VHDL-AMS

VHDL-AMS - Analog & Mixed Signal extensions

IEEE Standard 1076.1 (1999)

Superset of VHDL - IEEE Standard 1076-1993

Can be used to model electrical or mechanical systems

Mathematical Foundation

Equations describing continuous parts are differential-algebraic equations (DAEs)

DAE theory has been developed in the last 15 years

Theory covers properties and the numerical solution of DAEs of the form

F(x,dx/dt,t)=0 where x is the vector of unknowns and F is a vector of expressions

Reasons for development

Need for only one simulator as they are expensive

Support for modeling level above Spice

The growth of mixed signal systems

Pure VHDL Model of Differentiator

```
entity diff is
    generic (r, c: real);
    port (vi: in real; vo: out real);
end entity diff;

architecture simple of diff is
begin
    process (vi) is
        variable tnow, tlast: real;
    begin
        tnow := real(now/ns)*1.0e-9;
        vo <= -R*C(vi - vi'last_value)/(tnow - tlast);
        tlast := tnow;
    end process;
end architecture simple;
```

Unidirectional signals.
Does not suppost Kirchoff's law.

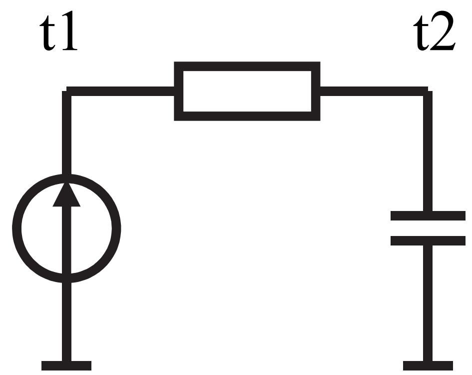
Connects time to real and control time step. The problem is event driven nature.

Write own formulae.

Quantities and Equations

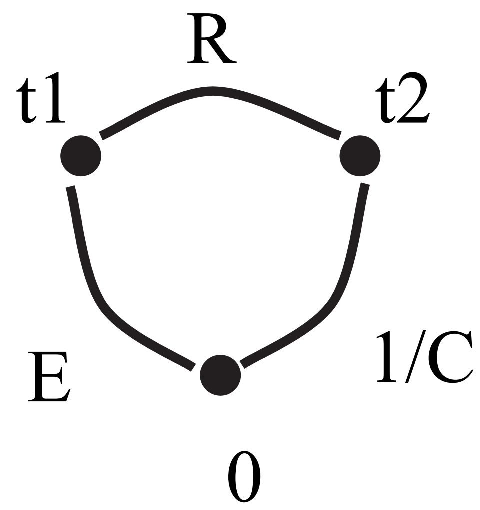
- Two New Objects for VHDL
  - Terminal
    - Either interface object or local object
    - Terminal associations create analog netlists

      terminal t1,t2:electrical;



- Two New Objects for VHDL
  - Quantities
    - Either interface object or local object
    - Quantity associations create *signal flow* models

      quantity a,b,c: voltage;




```
quantity_declaration::=  free_quantity_declaration
                         | branch_quantity_declaration
                         | source_quantity_declaration
free_quantity_declaration::=
          quantity identifier_list : subtype_indication [:= expression] ;
```

Implicit Quantities

- Q'Dot The time derivative of quantity Q
- Q'Integ The integral of Q from 0 to current time
- Q'Delayed(t) The quantity Q at time NOW-t
- S'Ramp[(tr[,tf])] A scalar quantity of the same type as signal S, that follows S with specified rise and fall times
- S'Slew[(max_rising_slope [,max_falling_slope])]
  Similar to S'Ramp, but with maximum slopes
- Q'Slew[(max_rising_slope,[max_falling_slope])]
  A scalar quantity that follows Q but with maximum slopes
- Q'ZOH(T,[initial_delay])
  Zero-order hold with specified sampling interval and first sampling time
- Q'Ltf(num,den) Laplace transfer function of Q (scalar)
- Q'Ztf(num,den,T [, initial_delay])
  Z-domain transfer function of Q (Scalar) with specified sampling interval

