# Meta-Programming with Modelica

## for MetaModeling and Model Transformations

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OpenModelica Course, 2011-09-15

# Extensibility and Modularity of Modeling Tools

- Modeling and simulation tools are too monolithic
- Models and tools need to be extensible and modular
- Creation, query, manipulation, composition and management of models
- Need for modeling of operations on models

# Some Semantics Modeling Approaches

- Extensibility - allow models to also model language properties
- Ontologies to classify application domains
  - For example, semantic web
- Equation-based approaches
  - Modelica – hybrid differential algebraic equations
  - Single-assignment equations – functional languages, SOS/Natural semantics
  - Unification equations: logic programming and functional languages, SOS/Natural semantics
  - Can usually be efficiently executed
- Logic approaches
  - First-order logic
  - Often computationally intractable for realistic applications in its general form

# Meta-Level Operations on Models

- Model Operations
  - Creation
  - Query
  - Manipulation
  - Composition
  - Management
- Manipulation of model equations for
  - Optimization purposes
  - Parallelization
  - Model checking
  - Simulation with different solvers
- Modularity
  - Allow model packages for tool extensions
  - Example: Automatic PDE discretization schemes

# Meta-Level Operations on Models, Cont.

- Model configuration for simulation purposes
  - Initial state
  - Initialization via xml data files or databases
- Simulation features
  - Running a simulation and display a result
  - Running more simulations in parallel
  - Handle simulation failures and continue the simulation in a different way
  - Possibility to generate ONLY specific data from a simulation
  - Possibility to manipulate simulation data for export to another tool

# Meta-Modelica Compiler (MMC) and Language

- MetaModelica is an extended *subset* of Modelica
    - RML compiler supports only MetaModelica
    - OMC supports Modelica 3.1 + MetaModelica
- Used for development of OMC
- Some MetaModelica Language properties:
    - Modelica syntax and base semantics
    - Pattern matching (named/positional)
    - Local equations (local within expression)
    - Recursive tree data structures
    - Lists and tuples
    - Garbage collection of heap-allocated data
    - Arrays (different from standard Modelica)
    - Vectors (array with local update as in standard Modelica)
    - Polymorphic functions
    - Function formal parameters to functions
    - Simple builtin exception (failure) handling mechanism
    - Many of these features come from functional programming languages

# A Simple match-Expression Example

- Example, returning a number, given a string

```
  String s;
  Real   x;
algorithm
  x :=
    matchcontinue s
      case "one"   then 1;
      case "two"   then 2;
      case "three" then 3;
      else              0;
    end matchcontinue;
```

# Tree Types – uniontype Declaration Example

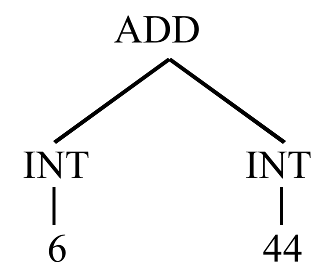
- Union types specifies a *union* of one or more record types
- Union types can be *recursive*
  - can reference themselves

MetaModelica tree type declaration:

```
uniontype Exp
  record INT  Integer x1;       end INT;
  record NEG  Exp x1;           end NEG;
  record ADD  Exp x1; Exp x2;   end ADD;
end Exp;
```

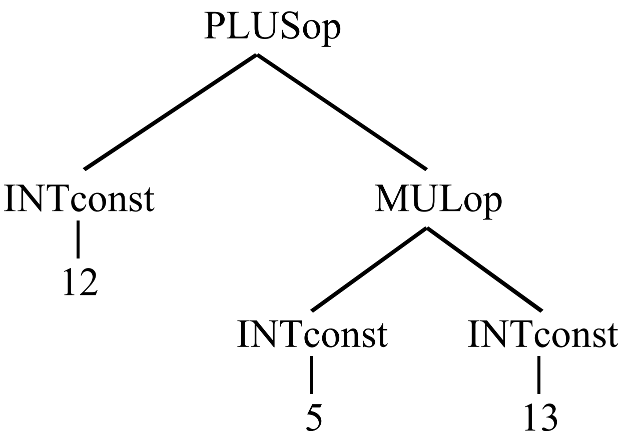
- The Exp type is a union type of three record types
- Record constructors INT, NEG and ADD
- Common usage is abstract syntax trees.

