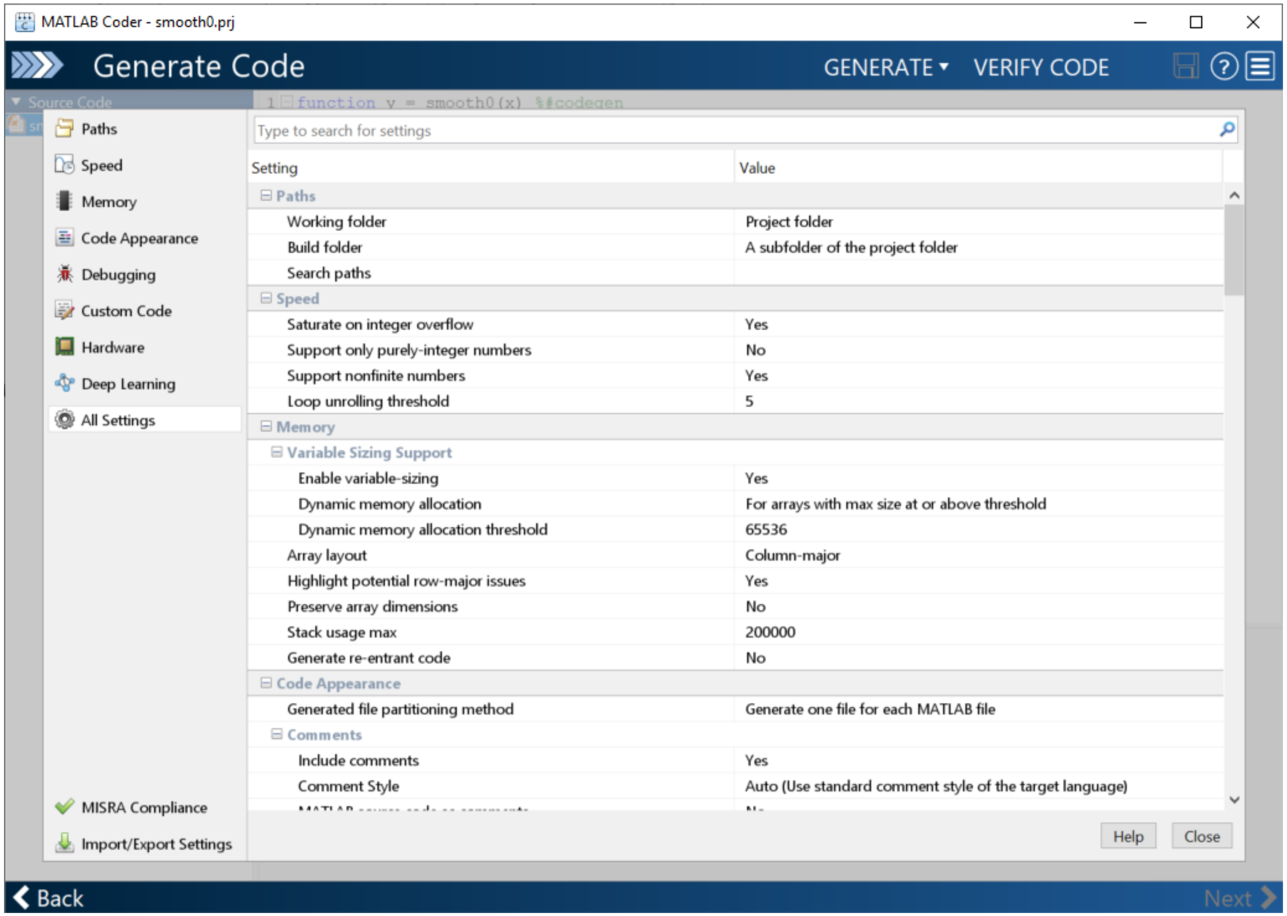


Click on the small arrow to open this settings page

Generates the code

MATLAB Code Generation – MATLAB Coder GUI

- More available settings depend on the build type



MATLAB Code Generation – MATLAB Coder Command Line

- Instead of using the GUI, the command line can be used as follows:

```
codegen smooth0 -args coder.typeof( rand(1,1200) )
```

- Generally, the (simplified) syntax is as follows:

```
codegen options function arguments
```

Options

MATLAB function name

Cell array of input arguments

- Example options:

```
-config:mex          % Generate MEX file (default)
-config:lib          % Generate static C/C++ library
-d output_folder     % Specify output folder
-o output_file_name  % Specify output file name
-report              % Generate code generation report
```

→ See next slide

MATLAB Code Generation – MATLAB Coder Generated Code

Generated MEX file

```c
#include "rt_nonfinite.h"
#include "smooth0.h"
#include "smooth0_data.h"

void smooth0(const emlrtStack *sp, const real_T x[1200],
real_T y[1184])
{
  int32_T iter;
  real_T b_y;
  int32_T k;

  /*  Calculate matrix multiplication */
  for (iter = 0; iter < 1184; iter++) {
    b_y = x[iter];
    for (k = 0; k < 16; k++) {
      b_y += x[(k + iter) + 1];
    }

    y[iter] = b_y / 17.0;
    if (*emlrtBreakCheckR2012bFlagVar != 0) {
      emlrtBreakCheckR2012b(sp);
    }
  }
}
```

Generated LIB file

```c
#include "smooth0.h"

void smooth0(const double x[1200], double y[1184])
{
  int iter;
  double b_y;
  int k;

  /*  Calculate matrix multiplication */
  for (iter = 0; iter < 1184; iter++) {
    b_y = x[iter];
    for (k = 0; k < 16; k++) {
      b_y += x[(k + iter) + 1];
    }

    y[iter] = b_y / 17.0;
  }
}
```

```matlab
function y = smooth0(x) %#codegen

y = zeros(1,length(x)-16);

% Calculate matrix multiplication
for iter = 1:length(x)-16
    y(iter) = mean(x(iter:iter+16));
end
```

3. MATLAB Coder Requirements & Best Practices

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MATLAB Coder Requirements & Best Practices – Supported MATLAB Language Features

- N-dimensional arrays
- Matrix operations, including deletion of rows and columns
- Variable-sized data
- Subscripting
- Complex numbers
- Double-precision, single-precision, and integer math
- Fixed-point arithmetic
- Program control statements if, switch, for, while, and break
- Arithmetic, relational, and logical operators
- Persistent and global variables
- Structures, cell arrays, tables and MATLAB classes
- Function handles
- Anonymous, recursive, and nested functions
- Subset of MATLAB toolbox functions
- Variable length input and output argument lists
- …

An incomprehensive list

Not supported:
- Scripts
- Implicit expansion
- GPU arrays
- `datetime` arrays
- Time series objects
- Java
- Map containers
- `try/catch` statements

As of MATLAB Version R2019b, refer to
https://de.mathworks.com/help/simulink/ug/matlab-language-features-supported-for-code-generation.html

MATLAB Coder Requirements & Best Practices – Code Design Considerations

- Data types

  C and C++ use static typing. To determine the types of your variables before use, MATLAB Coder requires a complete assignment to each variable.