Branch Quantities

branch_quantity_declaration ::=	**quantity** [across_aspect] [through_aspect] terminal_aspect;
across_aspect ::=	identifier_list [tolerance_aspect] [:= expression] **across**
through_aspect ::=	identifier_list [tolerance_aspect] [:= expression] **through**
terminal_aspect ::=	plus_terminal_name [**to** minus_terminal_name];

- Defines a named *flow* path or a named *effort* difference; for example current and voltage
- Declared with a plus terminal and minus terminal

  quantity v **across** j,i **through** t1 to t2;

- Plus terminal and minus terminal must have the same simple nature
- Minus terminals default to “ground”
- A branch quantity is composite if one of the terminals is composite
- Implicit quantity T’Reference is an across quantity directed from T to “ground”
- Implicit quantity T’Contribution is the signed sum of through quantities incident to T

Terminals and Natures

- Terminals belong to a nature

  Terminal_declaration::= **terminal** identifier_list : subnature_indication ;
- Two terminals may enter into a terminal association

  port map (anode => t1, cathode => t2);
- A locally declared terminal or an unassociated formal terminal is the *root terminal* of a node

nature_declaration ::=	**nature** identifier **is** nature_definition
nature_definition ::=	scalar_nature_definition | composite_nature_definition
scalar_nature_definition ::=	type_mark **across** type_mark **through**
subnature_declaration ::=	**subnature** identifier **is** subnature_indication

- Terminals may be associated only with terminals of like nature
- Across aspect represents effort-like effects -- voltage, temperature, pressure
- Through aspect represents flow-like effects -- current, heat flow rate, fluid flow rate
- N'reference is a terminal - the "ground" for all terminals with nature N

Example: Package for electrical systems

```
package electrical_system is
        subtype voltage is real;
        subtype current is real;
        subtype charge is real;
        subtype flux is real;

        nature electrical is voltage across current through;
        nature electrical_vector is array(natural range <>) of electrical;

        alias ground is electrical'reference;
end package electrical_system;
```

Source Quantities

source_quantity_declaration ::=
    quantity identifier_list : subtype_indication source_aspect;

source_aspect ::=
     spectrum magnitude_simple_expression, phase_simple_expression
    | **noise** magnitude_simple_expression

function FREQUENCY **return** real;

- Source Quantities specify small-signal stimulus
  - Spectral source quantity for AC simulation
  - Noise source quantity for small-signal noise simulation
- Magnitude and phase expressions may depend on quantities and FREQUENCY

Implicit DAEs

- Each Across quantity is the difference between reference quantities of its terminals
- The algebraic sum of through quantities at a root terminal is zero
- The reference quantities of each pair of associated terminals are equal
- Each pair of associated terminals are equal
- Each implicit quantity is constrained to its appropriate value

Simultaneous Statements

- Simultaneous Statements express explicit DAEs

  simultaneous_statement ::= simple_simultaneous_statement
  | simultaneous_if_statement
  | simultaneous_case_statement
  | simultaneous_procedural_statement
  | simultaneous_null_statement

- The semantics of if, case and procedural are derived from the semantics of the simple simultaneous statement

- The Simple Simultaneous Statement
  - Simultaneous statement has a collection of characteristic expressions

    simple_simultaneous_expression ::=
    [label:] simple_expression ==
    simple_expression [tolerance_aspect];

Simultaneous Statements

- Scalar expressions:
  - The statement has a single characteristic expression - the difference of the statement expressions
- Composite expressions:
  - There must be a matching scalar subelement of the right-hand expression for each scalar subelement of the left-hand expression
  - The characteristic expressions are the differences of the matching scalar subelements of the statement expressions

- The Simultaneous Conditional Statement
  - Selects one of the enclosed sequences of simultaneous statements

simultaneous_if_statement ::=

[if_label:] **if** condition **use** simultaneous_statement_part
[**elsif** condition **use** simultaneous_statement_part]
[**else** simultaneous_statement_part]
end use [if_label];