`ADD(INT(6),INT(44))`



# Another uniontype Declaration of Exp Expressions

Abstract syntax tree data type declaration of Exp:




```
uniontype Exp
  record INTconst Integer x1;  end INTconst;
  record PLUSop  Exp x1; Exp x2; end PLUSop;
  record SUBop   Exp x1; Exp x2; end SUBop;
  record MULop   Exp x1; Exp x2; end MULop;
  record DIVop   Exp x1; Exp x2; end DIVop;
  record NEGop   Exp x1;         end NEGop;
end Exp;
```

```
12+5*13
```

```
PLUSop(INTconst(12),
       MULop(INTconst(5),INTconst(13)))
```

# Simple Expression Interpreter – with equation keyword, match, case

```
function eval "Evaluates integer expression trees"
  input  Exp     exp;
  output Integer intval;
algorithm
 intval :=
  matchcontinue exp
    local Integer v1,v2; Exp e1,e2;
    case INTconst(v1) then v1;
    case PLUSop(e1,e2) equation
      v1 = eval(e1);  v2 = eval(e2); then v1+v2;
    case SUBop(e1,e2) equation
      v1 = eval(e1);  v2 = eval(e2); then v1-v2;
    case MULop(e1,e2) equation
      v1 = eval(e1);  v2 = eval(e2); then v1*v2;
    case DIVop(e1,e2) equation
      v1 = eval(e1);  v2 = eval(e2); then v1/v2;
    case NEGop(e1) equation
      eval(e1) = v1; then  -v1;
  end matchcontinue;
end eval;
```

Local variables with scope inside case expression

Pattern binding local pattern variables e1, e2

Local equations with local unknowns v1, v2

A returned value

# Transformation Example
# Simple Symbolic Differentiator

```
protected function diff
  input Exp expr;
  input String timevar;
  output Exp diffExpr;
algorithm
diffExpr :=
matchcontinue (expr,timevar)
  local
    String id,id1,id2;
    Exp e1prim,e2prim,e1,e2;
  // der of constant
  case (INT(_), _) then INT(0);
  // der of time variable
  case(IDENT(id1), id2)
    equation
      true = id1 ==& id2;
    then INT(1);
  // der of time-independent variable
  case (IDENT(_), _) then INT(0);
  ...
```

```
// (e1+e2)' => e1'+e2'
case (ADD(e1,e2),id)
  equation
    e1prim = diff(e1,id);
    e2prim = diff(e2,id);
  then ADD(e1prim,e2prim);
// (e1/e2)' => (e1'*e2 - e1*e2')/e2*e2
case (DIV(e1,e2),id)
  equation
    e1prim = diff(e1,id);
    e2prim = diff(e2,id);
  then DIV(
         SUB(MUL(e1prim,e2),
             MUL(e1,e2prim)),
         MUL(e2,e2));
// (-e1)' => -e1'
case (NEG(e1),id)
  equation
    e1prim = diff(e1,id);
  then NEG(e1prim);
...
```

# General Syntactic Structure of match-expressions

```
matchcontinue <expr>  <opt-local-decl>

  case <pat-expr>
    <opt-equations>
    then <expr>;
  case <pat-expr>
    <opt-equations>
    then <expr>;
  ...
  else
    <opt-equations>
    then <expr>;

end matchcontinue;
```

# Semantics of Local Equations in match-Expressions

- Only algebraic equations are allowed, no differential equations
- Only locally declared variables (local unknowns) declared by local declarations within the case expression are solved for
- Equations are solved in the order they are declared. (This restriction may be removed in the future).
- If an equation or an expression in a `case`-branch of a matchcontinue-expression fails, all local variables become unbound, and matching continues with the next branch.

