Cryogrid

This Documentation

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How to Set Up a New Model Run

1. Create a new folder *yourRunningNumber* in the results folder
2. Create (or copy) the files *CONSTANT_excel.xlsx* and *yourRunningNumber.xlsx* in that folder
3. Check if all *constants* you need are set up in *CONSTANT_excel.xlsx*
4. Set up your stratigraphy in *yourRunningNumber.xlsx*
5. Set up all necceassary *parameters* and *state variables* for the classes that you are using in *yourRunningNumber.xlsx*
6. Change the runningNumber in *main.m* to *yourRunningNumber*
7. Run main program *main.m*

Terminology

- *class*: Matlab class (https://se.mathworks.com/help/matlab/object-oriented-programming.html), realizes object-oriented programming in Matlab
- *CryoGrid class*: Matlab class with mandatory functions and properties which contains the defining equations for the time evolution of the ground, snow, etc. Note that many of the classes in the code are not CryoGrid classes, but do something else! A *module* is a realization of the class.
- *parameter file*: spreadsheet (in Excel at this point) used to set up a CryoGrid run
- *CryoGrid stratigraphy*: stratigraphy of connected CryoGrid classes

Folder structure

- *main.m*: main file to be executed
- *read_display_out.m*: displays the modulke *out* produced by the OUT class *OUT_all.m*. All CryoGrid classes stored in *out* must be initialized before this function works. You can also implement your own OUT class.
- **results**: contains the parameter file and the output files in a folder corresponding to the variable *run_number* in *main.m*
- **forcing**: contains the forcing data as *.mat*-files. If you use the FORCING class, the files must have the same structure as in the sample file provided.
- **modules**: contains the model code
- **modules/@CLASS_NAME**: code of individual CryoGrid classes
- **modules/INTERACTION**: code of interaction classes, which define interactions between two model classes
- **modules/FORCING**: code of FORCING classes which make forcing data accessible for the CryoGrid classes
- **modules/IO**: contains all code related to in/out user interactions (e.g. initialization), not relevant for the time integration in the CryoGrid classes
- **modules/IO/GRID**: GRID classes which provide options for different model grids (at this stage only one!), only used to interface with the user
- **modules/IO/STRATIGRAPHY**: STRATIGRAPY classes which provide options to provide initial stratigraphies for the different model variables, only used to interface with the user. Three options, STRAT_layers (layers with constant properties), STRAT_linear (linear interpolation between given points) and STRAT_classes (defines the stratigraphy of CryoGrid classes)
- **modules/IO/OUT**: OUT classes which store model output (only one option at this stage)
- **modules/IO/INITIALIZE_PARAMETER_FILE**: contains the Matlab code (functions, not classes) to read the parameter file

and initialize the CryoGrid stratigraphy.
- **modules/COMMON**: contains functions that could be used by classes at all levels in the class hierarchy

Inheritance

Stacking of different modules to form a stratigraphy is organised with pointers to the NEXT and PREVIOUS module, and special TOP and BOTTOM modules to indicate the current top and bottom positions. The same method is used for interactions.