Simultaneous Statement

- The Simultaneous Case Statement
  - Selects one of a number of alternative simultaneous statement lists

```
simultaneous_case_statement ::=
    [case_label:] case expression use
                        simultaneous_alternatives
                  end use [case_label];
simultaneous_alternative ::=
      when choices =>   simultaneous_statement_part
```

- The Simultaneous Procedural Statement
  - Allows the formulation of equation as in-line sequential code

```
simultaneous_procedural_statement ::=
      [procedural_label:]   procedural [is]
                                  procedural_declarative_part
                            begin
                                  sequential_statements
                            end procedural [procedural_label];
```

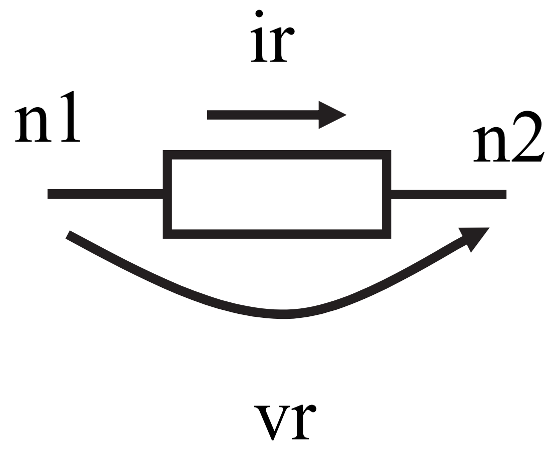
Simultaneous Statement

- Semantics of Simultaneous Procedural Statement
    - Defined by rewrite to the form:

      FP(Ta’(Q1,..Qm),X1,..Xn) ==Ta’(Q1,..Qm)
    - The Qs are quantities, the Xs are quantities, signals, constants or literals
    - FP contains local variable declarations corresponding with, and initialized to, the values of Q1..Qm
    - The members of Q1..Qm are just those variables that are “written” by sequential statements
    - FP returns the aggregate of the values of those variables

Examples of Simultaneous Statements

- A linear resistor



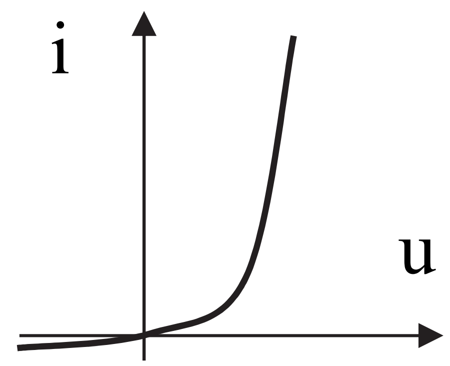
use electrical_system.**all**;
entity resistor **is**
    generic (resistance: real);
    port (**terminal** n1, n2: electrical);
end entity resistor;

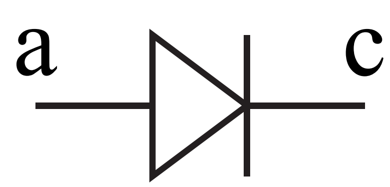
architecture signal_flow **of** resistor **is**
    quantity vr **across** ir **through** n1 **to** n2;
begin
    ir == vr / resistance;
end architecture signal_flow;