- Array sizing

  Variable-size arrays and matrices are supported for code generation. You can define inputs, outputs, and local variables in MATLAB functions to represent data that varies in size at run time.

- Memory

  You can choose whether the generated code uses static or dynamic memory allocation.
  - Static memory: + better speed - higher memory usage
  - Dynamic memory: + potentially less memory usage - time required to manage memory

- Speed

  Because embedded applications must run in real time, the code must be fast enough to meet the required clock rate. To improve the speed of the generated code:
  - Choose a suitable C/C++ compiler
  - Consider disabling run-time checks

Source: Modified from https://de.mathworks.com/help/simulink/ug/design-considerations-when-writing-matlab-code-for-code-generation.html

MATLAB Coder Requirements & Best Practices – Differences Between Generated Code and MATLAB Code

Code generation inevitably includes code optimization, which intentionally causes the generated code to behave differently, i.e., more efficiently. Therefore, the results of the generated code may vary from the results of the original MATLAB code!

To prevent unwanted code behavior, keep the following (possible) differences in mind and address them where necessary.

- Order of evaluation in expressions

  Generated code does not enforce order of evaluation in expressions. However, for expressions with side effects it is important to retain the order of evaluation (e.g. persistent/global variables, display data, write to files)

```
A = f1() + f2();
```

If `f1()` needs to be called before `f2()` to produce the desired result, rewrite the expression

```
A = f1();
A = A + f2();
```

- Character size → Do not perform arithmetic with characters

  MATLAB: 16 bits; Generated code: 8 bits (standard size for e.g. C)

- Size of variable-size N-D arrays → Use the two-argument form of `size`

Source: Modified from https://de.mathworks.com/help/simulink/ug/expected-differences-in-behavior-after-compiling-your-matlab-code.html

MATLAB Coder Requirements & Best Practices – Differences Between Generated Code and MATLAB Code

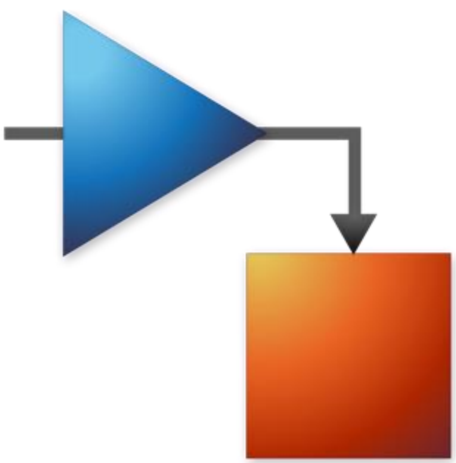
- Size of empty arrays
  - Instead of `size`, use `isempty`
  - Instead of `x=[]`, create an empty array `x` using `zeros`
- Termination behavior

  For instance, infinite loops are removed if they do not have side effects.
- Floating-point numerical results may be different
  - When computer hardware uses extended precision registers
  - For certain advanced library functions
  - For implementation of BLAS library functions
- NaN and infinity patterns

  The generated code might not produce exactly the same pattern of `NaN` and `inf` values as MATLAB code when these values are mathematically meaningless.
- Complex numbers, negative zero
- … For a complete list and possible workarounds, refer to the link below

Source: Modified from
https://de.mathworks.com/help/simulink/ug/expected-differences-in-behavior-after-compiling-your-matlab-code.html

