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Sequential Statement

- Wait Statement
- Assertion Statement
- Report Statement
- Generate Statement
- Signal Assignment
- Variable Assignment
- Procedure Call
- If
- Case
- Loop
- Next
- Exit
- Return
- Null

- **Case Statement**
- **If Statement**
- **Loop Statement**
- **Process Statement**
- **Subprogram Body**

- Sequential Signal Assignment

- Conditional Signal Assignment
- Selected Signal Assignment

X

Concurrent Statement

- Block Statement
- **Process Statement**
- Component Statement
- Generate Statement
- **Concurrent Signal Assignment**
- Concurrent Assertion
- Concurrent Procedure Call

- **Architecture Body**
- **Block Statement**
- **Generate Statement**

- **Conditional Signal Assignment**
- **Selected Signal Assignemnt**

Selected Signal Assignment

- Conditional Signal Assignment

```
Z <=  A or B  [ after 1 ns ]  when SEL = "00" else  
      A or C  [ after 2 ns ]  when SEL = "01" else  
      A or D  [ after 2 ns ]  when SEL = "10" else  
      A or E  [ after 3 ns ]  when SEL = "11" else  
      A or F  [ after 4 ns ]  ;
```

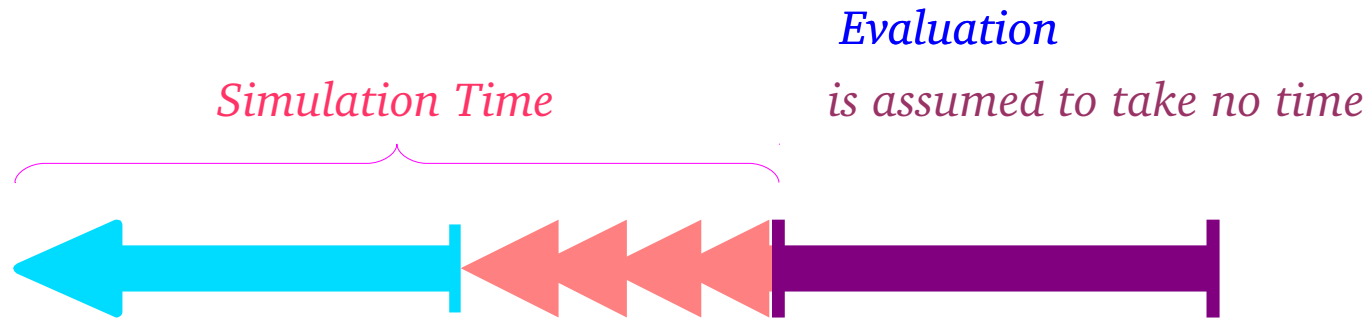
condition

- Selected Signal Assignment

```
with SEL select  
Z <=  A or B  [ after 1 ns ]  when "00",  
      A or C  [ after 2 ns ]  when "01",  
      A or D  [ after 3 ns ]  when "10",  
      A or E  [ after 4 ns ]  when "11",  
      A or F  [ after 5 ns ]  when others;
```

selection

Simulation Time (1)



