SUAVE: VHDL Extensions for System-Level Modeling

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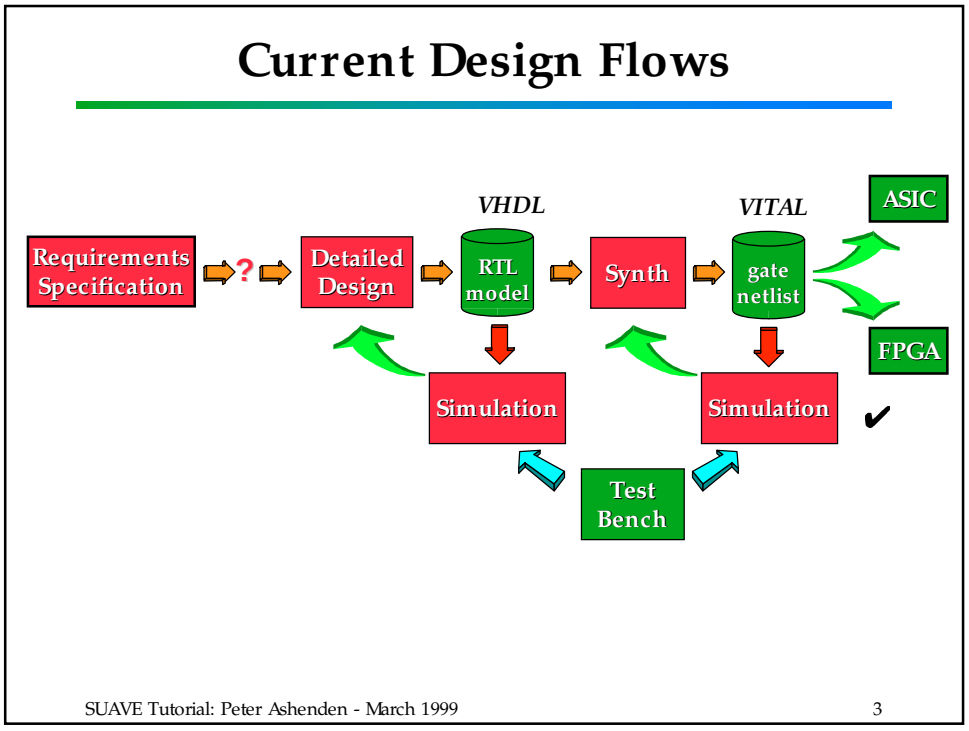
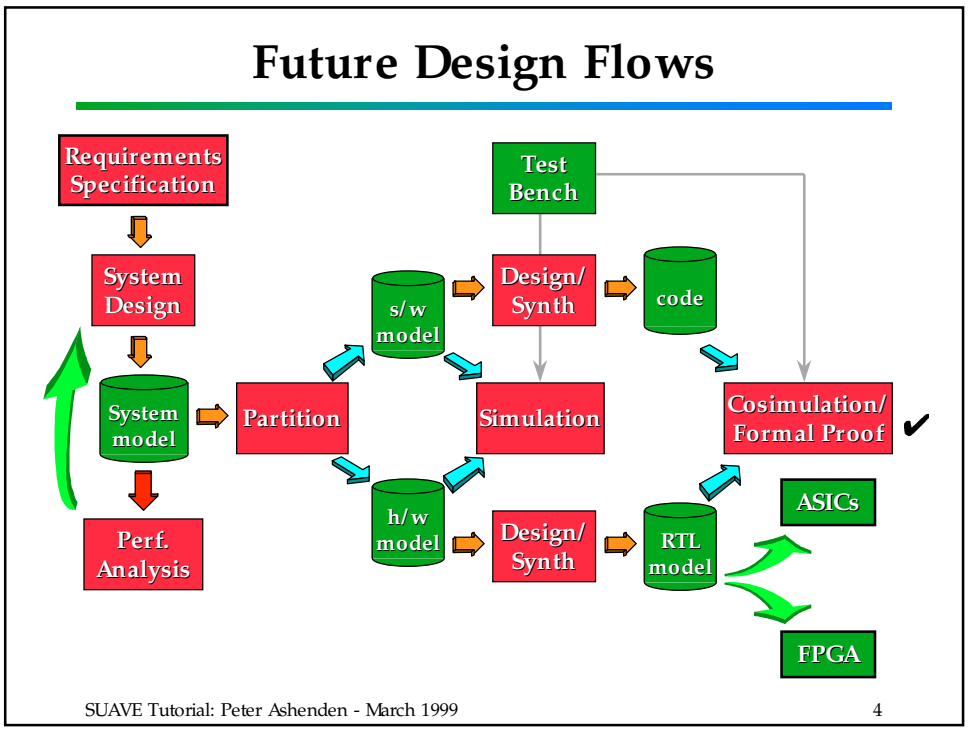
In a Nutshell ...