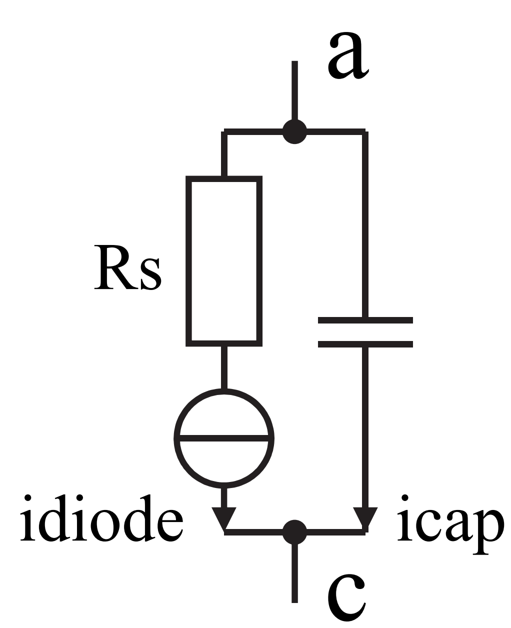
Examples of Simultaneous Statements

- A parameterized diode

```
use electrical_system.all, ieee.math_real.all;
entity diode is
        generic (Iss, n, Vt, tau, Rs, Cj0, Vj: real);
        port (terminal a, c: electrical);
end entity diode;
architecture level0 of diode is
        quantity vdiode across idiode, icap through a to c;
        quantity q: charge;
        quantity nsf: real noise sqrt(idiode/frequency);
begin
        idiode == iss * (exp((vdiode-Rs*idiode)/(n*Vt))-1)+nsf;
        q == tau * idiode - 2.0*Cj0*sqrt(Vj**2-Vj*vdiode);
        icap == q'dot;
end architecture level0;
```







Examples of Simultaneous Statements

- A sinusoid voltage source

```
use electrical_systems.all, ieee.math_real.all;
entity vsource is
        generic (magnitude, freq: real;
                 phase: real := 0.0);
        port (terminal a, c: electrical);
end entity vsource;

architecture sine of vsource is
        quantity v across i through a to c;
        quantity ac:real spectrum magnitude/sqrt(2.0),phase;
begin
        v == magnitude * sin(2.0*math_pi*freq*NOW) + ac;
end architecture sine;
```

Tolerances

- Each quantity and simultaneous statement belongs to a user-definable tolerance group, which can be specified for subtypes, subnatures, quantities and simultaneous statements

  subtype_indication ::=
  [resolution_function_name] type_mark [constraint] [tolerance_aspect]
  tolerance_aspect ::= **tolerance** string_expression
  subnature_indication ::= nature_mark [index_constraint]
  [**tolerance** string_expression **across** string_expression **through**
- The tolerance group of a quantity is specified by its subtype
  - The "closest" tolerance aspect found when tracing subtype (or subnature) indications back to the base type
  - The tolerance group of type real is indicated by ""
- The tolerance group of a simple simultaneous statement is
  - The tolerance group of the quantity if the statement is of the form

    quantity_name == simple_expression;
    simple_expression == quantity_name;
  - Can be specified explicitly

Tolerance Example

- In package electrical_system:

```
subtype voltage is real tolerance "low_voltage";
subtype current is real tolerance "low_current";
```

- In a design entity:

```
architecture two of resistor is
        quantity vr across it through n1 to n2;
        -- tolerance group of vr and ir defined by their subtype
        quantity power:real;
        -- default tolerance for power is empty string
begin
        ir == vr/resistance;   -- defult tolerance group from ir
        power == vr * ir tolerance "other";
end architecture two;
```

Time

- New Time for Mixed-Mode Simulation
  - The internal simulation time is redefined to be of a new definitional type Universal_Time
  - Conversion from Time or Real to Universal_Time is exact
  - Conversion from Universal_Time to Time and Real
    - Have identical slopes and intercepts
    - Are linear within the accuracy of the representation of Real and the resolution limit of Time
    - Always round down to the nearest Real or Time value

- Overloaded function NOW:

  impure function NOW **return** Real;

- Overloaded S'Last_event to return type Real

Time

- Allow Real expression in timeout clause of a wait statement:

```
wait for 0.5;
```

this is equivalent to

```
quantity q: Real; signal s: Real;
q == now-s'Ramp;
process begin
        s<=now;
        wait for 0 ns;
        wait on q'above(0.5);
        …
end process;
```