Unit: *ms, ns, ps, ...*

Unitless Delta Δ

Real Delay

– used for a simulator to
mimic parallel activities
simulator

$$1 \text{ ms} = 1000 \text{ ns}$$

$$1 \text{ ns} = 1000 \text{ ps}$$

$$1 \text{ ps} \neq n \cdot \Delta$$

*no integer n that make n delta
equal to 1 ps.*

$$n \cdot \Delta = 0 \text{ ps} = 0 \text{ ns} \dots$$

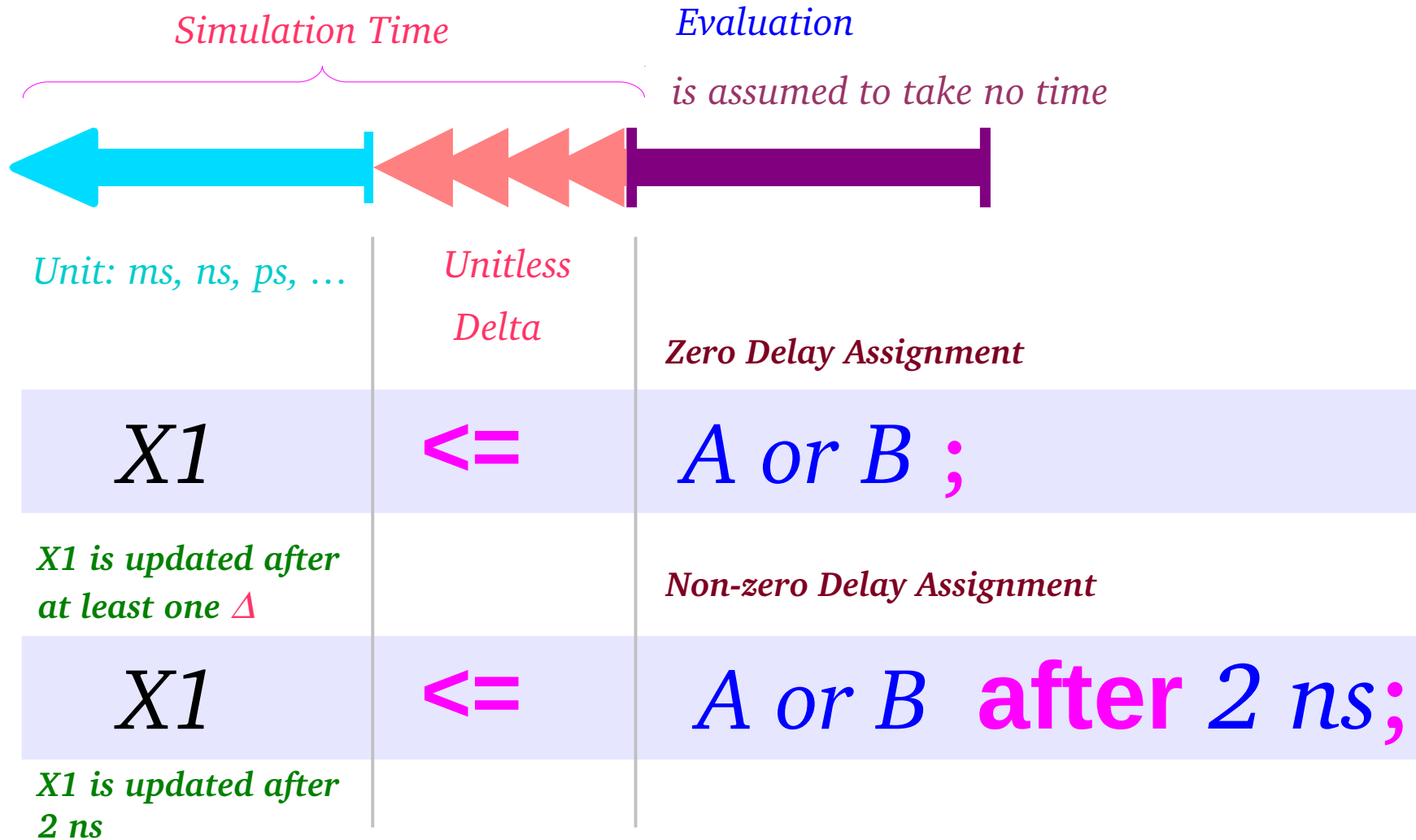
Zero Delay

Zero Delay Assignment

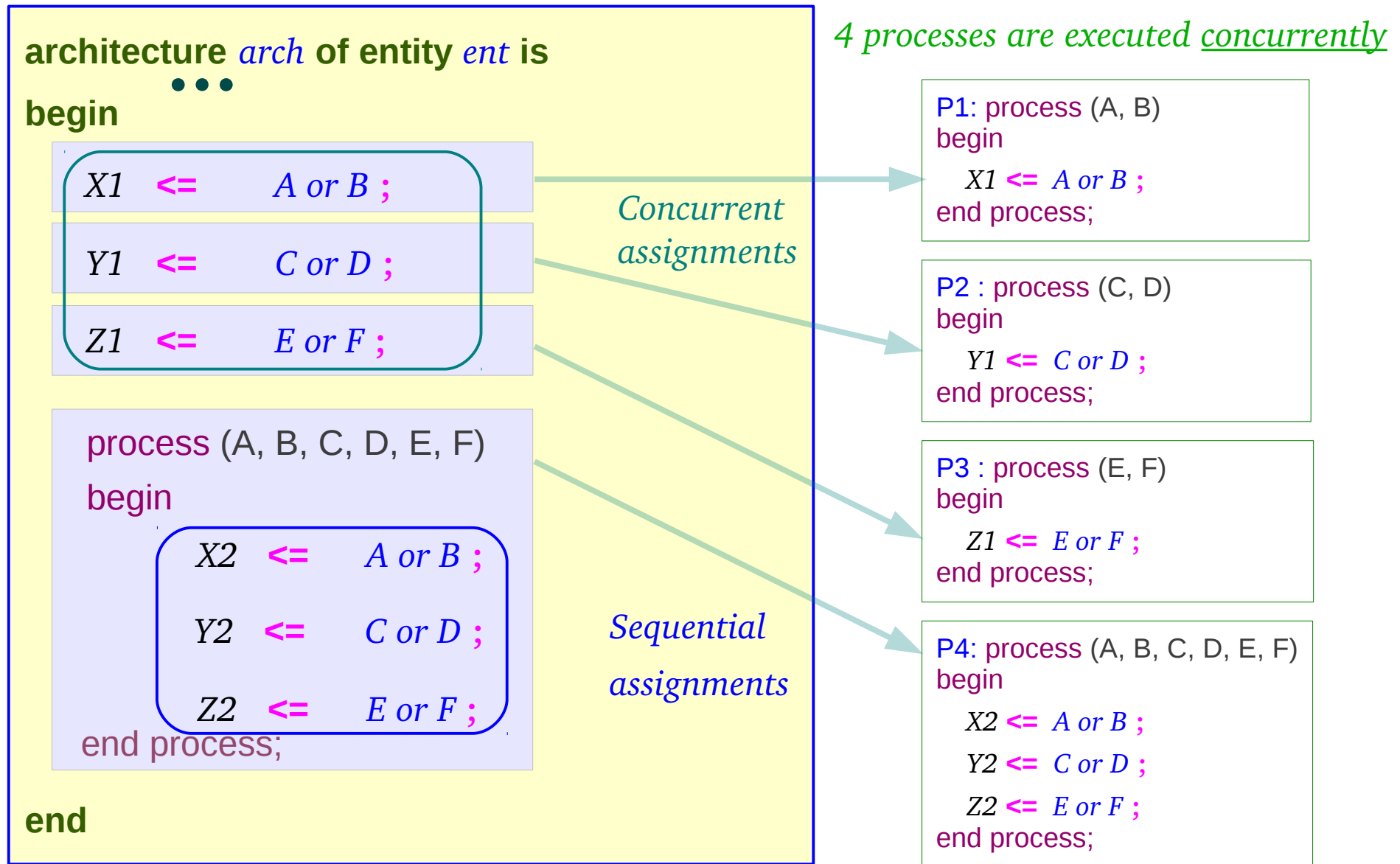
```
X1 <= A or B ;
```

```
X1 <= A or B after 0 ns;
```

Simulation Time (2)



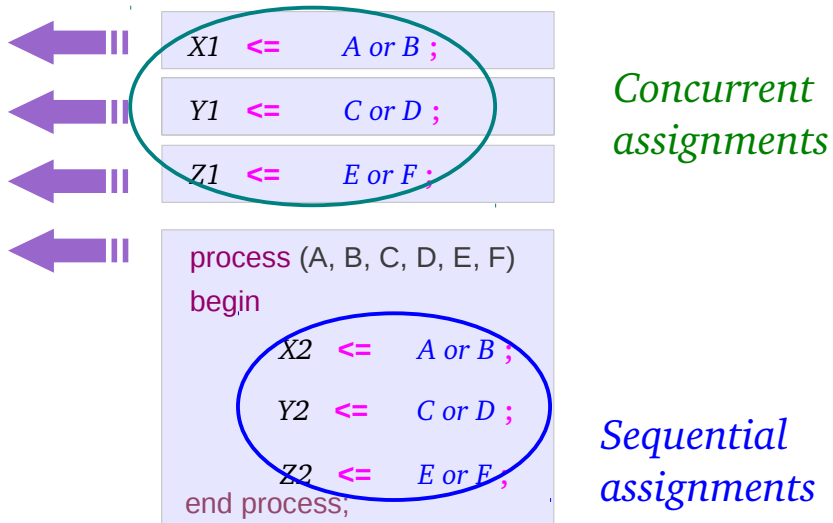
Concurrent vs Sequential (2)