- VHDL is a standard hardware description language, and is good for
  - register transfer level and behavioral modeling
  - structural modeling
- SUAVE makes it better!
  - at what it's already good for
  - and for modeling large complex systems
- **S**AVANT and **U**niversity of **A**delaide **V**HDL **E**xtensions
  - SAVANT: **S**tandard **A**nalyzer of **V**HDL **A**pplications for **N**ext-generation **T**echnology
    - Phil Wilsey, U. Cincinnati


Current Design Flows
VHDL
VITAL
ASIC
Requirements Specification
?
Detailed Design
RTL model
Synth
gate netlist
FPGA
Simulation
Simulation
✔
Test Bench
SUAVE Tutorial: Peter Ashenden - March 1999
3


Future Design Flows
Requirements Specification
Test Bench
System Design
s/w model
Design/ Synth
code
System model
Partition
Simulation
Cosimulation/ Formal Proof
✔
h/w model
Design/ Synth
RTL model
ASICs
Perf. Analysis
FPGA
SUAVE Tutorial: Peter Ashenden - March 1999
4

High-Level Modeling

- System-level models
  - describe behavior of complex systems at a high level of abstraction
- Test benches
  - manage complex data sets and test sequences
- It's really software engineering!

High-Level Modeling Support

- Need abstract data types (ADTs) to manage complexity
  - VHDL has poor encapsulation
- Need inheritance to classify abstractions and for re-use
  - object-oriented methods
  - VHDL has no form of inheritance
- Need late binding to support evolution
  - VHDL only has ad-hoc polymorphism
    - subprogram overloading

High-Level Modeling Support

- Need type-based genericity for re-use
  - VHDL only has constant-based genericity
- Need dynamic process creation to model dynamic reactive systems
  - VHDL only has static process creation
- Need abstract communication
  - VHDL communication is via "hardware" signals

SUAVE Extensions

- SUAVE adds
  - secure ADTs: private types and private parts in packages
  - OO features: tagged types, type extension, inheritance, class-wide polymorphic types
  - type generics
  - generic packages and subprograms
  - channels and message passing
  - process declarations and instantiation
- The ADT, OO and generic extensions are based on ADA-95
  - integrated cleanly into VHDL

Language Design Principles

- Simplicity of mechanism
- Orthogonality of mechanism
  - with clearly defined interactions
- Integration with existing
  - semantic mechanisms
  - syntax
  - language philosophies

Agenda

- ADTs
  - private types and private parts in packages
- OO features
  - inheritance, tagged types, type extension, class-wide polymorphic types
- Type generics
- Generic packages and subprograms
- Communication
  - channels and message passing
- Processes
  - declarations and instantiation

Abstract Data Types (ADTs)

- Key mechanism for managing complexity
- Consists of
  - encapsulated data type
  - visible set of operations
- ADT user can only manipulate data with the public operations
  - secure, prevents inadvertent corruption of state
- VHDL mechanism
  - type and operations declared in a package
  - operations implemented in the package body
  - *type details can't be hidden!*

Package Example

```
package test_queues is
    use work.tests.all;
    constant max_size : positive := 100;
    type queue_array is array (0 to max_size – 1) of test;
    type queue is record
        head, tail : natural range 0 to max_size – 1;
        size : natural range 0 to max_size;
        the_buffer : queue_array;
    end record queue;
    function is_empty ( Q : queue ) return boolean;
    function is_full ( Q : queue ) return boolean;
    procedure add ( Q : inout queue;  item : in test );
    procedure remove ( Q : inout queue;  item : out test );
end package test_queues;
```

Package Example

```
use work.test_queues.all;
variable init_test_queue : test_queues.queue;
…
if not is_full ( init_test_queue ) then
    add ( init_test_queue, next_test );
end if;
…
init_test_queue.size := 42;
```


Private Types/Private Parts

- SUAVE strengthens encapsulation for ADTs
- Private types in packages
  - ADT user knows type name, but not details
  - declared using reserved word **private**
- Private part in package declarations
  - delimits publicly visible from hidden aspects
  - separated by reserved word **private**
  - allows analyzer to know sufficient details of private types to allocate storage

Secure ADT Example

```
package test_queues is
    use work.tests.all;
    type queue is private;
    function is_empty ( Q : queue ) return boolean;
    ...
private
    constant max_size : positive := 100;
    type queue_array is array (0 to max_size – 1) of test;
    type queue is record
        head, tail : natural range 0 to max_size – 1;
        size : natural range 0 to max_size;
        the_buffer : queue_array;
    end record queue;
end package test_queues;
```


Limited Private Types

- Normal private types have predefined assignment and (in)equality operations
  - element-wise copy/comparison
  - may not be appropriate, eg for pointer-based types
- A *limited private type*
  - cannot be assigned by ADT user
  - does not have predefined (in)equality
  - ADT can define them if appropriate
- Private type containing a pointer must say so
  - use reserved word **access** in declaration
  - prevents use as type of signals

Limited Private Type Example

```
package test_queues is
    use work.tests.all;
    type queue is limited access private;
    constant empty_queue : queue;
    procedure copy ( from_Q : in queue; to_Q : inout queue );
    impure function "=" ( L, R : in queue ) return boolean;
    impure function "/=" ( L, R : in queue ) return boolean;
    ...
private
    ...
end package test_queues;
```


Limited Private Type Example

```
package test_queues is
    ...
private
    type queue_element;
    type queue_ptr is access queue_element;
    type queue_element is record
        the_test : test;
        next_element, prev_element : queue_ptr;
    end record queue_element;
    type queue is record
        head, tail : queue_ptr;
    end record queue;
    constant empty_queue : queue := queue'(null, null);
end package test_queues;
```