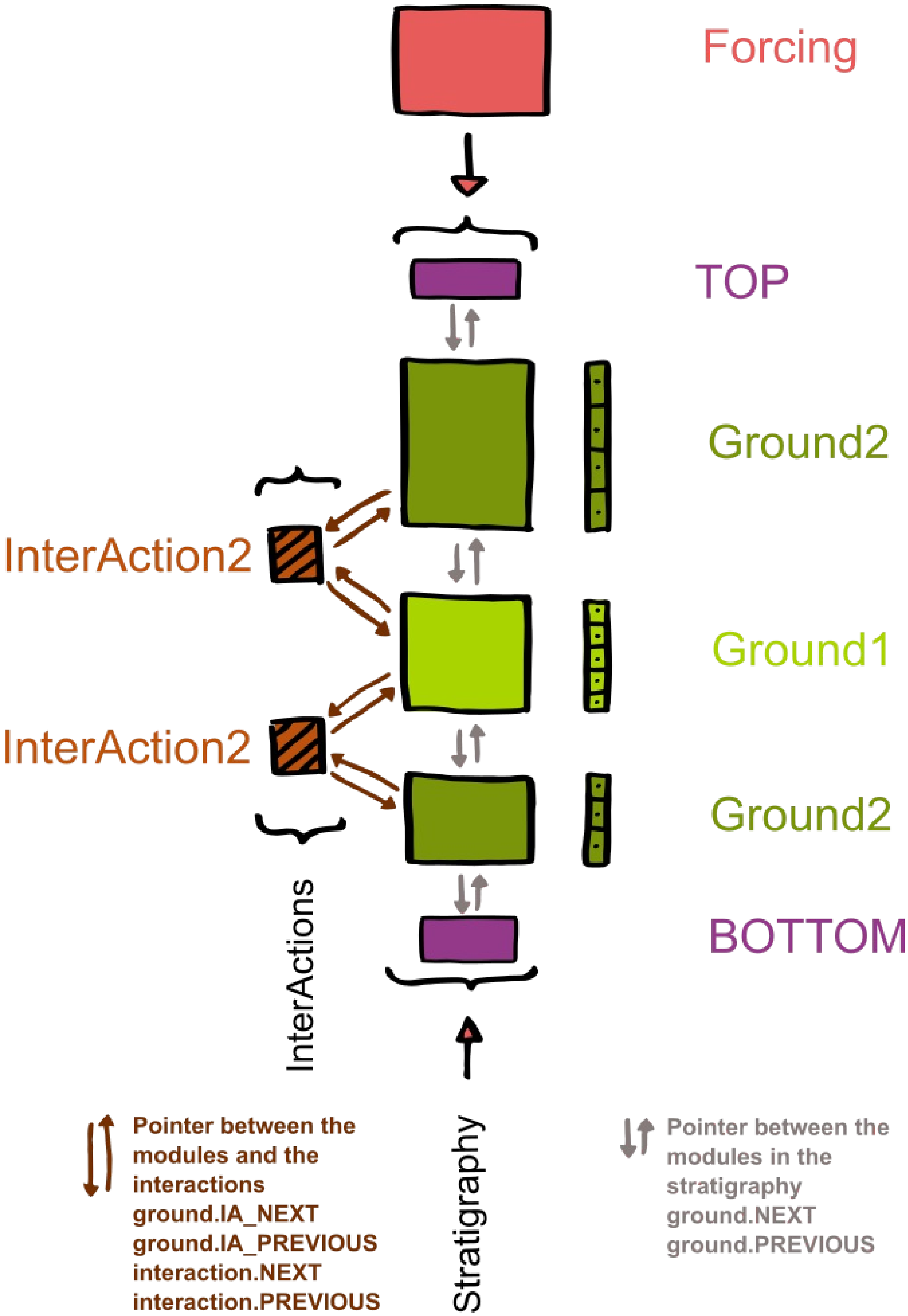
Therefore every class (interactions, ground, snow ...) need to be subclasses of *matlab.mixin.Copyable*. For the ground and snow classes, we recommend to use *GROUND_base_class* and *SNOW_base_class* as superclasses. This also guarantees the existence of (fallback) mandatory functions and variables.

We recommend to use a hierarchy of inhertance to introduce new functionalities, where on each level only one new functionality is implemented. The first level is the base class. The classes on level three and above should reference the superclasses in their name to make it obvious which class inherits fromwhere.
For the ground class with surface energy balance as boundary condition and energy as state variable the inheritance hierarchy could be