Concurrent vs Sequential (3)

Simulation of parallel activities

4 processes are executed concurrently

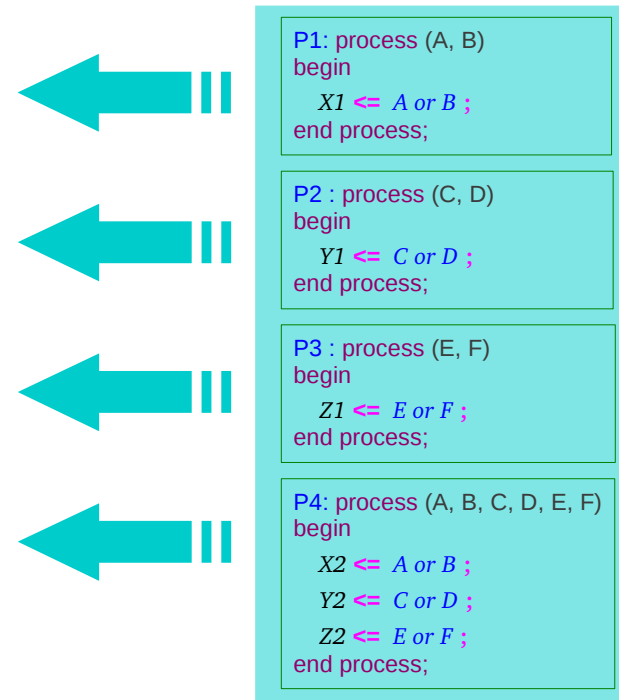


The order of statements is important

end

Non-deterministic Execution Order

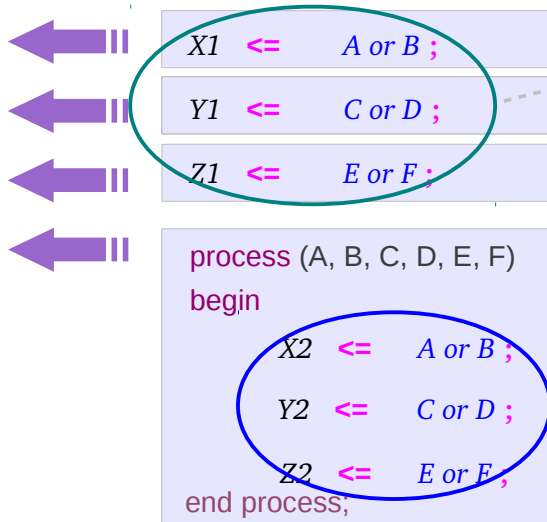
Don't know which process executes first among P1 ~ P4.



Concurrent vs Sequential (4)