Limited Private Type Example

```
use work.test_queues.all;
variable test_queue_1, test_queue_2 : test_queues.queue;
…
if test_queue_1 /= empty_queue then
    copy ( from_Q => test_queue_1, to_Q => test_queue_2 );
end if;
```


Lightweight Packages

- Currently packages are design units in VHDL
- SUAVE allows packages to be declared in any declarative part
  - eg, inside entities, architectures, process, subprograms, other packages
- Package declaration and body must appear in the same declarative region
- Allows local ADTs
- Like class definitions in C++

Package Example

```
architecture behavioral of microcontroller is
    package words is
        type word is range 0 to 2**16 – 1;
        function "+" ( L, R : in word ) return word;
        …
    end package words;
    package body words is
        function "+" ( L, R : in word ) return word is
        begin
            return (L + R) mod 2**16;
        end function "+";
        …
    end package body words;
    …
```


Package Example

```
    …
    use words.all;
    signal s : word;
    …
begin
    ...
end architecture behavioral;
```

Agenda

- ADTs
  - private types and private parts in packages
- OO features
  - inheritance, tagged types, type extension, class-wide polymorphic types
- Type generics
- Generic packages and subprograms
- Communication
  - channels and message passing
- Processes
  - declarations and instantiation

Primitive Operations & Inheritance

- For a type declared in a package
  - subprograms with parameters of the type are called *primitive operations*
- SUAVE allows new types to be *derived*
  - use the reserved word **new**
  - eg, **type** event_count **is new** natural;
  - distinct type from the parent (*cf* subtypes)
  - derived type inherits primitive operations of the parent
- If a type is derived within a package
  - may augment and override inherited primitive operations

Tagged Record Types

- SUAVE adopts tagged record types from Ada-95
  - use the reserved word **tagged**
  - tagged record object includes a runtime tag
  - identifies the specific type of the object
- Defining a tagged type and operations in a package is like defining a class

Tagged Record Example

```
package instructions is
    ...
    type instruction is
        tagged record
            opcode : opcode_type;
        end record instruction;
    function privileged ( instr : instruction;
                          mode : protection_mode ) return boolean;
    procedure disassemble ( instr : instruction;  L : inout line );
    ...
```

```
variable current_instruction : instruction
                    := instruction'(opcode => nop);
```

Type Extension

- OO involves refinement of data types
- A tagged type can be extended on derivation
- Defining a derived type in a package is like defining a subclass
  - inherits record elements and operations from parent
  - can add new record elements
  - can override and augment operations

Type Extension Example

```
type ALU_instruction is
    new instruction with record
        destination, source_1, source_2 : register_number;
    end record ALU_ instruction;
procedure disassemble ( instr : ALU_instruction;  L : inout line );
```

- ALU_instruction includes
  - opcode, destination, source_1 and source_2
  - inherits privileged operation
  - overrides disassemble operation

Abstract Types and Operations

- If type is to be used only as parent for derivation, declare it to be *abstract*
  - use reserved word **abstract**
  - cannot declare objects to be of an abstract type
- If an operation is required for all derived types, but not for parent type, declare it as an *abstract operation* of the parent type
  - no body for the abstract operation
  - must declare overriding operations for derived types
  - like C++ pure virtual functions

Abstract Type/Op Example

```
type memory_instruction is
    abstract new instruction with record
        base : register_number;
        offset : integer;
    end record memory_instruction;
function effective_address_of ( instr : memory_instruction )
                                    return integer;
procedure perform_memory_instruction
                ( instr : memory_instruction ) is abstract;
```

```
function effective_address_of ( instr : memory_instruction)
                                    return integer is
begin
    return read_register( instr.base ) + instr.offset;
end function effective_address_of;
```

Abstract Type/Op Example

```
type load_instruction is
    new memory_instruction with record
        destination : register_number;
    end record load_ instruction;
procedure perform_memory_instruction
                ( instr : load_instruction );
procedure disassemble ( instr : load_instruction;  L : inout line );
```

```
procedure perform_memory_instruction
                ( instr : load_instruction ) is
    variable ...
begin
    MDR := read_memory ( effective_address_of ( instr ) );
    ...
end procedure perform_memory_instruction;
```


Class-wide Types

- A *class-wide type*, T'class, includes
  - the type T (must be a tagged type)
  - all types derived directly or indirectly from T
- For example, instruction'class includes
  - instruction, ALU_instruction, memory_instruction, load_instruction, …
- SUAVE allows constants, variables and signals to be of class-wide types
  - such objects are *polymorphic*
  - can take on values of different specific types during their lifetimes

Dynamic Dispatch

- When an operation is applied to a polymorphic object
  - tag used to determine the specific type
  - appropriate version of the operation is invoked
  - *dynamic dispatch*, or *late binding*

```
signal fetched_instruction : instruction'class;
…
variable L : line;
…
disassemble ( fetched_instruction, L );
```


Class-wide Operations

- A subprogram can have parameters of class-wide types
- An entity can have ports of class-wide types
- Dynamic dispatch may be required

```
procedure execute ( instr : instruction'class ) is
    …
begin
    if privileged ( instr, current_mode ) then
        raise_exception ( privileged_instruction );
    else
        disassemble ( instr, L );
        …
    end if;
end procedure execute;
```

Example: Instruction Register

```
use work.instructions.all;
entity instruction_reg is
    port ( clk : in bit;  jam_nop : in bit;
           instr_in : in instruction'class;
           instr_out : out instruction'class );
end entity instruction_reg;
```