# Semantics of Local Equations cont...

- Certain equations in match-expressions do not solve for any variables – they may be called "constraints"
  - All variables are already bound in these equations
  - The equation may either be fulfilled (succeed) or not (fail)
  - Example:

```
local
  Real x=5; Integer y = 10;
equation
  true = x>4;   // Succeeds!
  true = y<10;  // Fails!!
```

- Thus, there can locally be more equations than unbound variables, if including the constraints

# List Data Structures

- `list` – `list`<type-expr> is a list type constructor
  - Example: `type RealList = list<Real>;` type is a list of reals
  - Example: `list<Real> rlist;` variable that is a list of reals
- `list` – `list`(el1,el2,el3, ...) is a list data constructor that creates a list of elements of identical type.
  - `{}` or `list`() empty list
  - `{2,3,4}` or `list`(2,3,4) list of integers
- Allow {el1,el2,el3, ...} overloaded array or list constructor, interpreted as `array`(...) or `list`(...) depending on type context.
- `{} or list()` denotes an empty reference to a list or tree. `cons` – `cons`(*element*, *lst*) adds an element in front of the list *lst* and returns the resulting list.
- Also as `::` operator – *element*`::`*lst*

# What Does PolyMorphic Mean?

- PolyMorphic – adapt to multiple types
- Poly – multiple, morphic – adapt

- Standard – An operation is only defined for one type, e.g.
  `arrayInsertElement(intelement, intArr)`

- A polymorphic function is defined for multiple types, e.g. elements in an array can be of any type:
  `arrayInsertElement(anyElement, anyArr)`

# Predefined Polymorphic List Operations

```
function listAppend<Eltype>
  input list<Eltype> lst1;
  input list<Eltype> lst2;
  output list<Eltype> lst3;
end listAppend;

function listReverse<Eltype>
  input list<Eltype> lst1;
  output list<Eltype> lst3;
end listReverse;

function listLength<Eltype>
  input list<Eltype> lst1;
  output Integer len;
end listLength;
```

```
function listMember<Eltype>
  input Eltype elem;
  input list<Eltype> lst2;
  output Boolean result;
end listMember;

function listNth<Eltype>
  input list<Eltype> lst1;
  input Integer elindex;
  output Eltype elem;
end listNth;

function listDelete<Eltype>
  input ListType lst1;
  input Integer  elindex;
  output ListType lst3;
type ListType = list<Eltype>;
end listDelete;
```

# Function Formal Parameters

- Functions can be passed as actual arguments at function calls.
- Type checking done on the function formal parameter type signature, not including the actual names of inputs and outputs to the passed function.

```
function intListMap   "Map over a list of integers"
  input  Functype func;
  input  list<Integer> inlst;
  output list<Integer> outlst;
public
  partial function Functype input Integer x1; output Integer x2; end Functype;
algorithm  ...
end intListMap;
```

```
function listMap<Type_a> "Map over elements of type Type_a, a type parameter"
  input  Functype func;
  input  list<Type_a> inlst;
  output list<Type_a> outlst;
partial function Functype  input Type_a x1; output Type_a x2; end Functype;
algorithm  ...
end listMap;
```

# Calling Functions with Function Formal Parameters and/or Parameterized Types

- Call with passed function arguments: `int_list_map(add1,intlst1)`
  Declared using type Int
- Compiler uses type inference to derive type of
  replaceable type parameter `Type_a = Integer`
  from input list type `list<Integer>` in `listMap(add1, intlst1);`

```
// call function intListMap   "Map over a list of integers"
list<Integer> intlst1 := {1,3,5,9};
list<Integer> intlst2;

intlst2 := intListMap(add1, intlst1);
```

```
// call function listMap   "Map over a list of Type_a - a type parameter"
list<Integer> intlst1 := {1,3,5,9};
list<Integer> intlst2;

intlst2 := listMap(add1, intlst1);  // The type parameter is inferred
```

# Tuple Data Structures

- Tuples are anonymous records without field names
- tuple<...> – tuple type constructor (keyword not needed)
  - Example: `type VarBND  = tuple<Ident, Integer>;`
  - Example: `tuple<Real,Integer> realintpair;`
- (..., ..., ...) – tuple data constructor
  - Example: `(3.14, "this is a string")`
- Modelica functions with multiple results return tuples
  - Example: `(a,b,c) := foo(x, 2, 3, 5);`