Simulation of parallel activities

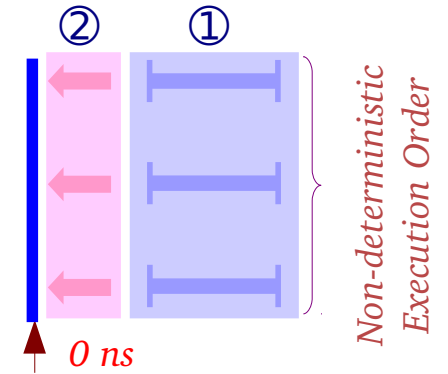
4 processes are executed concurrently



The order of statements is important

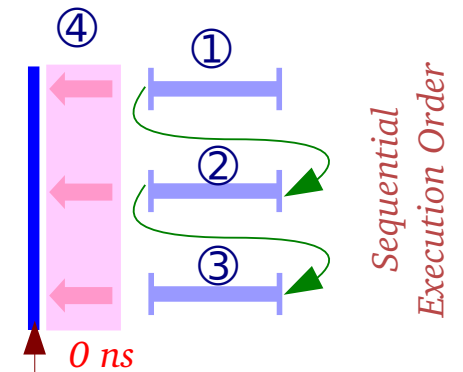
end

Concurrent assignments



Scheduled Time *Delta Evaluation Time*

Sequential assignments



Signals & Variables

Conditional Signal Assignment

```
Z <= A or B [ after 1 ns ] when S0 = '1' else  
      A or C [ after 2 ns ] when S1 = '1' else  
      A or D [ after 3 ns ] ;
```

```
Z <= A or B [ after 1 ns ] when S0 = '1' else  
      A or C [ after 2 ns ] ;
```

```
Z <= A or B [ after 1 ns ] when S0 = '1' ;
```