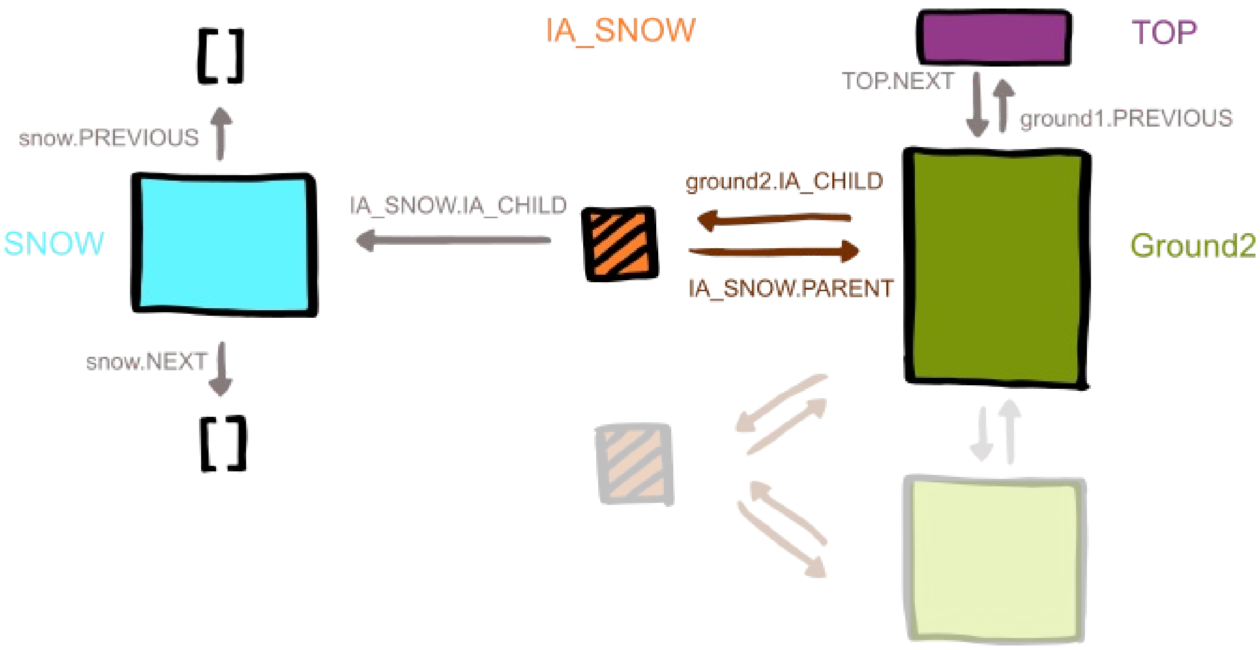
```
GROUND_base_class < GROUND_seb < GROUND_seb_snow
```

Basic Structure of the Soil Column

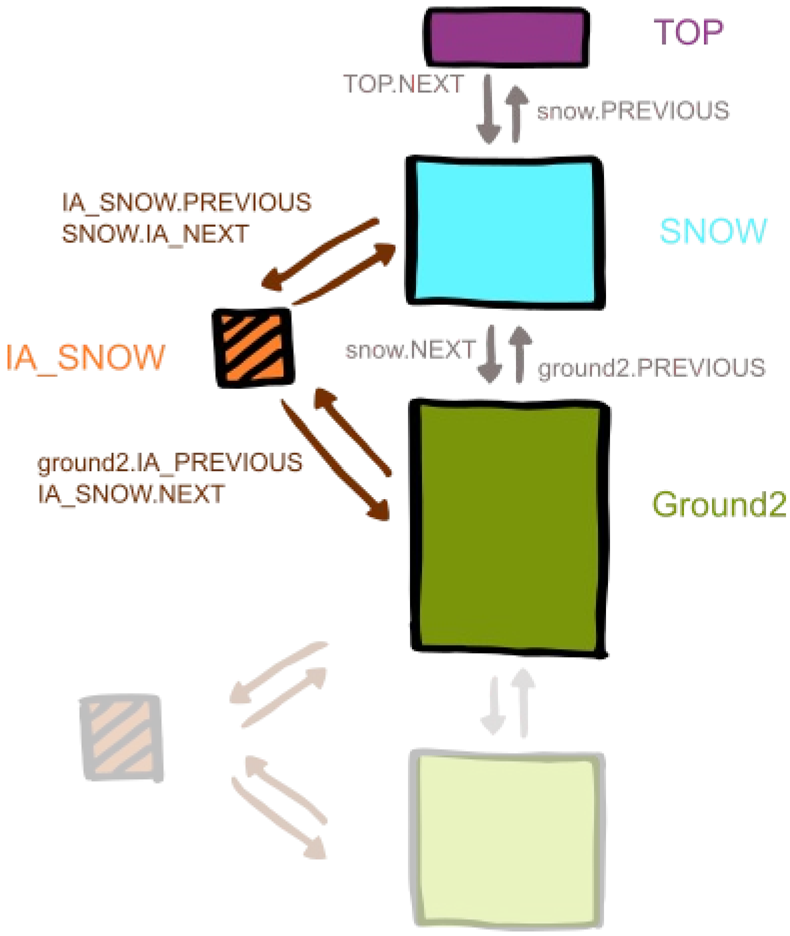
A model run needs a forcing module, the special TOP and BOTTOM modules and one (or more) ground/snow/... modules to build the stratigraphy of the 1D (soil-) column that is being modelled. The stacked ground (or snow) modules are linked with pointers *ground.NEXT* and *ground.*PREVIOUS*. Interaction (e.g. exchange of heat, salt, water) between modules happens with interaction classes. Again the connection is realised with pointers *ground.IA_NEXT* and *ground.IA_PREVIOUS* from the ground modules to the interaction and *interaction.NEXT* and *interaction.PREVIOUS* from the interaction to the ground modules. In this way the interaction has direct access to both involved ground modules.