Example: Instruction Register

```
architecture behavioral of instruction_reg is
begin
    store : process ( clk ) is
        constant nop_instruction : instruction
                    := instruction'(opcode => nop);
    begin
        if clk = '1' then
            if jam_nop = '1' then
                instr_out <= nop_instruction;
            else
                instr_out <= instr_in;
            end if;
        end if;
    end process store;
end architecture behavioral;
```

Type Conversion

- Invoking a parent-type operation
  - convert object to the parent type

```
procedure disassemble ( instr : ALU_instruction;  L : inout line ) is
    …
begin
    disassemble ( instruction(instr), L );  – – disassemble opcode
    write ( L, ' ' );
    disassemble_reg ( instr.destination, L );
    ...
end procedure execute;
```


Extension Aggregates

- Converting to a derived type
  - need to provide values for the extended elements
  - use an *extension aggregate*

```
variable potential_load : load_instruction;
constant nop_instruction : instruction
                    := instruction'(opcode => nop);
. . .
potential_load := load_instruction'( nop_instruction with
                                        base => 0, offset => 0,
                                        destination => 0 );
```

Encapsulation and Extension

- SUAVE provides mechanisms for integrating private types and extensible types
- A private type can be tagged
  - can be extended, but details of parent are hidden
  - can also be abstract, limited, …
- A tagged type can be extended with a *private extension*
  - details of extension are hidden
- Combination
  - a private tagged type can be extended with a private extension

Private Extension Example

```
package MAC_level is
    ...
    type MAC_packet is abstract tagged private;
    procedure set_MAC_dest ( pkt : inout MAC_packet;
                             dest : in MAC_level_address );
    …
private
    type MAC_packet is
        tagged record
            source, dest : MAC_level_address;
        end record MAC_packet;
end package MAC_level;
```

Private Extension Example

```
package body MAC_level is
    procedure set_MAC_dest ( pkt : inout MAC_packet;
                             dest : in MAC_level_address ) is
    begin
        pkt.dest := dest;
    end procedure set_MAC_dest;
    …
end package body MAC_level;
```


Private Extension Example

```
package network_level is
    use work.MAC_level.MAC_packet;
    …
    type network_packet is
        new MAC_packet with private;
    procedure set_network_dest ( pkt : inout network_packet;
                                 dest : in network_level_address );
    …
private
    type network_packet is
        new MAC_packet with record
            source, dest : network_level_address;
            control : control_type;
            time_to_live : hop_count;
        end record network_packet;
end package network_level;
```

Private Extension Example

```
package body network_level is
    procedure set_network_dest ( pkt : inout network_packet;
                                 dest : in network_level_address ) is
    begin
        pkt.dest := dest;
    end procedure set_network_dest;
    …
end package body network_level;
```

- The source and dest elements in the private extension are distinct from the source and dest elements in the parent
  - preserves information hiding

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Type Generics

- VHDL only allows generic constants
  - used to specify timing parameters, operational parameters, port index bounds
- SUAVE allows generic types
  - used for type of ports, internal data, ...
- Significantly enhances reuse

Example: Generic Mux

```
entity mux is
    generic ( type data_type is private;
              T_pd : time );
    port ( sel : in bit;
           d0, d1 : in data_type;  d_out : out data_type );
end entity mux;
```

```
architecture data_flow of mux is
begin
    mux_flow :
        d_out <= d0 after T_pd when sel = '0' else
                 d1 after T_pd;
end architecture data_flow;
```

Example: Generic Mux

```
signal sel : bit;
signal s0, s1, s_out : bit;
signal i0, i1, i_out : integer;
use work.network_level.all;
signal pkt0, pkt1, pkt_out : network_packet;

bit_mux : entity work.mux(data_flow)
    generic map ( data_type => bit, T_pd => 2 ns )
    port map ( sel => sel, d0 => s0, d1 => s1, d_out => s_out );
int_mux : entity work.mux(data_flow)
    generic map ( data_type => integer, T_pd => 5 ns )
    port map ( sel => sel, d0 => i0, d1 => i1, d_out => i_out );
pkt_mux : entity work.mux(data_flow)
    generic map ( data_type => network_packet, T_pd => 12 us )
    port map ( sel => sel, d0 => pkt0, d1 => pkt1, d_out => pkt_out );
```


Generic Type Definitions

- Different kinds of formal type definitions
  - restrict the actual type that can be associated on instantiation
  - imply information about the formal type that can be used in the generic unit
- Example
  - **generic** (**type** index **is** (<>));
  - actual type must be a discrete type
  - unit can use index'succ, "<", ...

Generic Type Definitions

[[**abstract**] **tagged**] [**limited**] [**access**] **private**	Formal is private, with specified restrictions. Actual is any type that meets the restrictions.
[**abstract**] **new** *type* [**with** [**access**] **private**]	Formal is a derived type. Actual must be derived from the specified type. If **with private** is specified, actual must be a tagged type.
(<>)	Formal is discrete. Actual must be discrete.
range <>	Formal is an integer type. Actual must be an integer type.
range <> . <>	Formal is a floating-point type. Actual must be a floating-point type.
units <>	Formal is a physical type. Actual must be a physical type.