Implicit Quantities

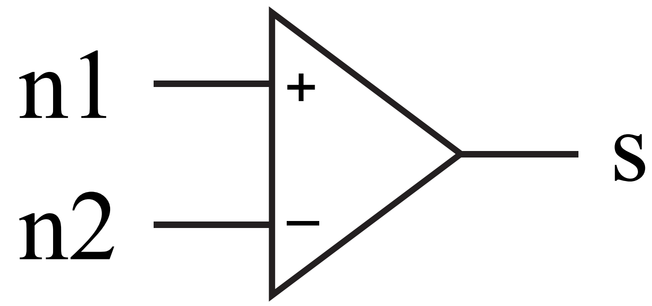
- S'Ramp[(tr[,tf])] A scalar quantity of the same type as signal S, that follows S with specified rise and fall times
- S'Slew[(max_rising_slope [,max_falling_slope])]
  Similar to S'Ramp, but with maximum slopes

- Q'Above(E)
  - Implicit Boolean Signal
  - TRUE when Q is above the threshold E and FALSE when Q is below the threshold
  - Q must be a scalar quantitiy, E must be an expression of the same type as Q
  - The transition between the two states creates an event on the signal
  - The value may be read in any non-static expression
  - The event may be used to trigger process execution

Example using Q'Above(E)

```
entity comparator is
        port (terminal n1, n2: electrical;
                signal s:out bit);
end entity comparator;

architecture ideal of comparator is
        quantity v across n1 to n2;
begin
        with v'Above(0.0) select
                s <=        '1' when true,
                            '0' when false;
end architecture ideal;
```



Simulation Cycle

- How does the simulation cycle work?
  - Analog simulation cycle must deteriorate into digital one in the limits
  - Analog simulation cycle based on Universal "Real" time
- Analog simulation cycle

a) Execute Analog Solver

b) Set Tc=Tn, terminate if Tn <=> Time'High or no active drivers

c) Update active explicit signals

d) If DOMAIN'Event, switch to time domain equations

f) Resume processes

g) Execute resumed nonpostponed processes

h) Determine Tn

i) If DOMAIN = INITIALIZATION_DOMAIN and Tn > 0 reset Tn to 0 and set the driver of DOMAIN to

- TIME_DOMAIN if a time domain simulation follows
- FREQUENCY_DOMAIN if a frequency domain simulation follows

j) Execute resumed postponed processes if Tn /= Tc

Discontinuous Models

- An abstract model may display discontinuities in its quantities as its DAEs change with time
- Any of the following *may*, but *does not always*, cause a discontinuity when used in a simultaneous statement:
    - An event on a signal
    - A conditional test on quantities
    - A function call
- NO implicit mechanism can be designed to efficiently and automatically detect every discontinuity without introducing phantoms

- An active break signal cues the analog solver to “process” the discontinuity
- The values of the ASP are the initial values for the next continuous interval

Synchronizing Analog to Digital

- A break statement announces a discontinuity in some quantity or its derivative at the instance of execution.
- Tells analog solver to reinitialize for next continuous interval.
- Both sequential and concurrent forms.
- New initial conditions may be specified at the same time.
- A model that causes a discontinuity at some time T and does not execute a break statement at T is erroneous.

```
with din select reff <=
        rof when 'Z';
        ron when others;
break on reff;
```

Synchronizing Digital to Analog

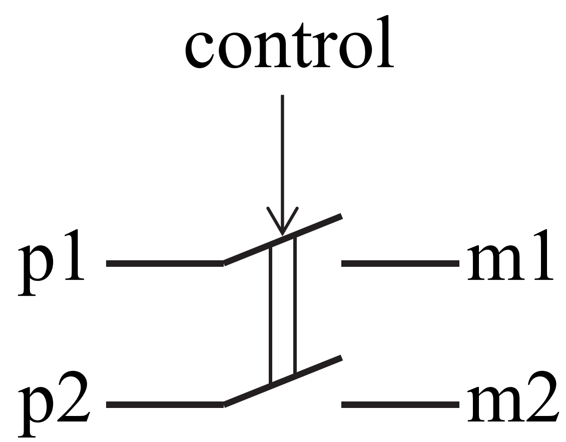
```
case s is
when 1 =>
        dout := '1';
        wait on vin'above(vlow);
when 2 =>
        dout := '0';
        wait on vin'above(vlow), vin'above(vhi);
```

- Q'above(E) is an attribute of Q.
- Q must be a scalar quantity. The result is a Boolean signal.
- An event occurs at the instance of threshold crossing.