A Module can delete itself, move itself to a new position, or initialize and insert a new module (from the same or different classes). This can be used for snow buildup and melt, sedimentation, erosion, ice lenses, lakes…. Here is a short example with snow to illustrate the process.



The uppermost ground module builds a child and connects to it w ith a interaction. The interaction initializes the child w ith empty pointers. In the next timesteps, the child gets filled up to a certain threshold (e.g. a certain snow w ater equivalent). Once this threshold is reached, i.e. the amount of snow is enough to justify a new module, the child gets inserted above the parent as the new top module and all pointers get relocated.



Structure of the Parameter File

In each class the variables are handled in different types: constants, parameter, state variables and temporal variables.
The constants get defined in *CONSTANT_excel.xlsx* globally for each run. Please use the naming convention detailed below.
The parameter get defined in *yourRunningNumber.xlsx* seperate for each used class.

The parameters need to be filled in as follows:

```
CLASS                  index
GROUND_yourName            1

value                           default         unit

other_parameter          value    default       [unit]    description

density                    300     350   [kg/m3]   snow density
albedo                     0.8        0.8       [-]   surface albedo
other_parameter          value    default       [unit]    description
CLASS_END
```

The file is scanned to the key words CLASS and than for pre-defined ("allowed") parameter names. Thus only the first three columns are read and the rest can be used for clarification and comments. Empty lines and lines with dashes can be used to devide the parameters.
The index besides the class name allows for different modules based an the same class, e.g. two ground modules with the same functionalities but different albedo.

The same structure is used for parameter setting of the forcing, the grid and the stratigraphy.

Style Guide

Compatibility

All modules can handle whichever state variable they need and use whichever boundary conditions. However, the boundary conditions need to be compatible with the used interaction class(es) and the used forcing. For example, if you have the temperature as a state variable and the interaction between two modules is handled as a heat flow, then your boundary conditions need to convert the forcing data into heat flows at the upper and lower boundaries.

The interaction classes get selected in **/modules/INTERACTION/** *get_IA_class.m* based on the combination of modules. If you write a new class or interaction, please insert your use cases in this function.

General Remarks

- Use meaningful names: Use short phrases for clarity rather than abbreviations for shortness.
- Physical properties should be named by their SI symbols.
- In functions, used variables from containers should be saved by their name, i.e. *theta = ground.CONST.theta*
- Variables and functions should be in lower case. Variable word separation may be indicated with camel case, word separation in function names with underscores.
- If you use equations and constants, cite their source in comments.

Documentation

Every author is responsible for the documentation of his*her own module. We use doxygen for the documentation of Cryogrid and therefore recommend the following conventions.

To use doxygen within your code write the documentation comments **above** the function/variable that you are explaining and start the line with "%> " (instead of just "% " for normal comments). Not every comment in the code needs to be forwarded to doxygen for the documentation - choose wisely!

Mandatory Functions and Variables

ground.CONST

Need to be allocated in *provide_CONST.m* for every class, or in the inheriting superclass(es). Need to be specified in *CONSTANT_excel.xlsx*

```
                year_sec = 365*24*3600; % s / yr
Latent heat     L_f = 334*1000*1000;    % J / m^3

Heat capacity   c_w = 4.2*1000*1000; % J / (K m^3)
                c_i = 1.9*1000*1000; % J / (K m^3)
                c_o = 2.5*1000*1000; % J / (K m^3)
                c_m = 2*1000*1000;   % J / (K m^3)

Thermal conductivity
  air           k_a = 0.025;       % W / m K  [Hillel(1982)]
  water         k_w = 0.57;        % W / m K  [Hillel(1982)]
  ice           k_i = 2.2;         % W / m K  [Hillel(1982)]
  organic       k_o = 0.25;        % W / m K  [Hillel(1982)]
  mineral       k_m = 3;           % W / m K
  quartz        k_q = 7;           % W / m K

Stefan-Boltzmann const.
                sigma = 5.67e-8;

Universal gas constant
                R = 8.314459; % J / K mol

Tortuousity     tau = 1.5;     % 1.5 standard

Freezing temperature of water
                Tmelt_free_water = 273.15; % K
```