Generic Type Definitions

array (*index_def'n*) **of** *element_def'n*	Formal is an array type. Actual must be an array type with the same index and element types.
access *type*	Formal is an access type. Actual must be an access type with the same designated type.
file of *type*	Formal is a file type. Actual must be a file type with the same element type.
formal subprogram	Formal is a subprogram. Actual must be a subprogram with the same signature.
formal package	Formal is an instance of a specified package. Actual must be a similar instance of the specified package.

Example: Generic Counter

```
entity counter is
    generic ( type count_type is ( <> ) );
    port ( clk : in bit;  data : out count_type );
end entity counter;
```

```
architecture behavioral of counter is
begin
    count_behavior : process is
        variable count : count_type := count_type'low;
    begin
        data <= count;
        wait until clk = '1';
        if count = count_type'high then
            count := count_type'low;
        else
            count := count_type'succ( count );
        end if;
    end process count_behavior;
end architecture behavioral;
```


Example: Generic Counter

```
subtype short_natural is natural range 0 to 255;
type state_type is ( idle, receiving, processing, replying );
...
```

```
short_natural_counter : entity work.counter(behavioral)
    generic map ( count_type => short_natural )
    port map ( clk => master_clk,  data => short_data );
state_counter : entity work.counter(behavioral)
    generic map ( count_type => state_type )
    port map ( clk => master_clk,  data => state_data );
```

Example: Generic Shift Register

```
entity shift_register is
    generic ( type index_type is ( <> );
                type element_type is private;
                type vector is array ( index_type range <> )
                                of element_type );
    port ( clk : in bit;
           data_in : in element_type;  data_out : out vector );
end entity shift_register;
```


Example: Generic Shift Register

```
architecture behavioral of shift_register is
begin
    shift_behavior : process is
        constant data_low : index_type := data_out'low;
        constant data_high : index_type := data_out'high;
        subtype ascending_vector is
            vector ( data_low to data_high );
        variable stored_data : ascending_vector;
    begin
        data_out <= stored_data;
        wait until clk = '1';
        stored_data( data_low to index_type'pred(data_high) )
            := stored_data( index_type'succ(data_low) to data_high );
        stored_data( data_high ) := data_in;
    end process shift_behavior;
end architecture behavioral;
```

Example: Generic Shift Register

```
signal master_clk, carry_in : bit;
signal result : bit_vector(15 downto 8);
```

```
bit_vector_shifter : entity work.shift_register(behavioral)
    generic map ( index_type => natural,
                  element_type => bit,
                  vector => bit_vector )
    port map ( clk => master_clk,
               data_in => carry_in,  data_out => result );
```


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Generic Packages/Subprograms

- SUAVE also allows generic clauses in
  - package declarations
  - subprogram declarations
- Generic packages and subprograms
  - cannot be used or called directly
  - must be instantiated first
- Adopted directly from Ada
  - adapted to integrate with VHDL syntax
  - similar to C++ templates

Example: Generic Queue

```
package queues is
    generic ( type element_type is private );
    type queue is access private;
    impure function new_queue return queue;
    impure function is_empty ( Q : in queue ) return boolean;
    procedure append ( Q : inout queue;  E : in element_type );
    procedure extract_head ( Q : inout queue;  E : out element_type );
private
    type element_node;
    type element_ptr is access element_node;
    type element_node is record
        next_element : element_ptr;
        value : element_type;
    end record element_node;
    type queue is record
        head, tail : element_ptr;
    end record queue;
end package queues;
```

Example: Generic Queue

```
type test_vector is …;
variable generated_test : test_vector;
package test_queues is new queues
    generic map ( element_type => test_vector );
variable tests_pending : test_queues.queue
                := test_queues.new_queue;
...
```

```
test_queues.append ( tests_pending, generated_test );
```


Example: Generic Swap

```
procedure swap
    generic ( type data_type is private )
    ( a, b : inout data_type ) is
    variable temp : data_type;
begin
    temp := a;  a := b;  b := temp;
end procedure swap;
```

```
procedure swap_times is new swap
    generic map ( data_type => time );
variable old_time, new_time : time;
```

```
swap_times ( old_time, new_time );
```

Example: Generic Collection

```
package ordered_collection_adt is
    generic ( type element_type is private;
              type key_type is private;
              function key_of ( e : element_type ) return key_type;
              function "<" ( l, r : key_type ) return boolean is <> );
    type ordered_collection is access private;
    function new_ordered_collection return ordered_collection;
    procedure insert ( c : inout ordered_collection;
                       e : in element_type );
    procedure traverse
        generic ( procedure action ( element : in element_type ) )
        ( c : in ordered_collection );
    ...
```


Example: Generic Collection

```
    …
private
    -- Concrete representation is a doubly linked list
    -- with a sentinel record pointing to head and tail.
    type ordered_collection_object;
    type ordered_collection_ptr is
        access ordered_collection_object;
    type ordered_collection_object is record
        next_element, prev_element : ordered_collection_ptr;
        element : element_type;
    end record ordered_collection_object;
    type ordered_collection is new ordered_collection_ptr;
end package ordered_collection_adt;
```

Example: Generic Collection

```
package body ordered_collection_adt is
    function new_ordered_collection return ordered_collection is
        variable result : ordered_collection_ptr
                        := new ordered_collection_object;
    begin
        result.next_element := result;
        result.prev_element := result;
        return ordered_collection(result);
    end function new_ordered_collection;
    ...
```