4. Simulink Code Generation & Deployment



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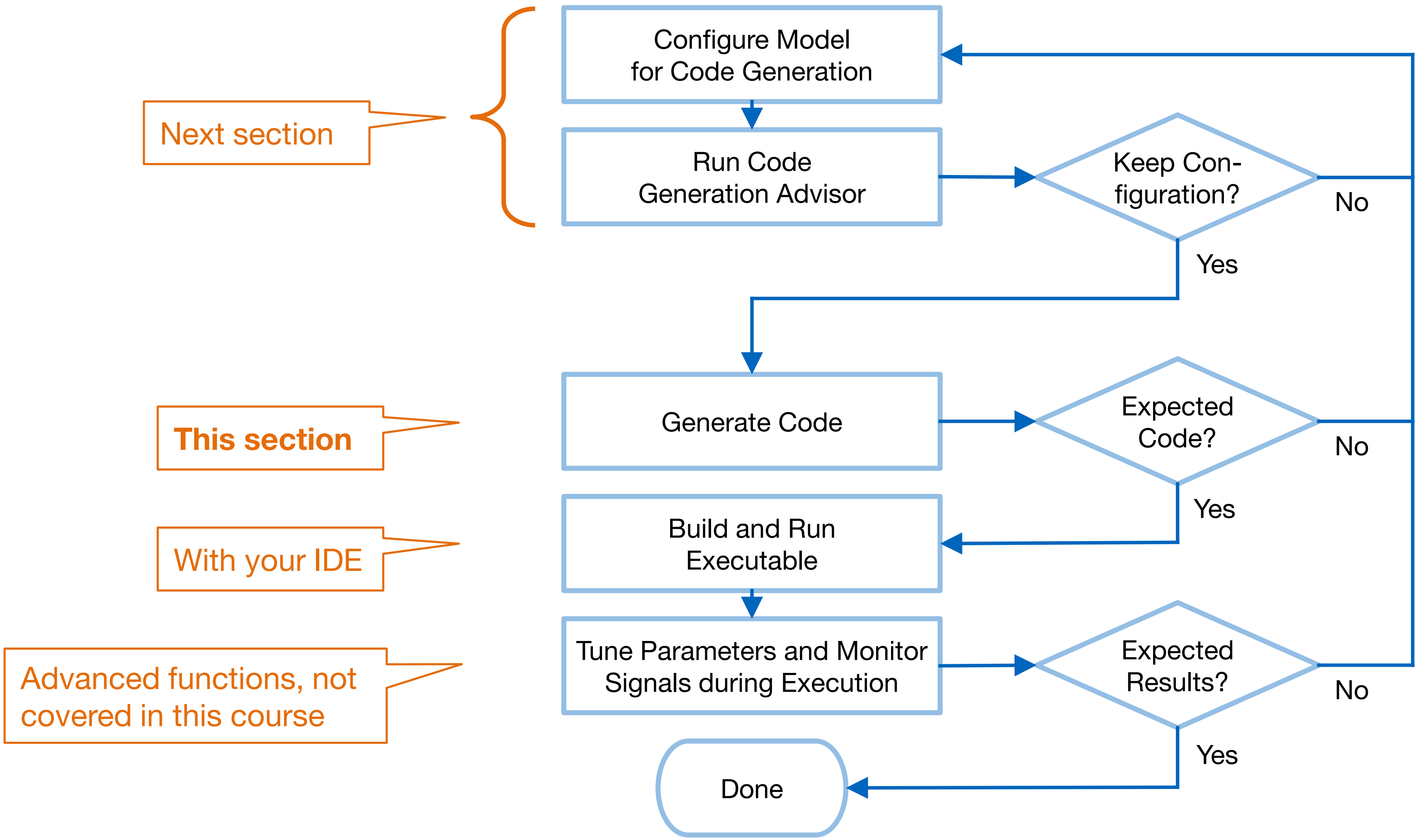
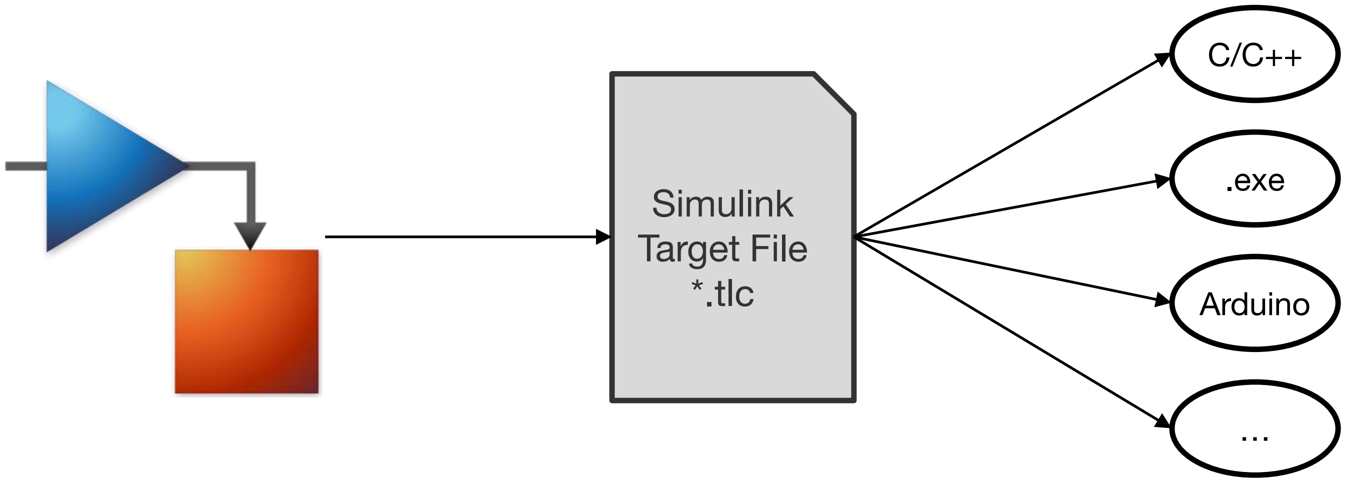
Simulink Code Generation & Deployment – Workflow



Simulink Code Generation & Deployment – Targets

Definition: A **target** is an environment for generating and building code for execution on a certain hardware or operating system platform.

- Target Language Compiler (TLC) files
  - Defines how the model is translated to code and executables
  - Specify the target environment
  - Support for built in / third party / custom targets

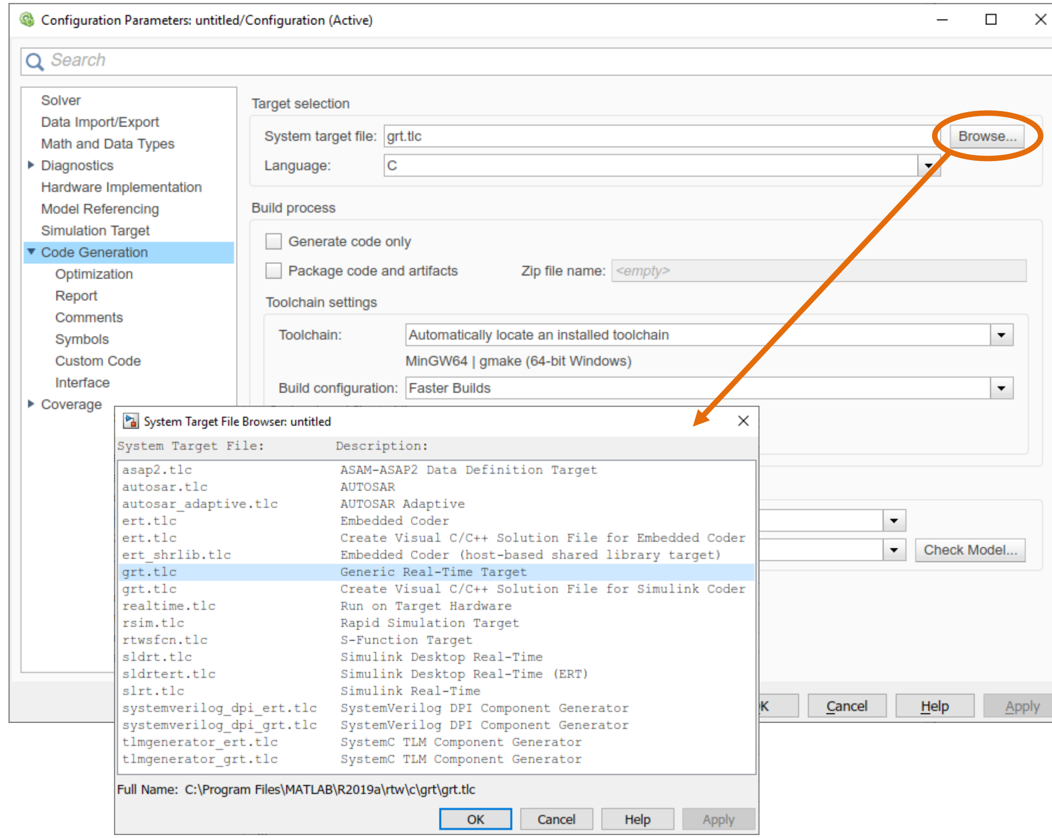


- The **application** determines the target file to be used!