ground.PARA

Need to be allocated in *provide_PARA.m* for every class, or in the inheriting superclass(es). Need to be specified in *yourRunningNumber.xlsx* for every class w ithin the block for that class.

```
Default heat flux at lower boundary
                heatFlux_lb = 0.05;    % W / m^2
Albedo          albedo = 0.15;  %
Emissivity      epsilon = 0.99; %
                rs = 100;       %
Measurement height
                z =2;           % m
Roughness length
                z0 = 1e-3;      % m
Maximum time step
                dt_max = 3600 ; % s
Maximum energy change per time step
                dE_max = 0.5e5;      % J / m^3
Maximum temperature change per time step
                dT_max = 0.5e5;      % K
Maximum salt concentration change per time step
                dsaltConc_max        %
Snow water equivalent per cell
                swe_per_cell = 0.01;  % m  must be the same as in SNOW class, should be taken from input file
Sedimentation Rate
                sedRate               % m / yr
Soil Type
                soilType = 1 .* ones(size(grid_cell_size)); %0 - sand, 1 - silt
```

ground.STATVAR (depends on your choice of state variables)

Need to be allocated in *provide_STATVAR.m* for every class, or in the inheriting superclass(es). Need to be specified in *yourRunningNumber.xlsx* for the stratigraphy and in *finalize_STATVAR.m* for every class.

```
                upperPos = grid(1);
                lowerPos = grid(end);

                layerThick  % the distances between layer boundaries in m

                % Should be sufficient to save only upperPos, lowerPos and layerThick
                % However, if you want to save other info, please use the following
                midptDepth      % the depths of module layer midpoints in m
                midptThick      % the distances between layer midpoints in m
                layerDepth      % the depths of the module layer boundaries in m

Initial fractional volumes
                water = 0.4 .* ones(size(grid_cell_size)); %fraction of volume "m^3/m^3"
                ice = 0 .* ones(size(grid_cell_size)); %fraction of volume
                organic = 0 .* ones(size(grid_cell_size)); %fraction of volume
                mineral = 1.1 * 0.6 .* ones(size(grid_cell_size)); %fraction of volume

Salt diffusivity
                saltDiff          % m^2 / s
Bulk thermal conductivity
                thermCond         % W / m K
Effective heat capacity
                c_eff             % J / m^3
Liquid water content
                liqWater          % fraction of volume
Freezing temperature of solution
                Tmelt             % K

% Of the following choose your state variables
Initial temperature
                T                 % °C
Initial salinity - salt concentration in liquid water
                saltConc = 895 .* ones(size(grid_cell_size)); % mol / l [Dimitrenko 2011]
Initial energy
                E                 % J
Initial total ions - salt concentration per layer volume
                salt              % mol
```

ground.TEMP

To be calculated in the appropriate functions (*get_boundary_condition_***, *get_derivatives_prognostic*, interactions, etc.) - depends on choice of state variables - needed boundary conditions depend also on the chosen interaction

```
% Boundary conditions for the chosen state variable(s) -
Temperature at upper boundary (for updating of thermal properties)
                T_ub              % °C
Heat flux at upper boundary
                heatFlux_ub       % W / m^2
Heat flux at lower boundary
                heatFlux_lb       % W / m^2

Salt flux at upper boundary
                saltFlux_ub       %
Salt flux at lower boundary
                saltFlux_lb       %

Temperature divergence
                divT              %
Salt concentration divergence
                divsaltConc       %
```

forcing.PARA

Need to be specified in *yourRunningNumber.xlsx* in the forcing block. Other parameter of the forcing depends on the chosen forcing class.

```
Starttime of forcing data
                startForcing
Time step of forcing data
                dtForcing
Endtime of forcing data
                endForcing

% Other depending on your forcing data
```

forcing.DATA

to be calculated in *generateForcing*. All variable are vectors w ith the same length

```
Vector of discrete time steps
                timeForcing = [startForcing:dtForcing:endForcing]';
Vector of forcing temperature
                TForcing
Vector of forcing salt concentration
                saltConcForcing
```

forcing.TEMP

to be calculated in *interpolateForcing* - depending on the choice of state variables.
All variables are single values - interpolated for each time step

```
Surface temperature at this time point
                TForcing
Surface salt concentration at this time point
                saltConcForcing
```