Example: Generic Collection

```
    …
    procedure insert ( c : inout ordered_collection;
                       e : in element_type ) is
        variable current_element : ordered_collection_ptr
                        := ordered_collection_ptr(c).next_element;
        variable new_element : ordered_collection_ptr;
    begin
        while current_element /= ordered_collection_ptr(c)
                and key_of(current_element.element) < key_of(e) loop
            current_element := current_element.next_element;
        end loop;
        -- insert new element before current_element
        new_element := new ordered_collection_object'(
                           element => e,
                           next_element => current_element,
                           prev_element => current_element.prev_element );
        new_element.next_element.prev_element := new_element;
        new_element.prev_element.next_element := new_element;
    end procedure insert;
```

Example: Generic Collection

```
    …
    procedure traverse
        generic ( procedure action ( element : in element_type ) )
        ( c : in ordered_collection ) is
        variable current_element : ordered_collection_ptr
                    := ordered_collection_ptr(c).next_element;
    begin
        while current_element /= ordered_collection_ptr(c) loop
            action ( current_element.element );
            current_element := current_element.next_element;
        end loop;
    end procedure traverse;
end package body ordered_collection_adt;
```


Example: Generic Collection

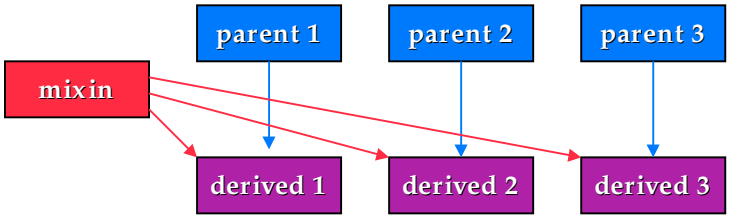
```
type stimulus_element is
    record
        application_time : delay_length;
        pattern : std_logic_vector (0 to stimulus_vector_length – 1);
    end record stimulus_element;
function stimulus_key ( stimulus : stimulus_element ) return delay_length is
begin
    return stimulus.application_time;
end function stimulus_key;
package ordered_stimulus_collection_adt is
    new ordered_collection_adt
        generic map ( element_type => stimulus_element,
                      key_type => delay_length,
                      key_of => stimulus_key,
                      "<" => std.standard."<" );
signal dut_inputs : std_logic_vector (0 to stimulus_vector_length – 1);
```

Example: Generic Collection

```
stimulus_generator : process is
    use ordered_stimulus_collection_adt.all;
    variable dut_stimuli : ordered_collection := new_ordered_collection;
    procedure apply_stimulus ( stimulus : stimulus_element ) is
    begin
        wait for stimulus.application_time – now;
        dut_inputs <= stimulus.pattern;
    end procedure apply_stimulus;
    procedure apply_all_stimuli is new traverse
        generic map ( action => apply_stimulus );
begin
    apply_all_stimuli ( dut_stimuli );
    wait;
end process stimulus_generator;
```


Mixin Inheritance

- Specification of elements and operations to be inherited by several different derived types
  - *mixed-in* with the parent types
- In SUAVE, combine OO features with formal generic derived types
  - *cf* Java interfaces: but with bodies
  - *cf* C++: requires multiple inheritance



Example: Addressing Modes

- Given type instruction and operations as defined earlier
  - define load and store instructions with different addressing modes
  - indexed, displacement, ...

```
type load_instruction is
    abstract new instruction with record
        destination : register_number;
    end record load_instruction;
type store_instruction is
    abstract new instruction with record
        source : register_number;
    end record store_instruction;
```


Example: Addressing Modes

```
package indexed_addressing_mixin is
    generic ( type parent_instruction is new instruction with private );
    type indexed_instruction is
        new parent_instruction with record
            index_base, index_offset : register_number;
        end record indexed_instruction;
    function effective_address ( instr : indexed_instruction )
                return integer;
end package indexed_addressing_mixin;
```

```
package indexed_loads is new indexed_addressing_mixin
    generic map ( parent_instruction => load_instruction );
alias indexed_load_instruction is indexed_loads.indexed_instruction;
package indexed_stores is new indexed_addressing_mixin
    generic map ( parent_instruction => store_instruction );
alias indexed_store_instruction is indexed_stores.indexed_instruction;
```

Agenda

- ADTs
  - private types and private parts in packages
- OO features
  - inheritance, tagged types, type extension, class-wide polymorphic types
- Type generics
- Generic packages and subprograms
- Communication
  - channels and message passing
- Processes
  - declarations and instantiation

Communication

- VHDL signals closely mirror electrical signals
  - assignment to drivers involves inertial or transport delay
  - event times and delays specified exactly
  - multiple drivers require resolution
  - receiver must sense signal values at the correct time, otherwise values are lost
    - require signalling protocol
- High-level modeling
  - prefer more abstract communication model
  - Causality-based synchronization
  - Queuing of values between processes

Abstract Communication

- SUAVE provides
  - named, typed communication channels
  - message-passing
    - synchronous, bounded asynchronous, or unbounded asynchronous
    - messages queued on channel until received
    - send, receive and select statements
  - point-to-point and multicast connection