Simulink Code Generation & Deployment – Target Files

The target file can be selected in the Configuration Parameters window.
Some examples…

- Generic Real Time (**`grt.tlc`**)
  - Simulate model as standalone on computer → confirm that generated code runs correct
  - Run Simulink model in external mode
  - Use grt target file as template for custom *.tlc files
- Rapid Simulation Target (**`rsim.tlc`**)
  - Run on remote computer
  - Distributed computing (e.g. Monte Carlo)
  - Stand-alone (pseudo) realtime simulation
  - Variable-step solver possible!



Usually, a fixed-step solver must be used for code generation.

Simulink Code Generation & Deployment – Target Files

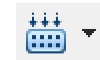
- Embedded Real Time Target (**`ert.tlc`**)
  - Embedded code applications
  - Highly optimized code (RAM and ROM)
  - Runs on virtually any processor

- AUTomotive Open System ARchitecture (**`autosar.tlc`**)
  - Automotive applications

- Shared Library Target (**`ert_shrlib.tlc`**)
  - Generate shared library
    - Windows: Dynamic Link Library DLL
    - Unix: Shared Object SO

- A comparison of the supported system target files can be found in the Simulink documentation, refer to (requires login):
  - https://de.mathworks.com/help/rtw/ug/compare-system-target-file-support.html
  - https://de.mathworks.com/help/rtw/ug/customizing-system-target-files.html

Simulink Code Generation & Deployment – Code Generation / Build Settings

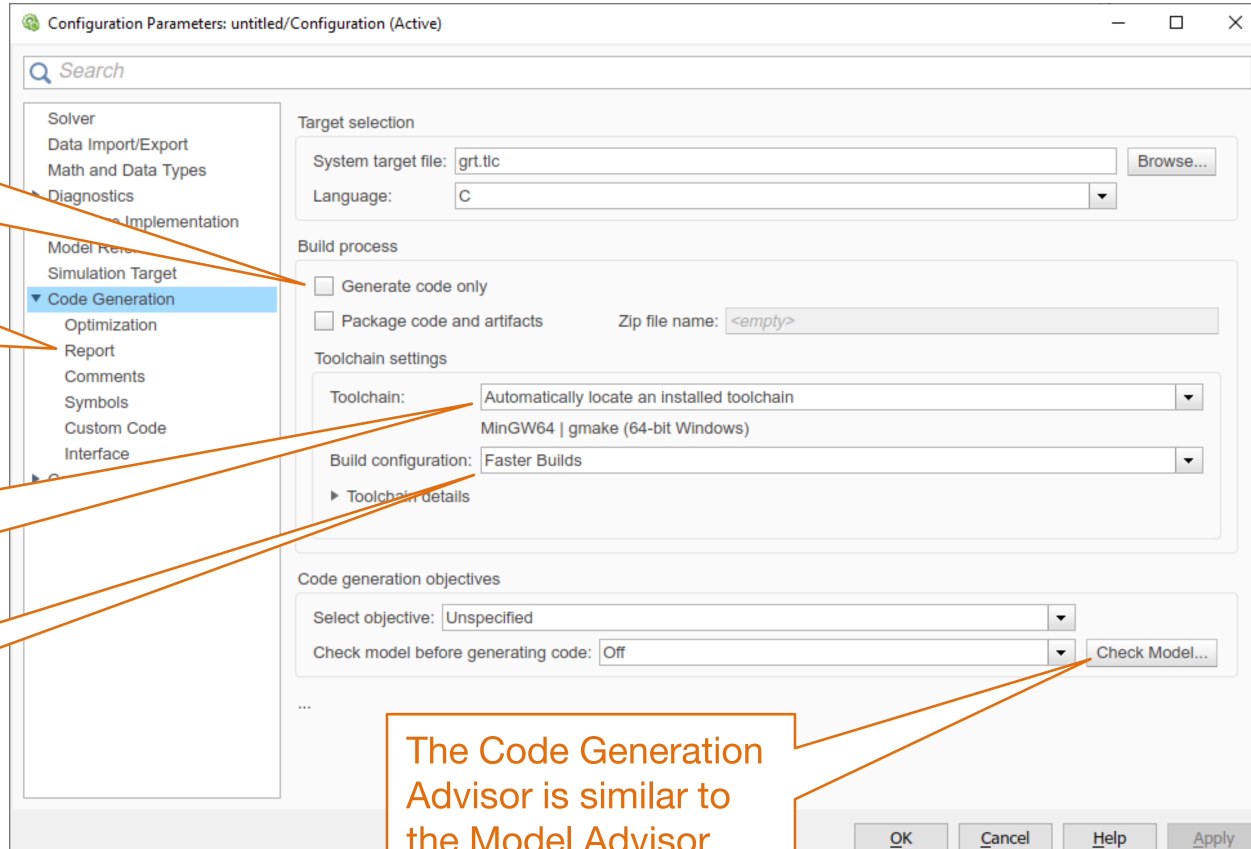
- Build generation can be triggered in the model window with this button: 

You can choose to generate code only (or also execute the make file / build) …

… and generate a code generation report.