OUT und *RUN_INFO*

```
Save interval   dtSave
```

How to Write a New Forcing

A new forcing module loads or generates forcing data. The state variables that are provided by the forcing module need to match the ones that are needed by the used ground modules.

```
%> here goes the documentation of the focing module
classdef FORCING
  properties
    DATA    %all data
    TEMP    %at each timestep
    PARA
    STATUS  %forcing data suitable for the modules that are to be run -> can be used
  end

  methods     %mandatory functions

    %> Descitption of the functions, input and output parameters
    function forcing = initalize_from_file(forcing, section)
        %This function initializes the parameter from the section of the excel file to forcing.PARA
    end

    %> Descitption of the functions, input and output parameters
    function forcing = load_forcing_from_mat(forcing)
```

```
        %This function loads/generates the forcing and stores it in forcing.DATA
    end

    %> Descitption of the functions, input and output parameters
    function forcing = interpolate_forcing(t, forcing)
        %This function will be called by ground modules and should return all state variables, that are needed
    end
  end
end
```

How to Write a New Interaction Class

The interaction classes handle the boundary conditions for all modules in the stratigraphy that share an *inner boundary* w ith another module. The interaction has pointers to the tw o interacting modules and can therefore change both modules directly. The interaction needs to match the boundary conditions that are used in the modules. The interaction classes get selected in **/modules/INTERACTION/** *get_IA_class.m* based on the combination of modules. If you w rite a new class or interaction, please insert your use cases in this function.

```
%> Here comes the documentation of your interaction class
classdef IA_HEAT < matlab.mixin.Copyable

    properties
        PREVIOUS
        NEXT
    end

    methods

    %> Descitption of the functions, input and output parameters
    function get_boundary_condition_m(ia_heat)
        stratigraphy1 = ia_heat.PREVIOUS;
        stratigraphy2 = ia_heat.NEXT;

        %put interaction here
        %it should act as the boundary conditions for both involved section,
        %i.e. get_boundary_condition_l for stratigraphy1 and as get_boundary_condition_u for stratigraphy2
    end
  end
end
```

How to Write a New Module

The definition of a new module should look like follow s. The functions are mandatory for the time loop to w ork. The "initialize" function may take additional input parameters, as you only use it before entering the time loop, the other functions may not.

```
%> Here comes the documentation of your new module
classdef GROUND_yourName
  properties
    CONST     %constants
    PARA      %external service parameters, all other
    STATVAR   %state variables - choose wisely
    TEMP      %derivatives in prognostic

    PREVIOUS  %pointer to previous module
    NEXT      %pointer to next module
    IA_PREVIOUS %pointer to interaction with previous module
    IA_NEXT   %pointer to interaction with next module
  end

  methods     %mandatory functions for each class

    %> Descitption of the functions, input and output parameters
    function ground = provide_variables(ground)
```

```
        %initializes the variables in ground.CONST, ground.PARA and ground.STATVAR as empty arrays.
        %You may also use this function from the superclass
       end

       function variable = initialize_from_file(ground, variable, section)
          %fills variables in ground.CONST and ground.PARA with info from the appropriate section in the excel file
       end

       function ground = assign_global_variables(ground, forcing)
           %assign variables from forcing to module
       end

       function ground = initialize_STATVAR_from_file(ground, grid, forcing, depths)
           %initialize state variables in ground.STATVAR with info from the appropriate section in the excel file
       end

      %> Descitption of the functions, input and output parameters
      function ground = get_boundary_condition_u(ground, forcing)
          %put upper boundary here
          %this function needs to be compatible with the used interaction class, i.e. if you use heatflux here,
          %you also need to use it in the interaction class
      end

      %> Descitption of the functions, input and output parameters
      function ground = get_boundary_condition_l(ground)
          %put lower boundary here
      end

      function ground = get_derivatives_prognostic(ground)
          %put spatial derivative here
      end

      %> Descitption of the functions, input and output parameters
      function timestep = get_timestep(ground)
          %put estimate for maximum timestep which allows stable forward Euler here

      end

      %> Descitption of the functions, input and output parameters
      function ground = advance_prognostic(ground, timestep)
          %put advancing in time here
          %real timestep derived as minimum of several classes in [sec] is used here!
      end

      %> Descitption of the functions, input and output parameters
      function ground = compute_diagnostic_first_cell(ground, forcing)
          %put stuff that happens only if this cell is the first cell here
      end

      %> Descitption of the functions, input and output parameters
      function ground = compute_diagnostic(ground, forcing)
          %put stuff that happens in every cell here
      end

      end
    end
  end
```