Example: Single-pole double-throw switch

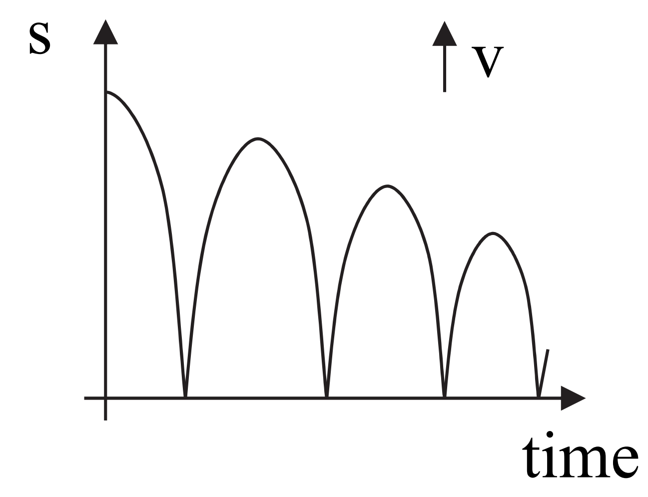
```
entity double_throw  is
        port(       signal control:IN bit;
                    terminal p1,m1,p2,m2:electrical);
end entity double_throw;

architecture ideal of double_throw is
        quantity v1 across i1 through p1 to m1;
        quantity v2 across i2 through p2 to m2;
begin
        if control = '0' use
                i1 == 0.0; i2 == 0.0;
        else
                v1 == 0.0; v2== 0.0;
        end use;
        break on control;       -- concurrent break statement
end architecture ideal;
```



Example: Bouncing Ball

```
entity bouncer is end entity bouncer;
architecture ball of bouncer is
        quantity v:velocity;                  -- m/sec
        quantity s:displacement;              -- m
        constant g: real := 9.81;             -- m/sec**2
        constant air_res : real := 0.001;     -- 1/m
begin
        s'Dot == v;
        if v>0.0 use
                v'Dot == -g - v**2*air_res;
        else
                v'Dot == -g + v**2*air_res;
        end use;
        break v => -v when not s'Above(0.0);       -- Announce discontinuity, reset
                                                   -- velocity value
        break v => 0.0, s => 10.0;                 -- Specify initial conditions
end architecture ball;
```



Frequency Domain Simulation

- Small signal-model defined as first term of Taylor expansion of $\underline{F}(\underline{x})$ about quiescent point
- AC Simulation
  - Find quiescent point
  - Set simulation frequency
  - Replace base set of CEs with CEs defined by small-signal model
  - Augment small-signal model with frequency domain augmentation set
  - Solve resulting (linear) equations
- Noise Simulation
  - Find quiescent point
  - Set simulation frequency
  - Replace base set of CEs with CEs defined by small-signal model
  - Augment small-signal model with noise augmentation set
  - Create a noise variable corresponding to each quantity
  - For each noise source quantity NQ
    - Replace corresponding CE by NQ - magnitude
    - Solve resulting (linear) equations
    - Add to each noise variable the square of the magnitude of the corresponding quantity
    - Restore CE
  - Set each quantity to square root of corresponding noise variable

Intentionally left out

- Special definitions for mixed netlists
    - A designer cannot simple “connect” a quantity port with a terminal or vice-versa, nor a quantity port with a signal
    - Simultaneous statements defining the intended connection must be explicitly specified, for example

```
terminal t:electrical;
quantity v across i through t;                  -- branch to ground
quantity q: voltage;
component foo is
        port(quantity iq:out voltage);          -- quantity “drives” terminal
end component foo;

c1: foo port map( iq => q);
v == q;                                         -- ideal connection
```