You can specify and validate the code generation toolchain, and …

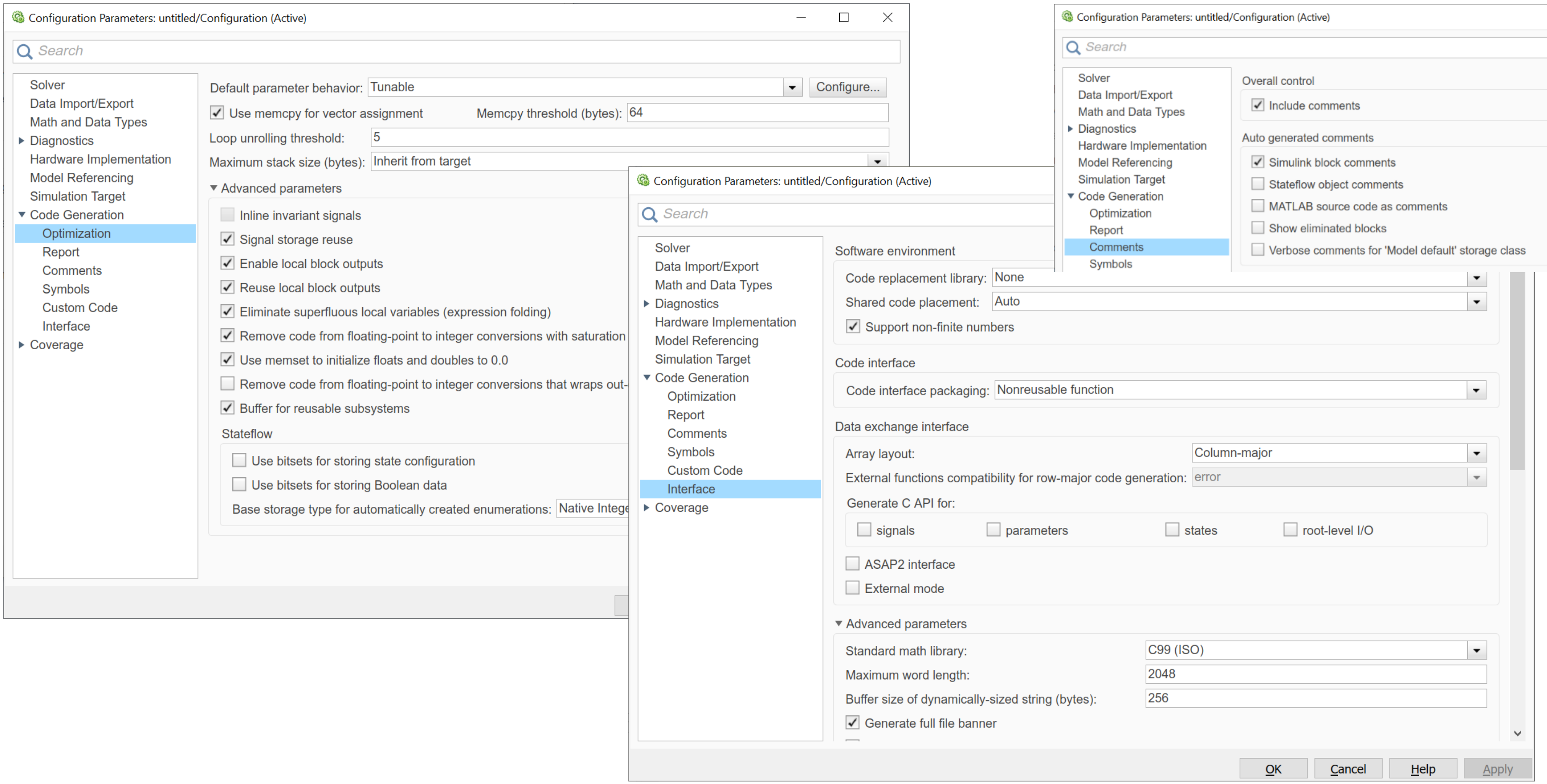
… you can prioritize build time, execution time, etc.



The Code Generation Advisor is similar to the Model Advisor (see next section).

Simulink Code Generation & Deployment – Code Generation / Build Settings

- Model configuration parameters: Available options depend on selected TLC file.



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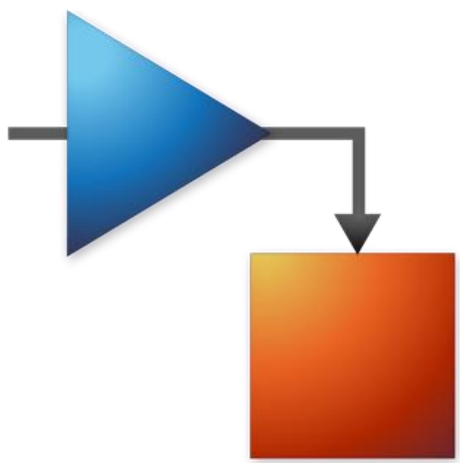
5. Simulink Coder Model Architecture & Design



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Simulink Coder: Model Architecture & Design – Basic Modeling Considerations

- Products and blocks used: Do they support code generation?
- Signal naming: Which signals should carry a meaningful name?

…so they can later be identified in the code!
→ see next slides

- Model componentization: Subsystems, libraries or model referencing?
  - **Subsystems** and **Libraries**: Code generation supported, with limitations.
    For detected identical subsystems, the generated code includes only one copy of code for the multiple subsystems. Note: subsystems can be virtual or atomic (see next slides).
  - **Model referencing**: Well suited for code generation.
    The generated code reflects the model structure.
- Subsystems: Virtual or atomic?

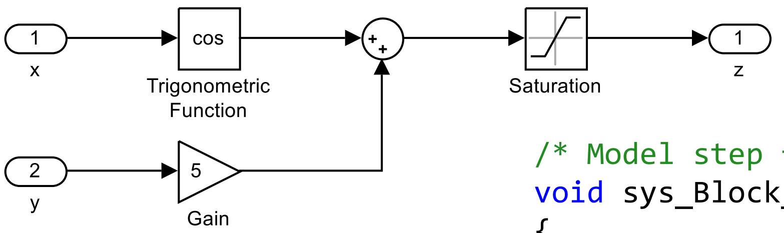
→ see next slides

- Parameterization: Virtual parameters or parameter objects?

→ see next slides

Simulink Coder: Model Architecture & Design – Basic Modeling Considerations: Signal Naming

- If possible, signals between blocks are automatically resolved during code generation.



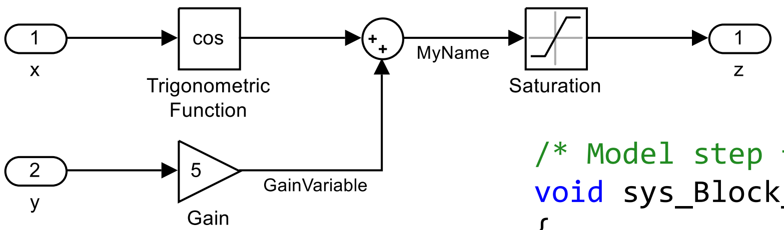
Input and output names in code are taken from Simulink model.