Channel Types

- Channel types
  - types representing channels with a specified message types
  - null channel: empty message type
    - used for synchronization without data transfer
- Unbounded channel types
- Bounded channel types
  - specified buffer capacity for a channel
  - may be 0, $\Rightarrow$ synchronous communication
- Unconstrained bounded channel types
  - buffer capacity unspecified

Channel Objects

- Channels
  - declared objects of channel types
  - may be declared in the same places as signals
- Interface channels
  - ports of entities, components and blocks
  - parameters of subprograms
  - **in** or **out** mode

Channel Example

```
type request_message is …;
type result_message is …;

type acknowledgment_channel is null channel;

type blocking_request_channel is
    channel buffer 4 of request_message;
type bigger_request_channel is
    channel buffer 2 * blocking_request_channel'length
        of request_message;

type result_channel is channel buffer <> of result_message;

subtype blocking_result_channel is result_channel buffer 2;

channel acknowledgment : acknowledgment_channel;
channel request : blocking_request_channel;
channel result_1 : result_channel buffer 1;
channel result_2 : blocking_result_channel;
```

Interface Channel Conformance

- To connect a formal channel port to an actual channel...
- if formal is unbounded
  - actual must be unbounded
- if formal is constrained bounded
  - actual must be constrained bounded
  - buffer sizes must match
- if formal is unconstrained bounded
  - actual must be constrained bounded
  - buffer size of formal inferred from actual

Interface Channel Example 1

```
architecture performance_modeling of motion_detector is
    …
    type image_channel is channel of image_token;
    component image_filter is
        port ( channel raw_image : in image_channel;
                    channel filtered_image : out image_channel );
    end component image_filter;
    channel source_image, intermediate_image : image_channel;
    …
begin
    filter : component image_filter
        port map ( raw_image => source_image,
                        filtered_image => intermediate_image );
    …
end architecture performance_modeling;
```

Interface Channel Example 2

```
type pipe_link is channel buffer <> of link_data;

component pipe_stage is
    generic ( size : natural );
    port ( channel link_in : in pipe_link buffer size;
           channel link_out : out pipe_link buffer size );
end component pipe_stage;

channel link1, link2 : pipe_link buffer link_buffer_size;
...

stage1 : component pipe_stage
    generic map ( size => link_buffer_size )
    port map ( link_in => link1,  link_out => link2 );
```


Message Passing: Send

- Send statement
  - may block if channel message queue is full
    - never if channel is unbounded
  - adds message to tail of channel message queue
  - sending process then continues execution

```
send result_message'( ... ) to result;
send to request_ack;
```

- Concurrent sends from different processes
  - all messages added to queue, order undefined

Message Passing: Receive

- Receive statement
  - remove a message from head of channel message queue and assign the value to a variable
  - receiving process blocks if queue is empty

```
receive next_request from request;
receive from result_ack;
```

- Multiple processes receiving from a channel
  - all processes receive each message sent to the channel, and in the same order

Send & Receive Example

```
type image_token is …;
type image_channel is channel of image_token;
channel source_image, intermediate_image, … : image_channel;
```

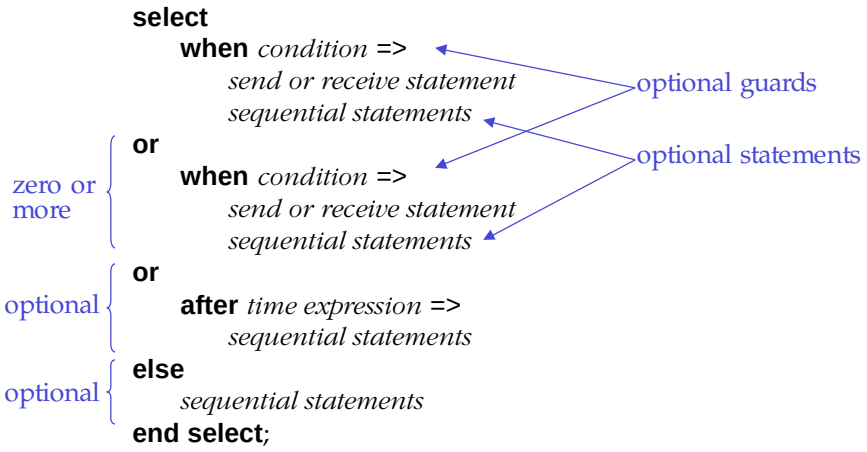
```
camera_controller : process is
    variable acquired_image : image_token;
begin
    acquired_image := … ;      -- acquire next image
    send acquired_image to source_image;
end process camera_controller;

first_filter : process is
    variable raw_image, filtered_image : image_token;
begin
    receive raw_image from source_image;
    filtered_image := … ;      -- filter the raw image
    send filtered_image to intermediate_image;
end process first_filter;

…
```

Message Passing: Select

- Non-deterministic choice between alternative sources for message reception



Select Example

- Readers and writers arbiter
  - reader requests access to resource, waits for acknowledgment, reads resource, then sends "finished" message
  - writer obeys similar protocol
  - multiple readers allowed when no writers are active
  - at most one writer allowed, but only when no readers are active

Select Example

```
type read_request_channel is channel of … ;      – – includes reader id
type read_finished_channel is null channel;
type write_request_channel is channel of … ;     – – includes writer id
type write_finished_channel is null channel;
channel read_request : read_request_channel;
channel read_finished : read_finished_channel;
channel write_request : write_request_channel;
channel write_finished : write_finished_channel;
…
```

```
access_controller : process is
    variable number_of_readers, number_of_writers : natural := 0;
    variable read_request_info : … ;
    variable write_request_info : … ;
…
```