# Option Type Constructor

- The `Option` type constructor, parameterized by some type (e.g.,`Type_a`) creates a kind of uniontype with the predefined constructors `NONE()` and `SOME(...)`:

```
replaceable type Type_a subtypeof Any;
type Option_a = Option<Type_a>;
```

- The constant `NONE()` with no arguments automatically belongs to any option type. A constructor call such as `SOME(x1)` where `x1` has the type `Type_a`, has the type `Option<Type_a>`.
- Roughly equivalent to:

```
uniontype Option<Type_a>
  record NONE  end NONE;
  record SOME  Type_a x1;  end SOME;
end Option;
```

# Testing for Failure

- A local equation may fail or succeed.
- A builtin equation operator `failure`(arg) succeeds if *arg* fails, where *arg* is a local equation

Example, testing for failure in Modelica:

```
case ((id2,_) :: rest, id)
  equation
    failure(true =  id ==& id2);  value = lookup(rest,id);
  then value;
```

# Generating a fail "Exception"

- A call to `fail()` will fail the current case-branch in the match-expression and continue with the next branch.
- If there are no more case-branches, the enclosing function will fail.
- An expression or equation may fail for other reasons, e.g. division by zero, no match, unsolvable equation, etc.

# as-expressions in Pattern Expressions

- An unbound local variable (declared `local`) can be set equal to an expression in a pattern expression through an as-expresson (`var as subexpr`)
- This is used to give another name to `subexpr`
- The same variable may only be associated with one expression
- The value of the expression equation (`var as subexpr`) is `subexpr`
- Example:
  - `(a as Absyn.IDENT("der"), expl,b,c)`


MODELICA

# match and matchcontinue

- MetaModelica has two different match-expressions
  - matchcontinue runs all matching cases in order until it finds one that succeeds
  - match runs only the first matching case
  - both are useful to describe different program flows

```
function notOne "Fails if the input is not 1"
  input  Integer i;
algorithm
  _ := match i
    case 1 then fail();
    // Do stuff
  end match;
end notOne;
```

```
function notOne "Fails if the input is not 1"
  input  Integer i;
algorithm
  _ := matchcontinue i
    case i
      equation
// This constraint needs to be added to the
// beginning of every subsequent case
        false = i == 1;
        // Do stuff
  end matchcontinue;
end notOne;
```

# Summary of New MetaModelica Reserved Words

- `_` Underscore is a reserved word used as a pattern placeholder, name placeholder in anonymous functions, types, classes, etc.
- `match` is used in match-expressions.
- `matchcontinue` is used in matchcontinue-expressions.
- `case` is used in match/matchcontinue-expressions.
- `local` is used for local declarations in match expressions, etc.
- `uniontype` for union type declarations, e.g. tree data types.
- `as` for as-expressions

# Summary of New Reserved Words Cont'

- `list` could be a reserved word, but this is not necessary since it is only used in `list(...)` expressions
- `Option` is a predefined parameterized union type

# Summary of New Builtin Functions and Operators

- `list`<...> – list type constructor, in type context
- `tuple`<...> – tuple type constructor
- `list`(...) – list data constructor, in expression context
- `cons`(*element*, *lst*) – attach *element* at front of list *lst*
- `fail`() – Raise fail exception, having null value
- (..., ..., ...) or `tuple`(..., ..., ...) – tuple data constructor
- `::` – List `cons` operator

# Conclusions

- Meta-modeling increasingly important, also for the Modelica language and its applications
- Meta-modeling/meta-programming extensions allow writing a Modelica compiler in Modelica
- Extensions are recursive union types (trees), lists, and match-expressions – standard constructs found in functional languages
- OpenModelica compiler implemented using MetaModelica extensions since March 2006.
- Bootstrapping - Ongoing work to compile OpenModelica compiler using itself, completed spring 2011 (excluding garbage collection)