Intermediate variable u0 is created by the code generator.

```c
/* Model step function */
void sys_Block_custom(real_T *arg_x, real_T *arg_y, real_T *arg_z)
{
  real_T u0;

  u0 = 5.0 * *arg_y + cos(*arg_x);

  /* Saturate: '<Root>/Saturation' */
  if (u0 > sys_BlockAndSignal_P.Saturation_UpperSat) {
    /* Outport: '<Root>/z' */
    *arg_z = sys_BlockAndSignal_P.Saturation_UpperSat;
  } else if (u0 < sys_BlockAndSignal_P.Saturation_LowerSat) {
    /* Outport: '<Root>/z' */
    *arg_z = sys_BlockAndSignal_P.Saturation_LowerSat;
  } else {
    /* Outport: '<Root>/z' */
    *arg_z = u0;
  }

  /* End of Saturate: '<Root>/Saturation' */
}
```

Simulink Coder: Model Architecture & Design – Basic Modeling Considerations: Signal Naming

- Variable names can be enforced by specifying signal names.



- Double-click on signal, or
- Right click on signal → *Properties*

```
/* Model step function */
void sys_Block_custom(real_T *arg_x, real_T *arg_y, real_T *arg_z)
{
  /* Gain: '<Root>/Gain' incorporates:
   *  Inport: '<Root>/y'
   */
  GainVariable =  5.0 * *arg_y;

  /* Sum: '<Root>/Sum' incorporates:
   *  Inport: '<Root>/x'
   *  Trigonometry: '<Root>/Trigonometric Function'
   */
  MyName = cos(*arg_x) + GainVariable;

  /* Saturate: '<Root>/Saturation' */
  if (MyName > sys_BlockAndSignalName_P.Saturation_UpperSat) {
    /* Saturation block implementation not shown */
  }
  /* End of Saturate: '<Root>/Saturation' */
}
```

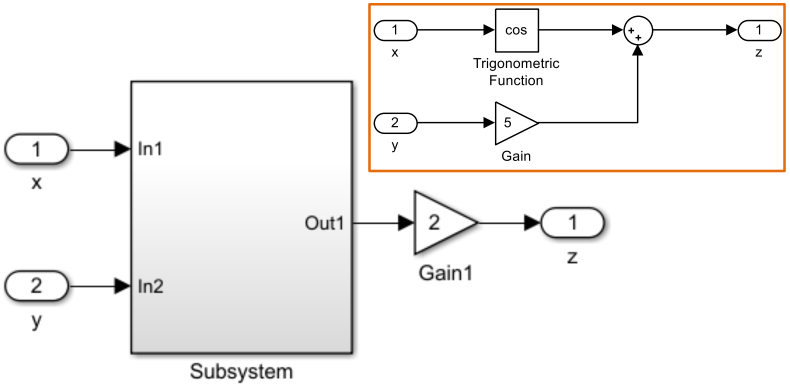
Intermediate variables `GainVariable` and …

… MyName are created by the code generator.

Simulink Coder: Model Architecture & Design – Basic Modeling Considerations: Virtual vs. Atomic Subsystems

- Virtual subsystems are automatically resolved for code generation.

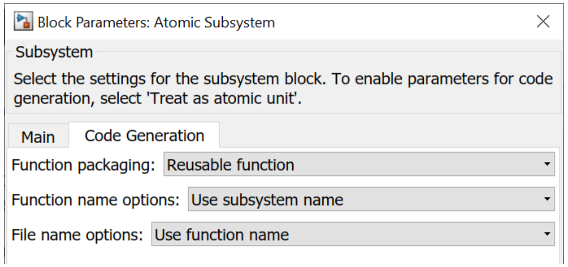
Note: Virtual subsystems or blocks merely change the graphical representation of the model!

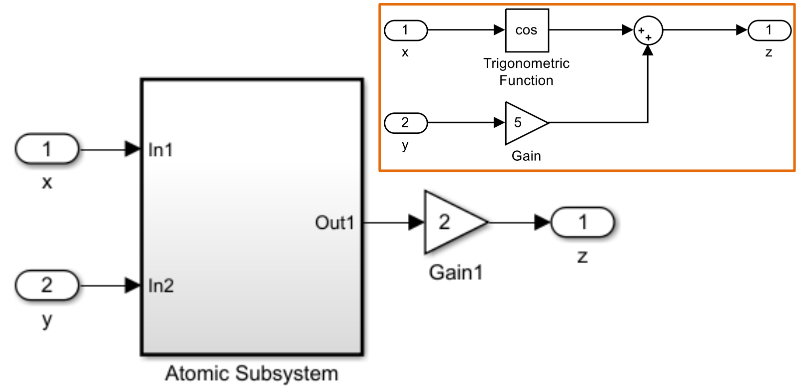



```
/* Model step function */
void sys_Block_custom(real_T *arg_x, real_T *arg_y,
real_T *arg_z)
{
  /* Outport: '<Root>/z' incorporates:
   *  Gain: '<Root>/Gain1'
   *  Gain: '<S1>/Gain'
   *  Inport: '<Root>/x'
   *  Inport: '<Root>/y'
   *  Sum: '<S1>/Sum'
   *  Trigonometry: '<S1>/Trigonometric Function'
   */
  *arg_z = (5.0 * *arg_y + cos(*arg_x)) * 2.0;
}
```

Simulink Coder: Model Architecture & Design – Basic Modeling Considerations: Virtual vs. Atomic Subsystems

- By using atomic subsystems, you can enforce the creation of (reusable) functions.