Select Example 1

```
begin
    select
        when number_of_writers = 0 =>
            receive read_request_info from read_request;
            number_of_readers := number_of_readers + 1;
            …    – – acknowledge read request
    or
        receive from read_finished;
        number_of_readers := number_of_readers – 1;
    or
         when number_of_readers = 0 and number_of_writers = 0 =>
            receive write_request_info from write_request;
            number_of_writers := number_of_writers + 1;
            …    – – acknowledge write request
    or
        receive from write_finished;
        number_of_writers := number_of_writers – 1;
    end select;
end process access_controller;
```

Select Example 2

```
type bounded_channel is
    channel buffer max_size of message_type;
channel message_stream : bounded_channel;
...
message_source : process is
    variable next_message : message_type;
begin
    ...  – – construct next message in stream
    select
        send next_message to message_stream;
        ...  – – log successful send
    or after 0 fs =>
        ...  – – log loss of message from stream
    end select;
end process message_source;
```


Dynamically Created Channels

- In some cases, need to create channels dynamically (during simulation)
- Use *access-to-channel* type
  - access type designating a channel type
- Use **new** to allocate a channel
- Use deallocate to delete a channel

```
type result_ref is access result_channel;
variable result : result_ref := new result_channel;
…
deallocate ( result );
```

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Abstraction of Concurrency

- VHDL allows statically defined processes
- If system being modeled has a dynamically varying number of active objects
  - VHDL is inadequate
- Eg, client/server system
  - dynamically created agents to handle requests
- SUAVE allows dynamically created processes
  - instances of declared processes
  - process declaration includes generic & port lists
  - instances include generic and port maps
  - static or dynamic instances

Process Declarations

- May have separate declaration and body
  - or just body

```
process identifier is
    generic ( ... );
    port ( ... );
end process identifier;
```

omit if empty

```
process identifier is
    generic ( ... );
    port ( ... );
    declarations
begin
    sequential statements
end process identifier;
```

omit if empty

Static Process Instantiation

- Process instantiation statement
  - concurrent statement, like a process statement
  - makes an instance of a declared process
  - created at elaboration-time

```
label : process process_name
        generic map ( ... )
        port map ( ... );
```

omit if empty

Dynamic Process Instantiation

- Sequential process instantiation statement
  - sequential statement, occurs in a process or subprogram body
  - makes an instance of a declared process
    - *depends* on the process containing the declaration of the instantiated process
  - created at simulation-time

label : **process** *process_name*
generic map (…)
port map (…);

omit if empty

Process Termination

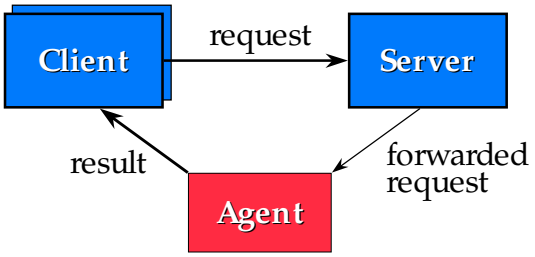
- A process may execute a *terminate statement*

terminate;

- Termination involves
  - waiting until all dependent processes terminate
  - disconnecting drivers
  - disassociating actual signals and channels from ports

Example: Client/Server System

- Client-server system
  - number of clients not known *a priori*
  - multi-threaded server
  - creates new process to handle a request



Example: Client/Server System

```
architecture system_level of client_server_system is

    type result_value is … ;
    type result_channel is channel of result_value;
    type result_ref is access result_channel;

    type request_info is record
        … ; – – info for the transaction
        result_please : result_ref;
    end record request_info;
    type request_channel is channel of request_info;
    type request_ref is access request_channel;

    process client is
        port ( channel request : out request_channel );
    …

    process server is
        port ( channel request : in request_channel );
    …

    channel server_request : request_channel;

…
```

Example: Client/Server System

```
begin
    the_server : process server
        port map ( request => server_request );
    client_pool : for client_index in 1 to number_of_clients generate
        a_client : process client
            port map ( request => server_request );
    end generate client_pool;
end architecture system_level;
```

```
    process client is
        port ( channel request : out request_channel );
        variable result : result_ref := new result_channel;
    begin
        …
        send ( …, result ) to request;
        receive … from result.all;
        …
    end process client;
```


Example: Client/Server System

```
    process server is
        port ( channel request : in request_channel );
        process agent is
            port ( channel request : in request_channel );
            variable info : request_info;
        begin
            receive info from request;
            … ; -- perform transaction
            send … to info.result_please.all;
            terminate;
        end process agent;
        variable info : request_info;
        variable new_agent_request : request_ref;
    begin
        receive info from request;
        new_agent_request := new request_channel;
        process agent
            port map ( request => new_agent_request.all );
        send info to new_agent_request.all;
    end process server;
```

Conclusion

- Complexity management ⇒ abstraction
- SUAVE: abstraction for
  - data modeling
  - communication & timing
  - concurrency
- System-level modeling
  - pre- hardware/software partitioning
- Further info
  - http://www.cs.adelaide.edu.au/~petera/