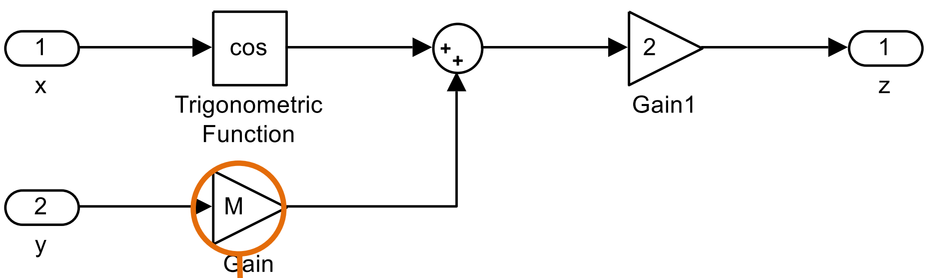




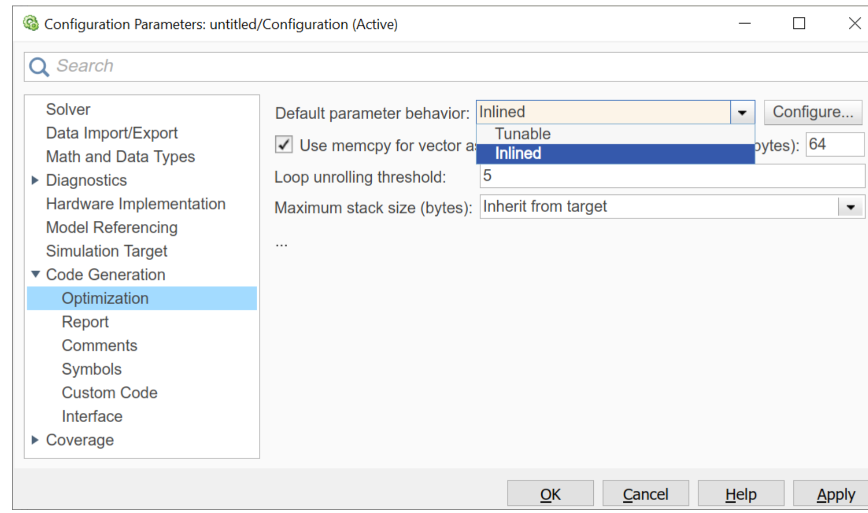

```c
/* Output and update for atomic system: '<Root>/Atomic Subsystem' */
void sys_AtomicSubsy_AtomicSubsystem(real_T rtu_In1, real_T rtu_In2,
  B_AtomicSubsystem_sys_AtomicS_T *localB)
{
  localB->Sum = 5.0 * rtu_In2 + cos(rtu_In1);
}

/* Model step function */
void sys_Block_custom(real_T *arg_x, real_T *arg_y, real_T *arg_z)
{
  sys_AtomicSubsy_AtomicSubsystem(*arg_x, *arg_y,
    &sys_AtomicSubsystem_B.AtomicSubsystem);

  *arg_z = 2.0 * sys_AtomicSubsystem_B.AtomicSubsystem.Sum;
}
```

Simulink Coder: Model Architecture & Design – Basic Modeling Considerations: Virtual Parameters vs. Parameter Objects

- Virtual parameters: Workspace values are hard-coded into the generated code



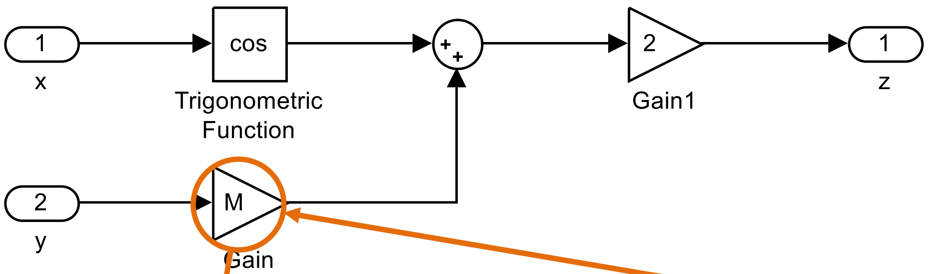

```
/* Model step function */
void sys_Block_custom(real_T *arg_x, real_T *arg_y,
real_T *arg_z)
{
  /* Outport: '<Root>/z' incorporates:
   *  Gain: '<Root>/Gain'
   *  Gain: '<Root>/Gain1'
   *  Inport: '<Root>/x'
   *  Inport: '<Root>/y'
   *  Sum: '<Root>/Sum'
   *  Trigonometry: '<Root>/Trigonometric Function'
   */
  *arg_z = (5.0 * *arg_y + cos(*arg_x)) * 2.0;
}
```

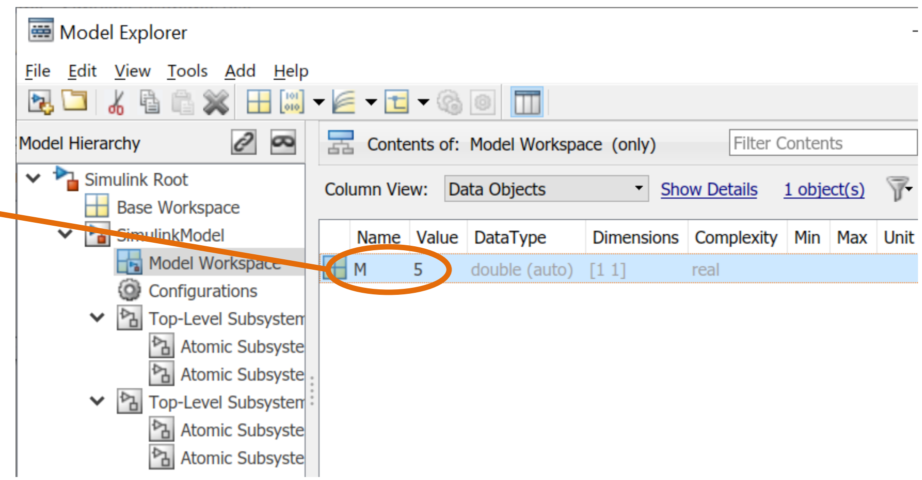


In many cases (e.g. model referencing), setting the inline parameter option is required.

Simulink Coder: Model Architecture & Design – Basic Modeling Considerations: Virtual Parameters vs. Parameter Objects

- Parameter objects, which can be created in the Model Explorer, cause the parameter to be defined globally in the code.






```
/* Definition for custom storage class: Define */
#define M                                    5.0

/* Model step function */
void sys_Block_custom(real_T *arg_x, real_T *arg_y, real_T
*arg_z)
{
  *arg_z = (M * *arg_y + cos(*arg_x)) * 2.0;
}
```

Simulink Coder: Model Architecture & Design – Some More Modeling Considerations…

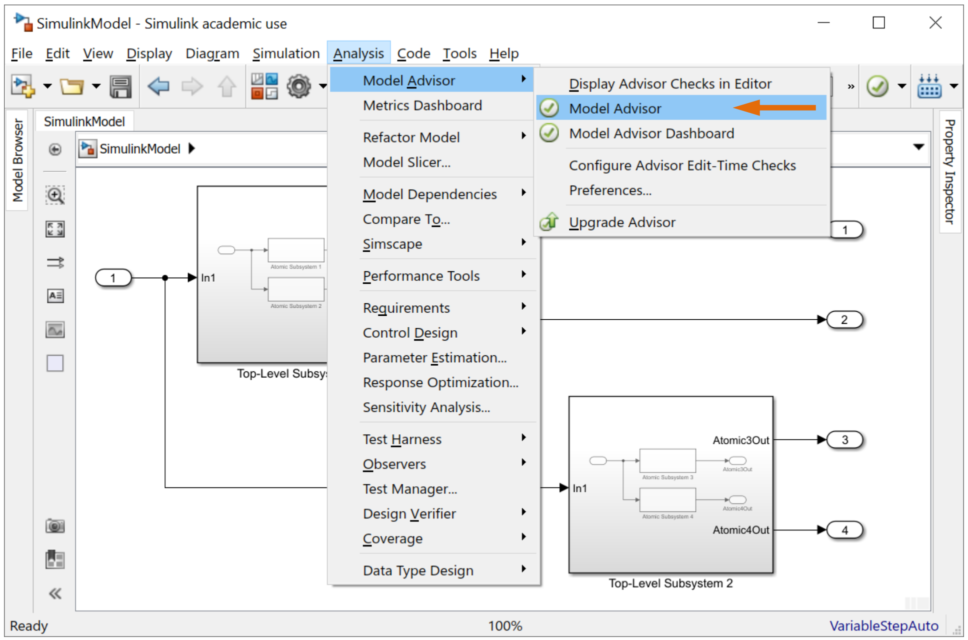
- Blocks
  - Zero-based indexing
  - Evenly spaced breakpoints in lookup tables
  - Precalculated signals and parameters
  - Modeling global shared memory using data stores
  - Modeling local shared memory using data stores

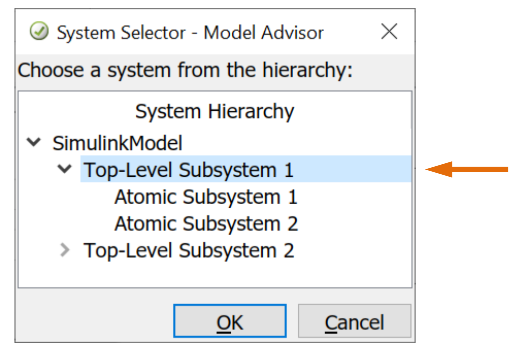
- Modeling Patterns
  - Redundant Unit Delay and Memory blocks
  - Usage of For, While, and For Each subsystems with vector signals
  - Vector and bus signals crossing into atomic subsystems or Model blocks
  - Signal handling for multirate models
  - Data integrity and determinism in multitasking models

- Configuration Parameters
  - Prioritization of code generation objectives for code efficiency
  - Diagnostic settings for multirate and multitasking models

Simulink Coder: Model Architecture & Design – Model Advisor

- A useful tool in verifying that a model is ready for code generation is the Model Advisor.





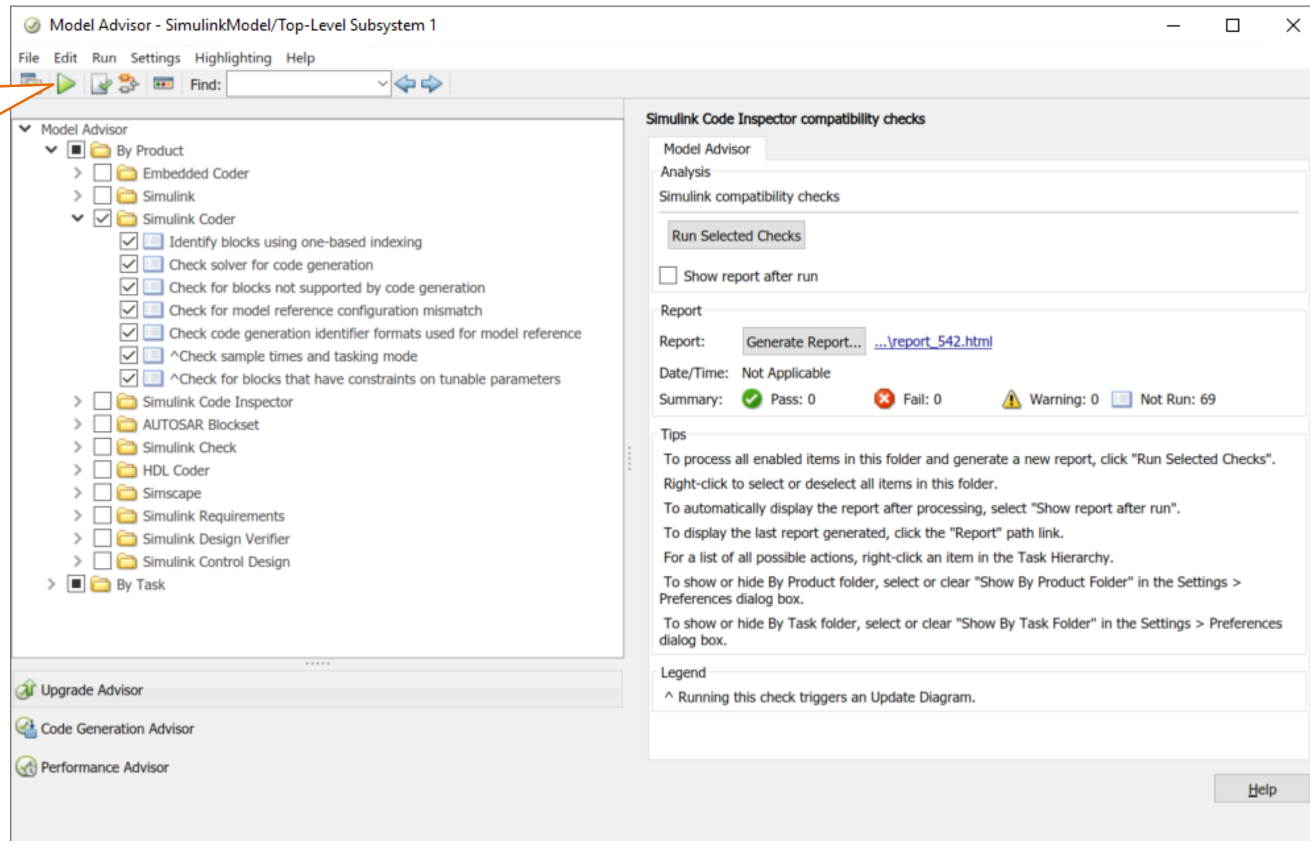
- Before the actual Model Advisor opens, you need to select the system you want to analyze from the system hierarchy

Simulink Coder: Model Architecture & Design – Model Advisor

- In the Model Advisor window, you can select the checks you want to run on the left pane.

You can then run the selected checks by clicking

Alternatively, you can select one single check and click Run This Check



Simulink Coder: Model Architecture & Design – Model Advisor

- After running one or more checks, you can see the result on the right pane.
- Address the issues pointed out by the Model Advisor's relevant checks (most notably those in the category Simulink Coder) to prepare your model for code generation.