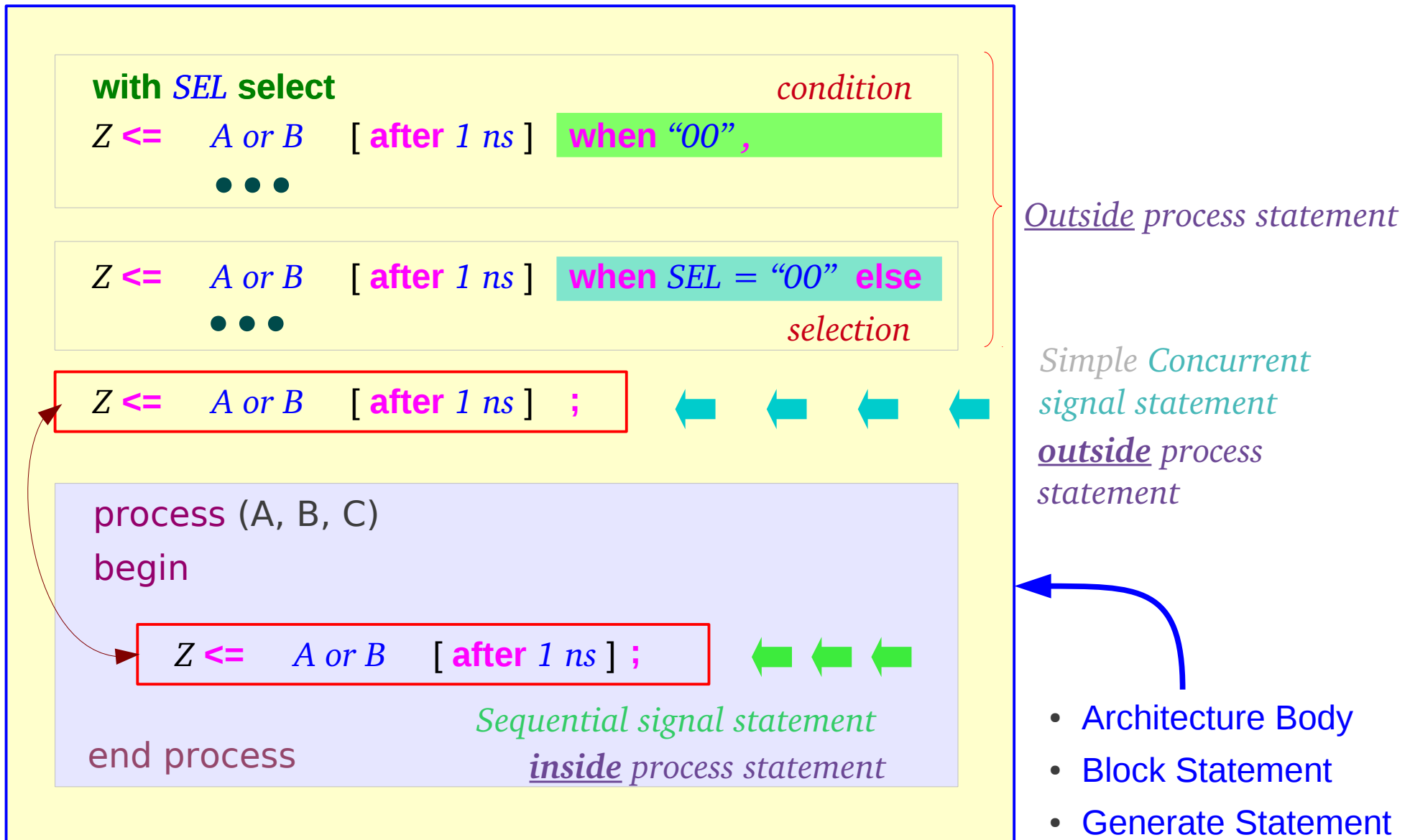
```
Z <= A or B [ after 1 ns ] ;
```

← *simple concurrent statement*

• Concurrent Signal Assignment

- Conditional Signal Assignment
- Selected Signal Assignment

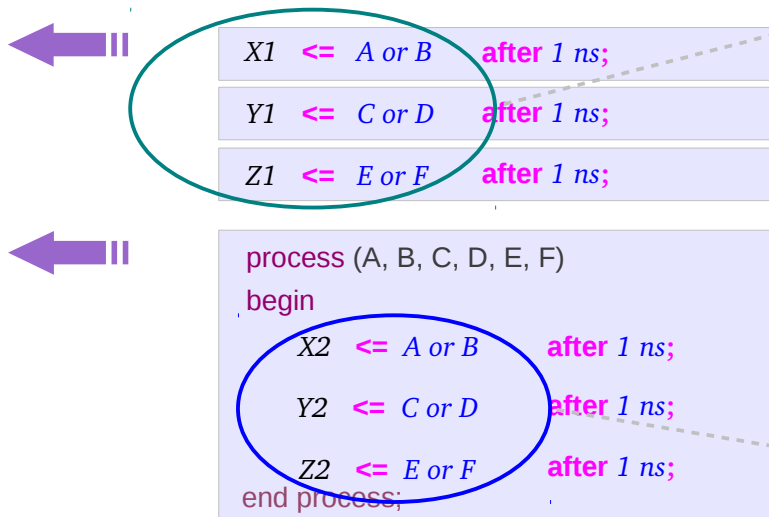
Concurrent vs Sequential (1)



Concurrent vs Sequential (5)

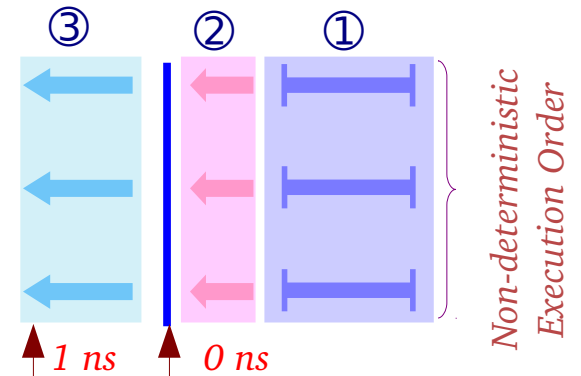
Simulation of parallel activities

4 processes are executed concurrently



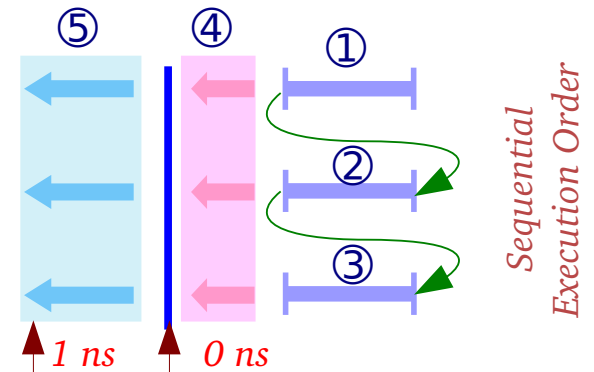
The order of statements is important

Concurrent assignments



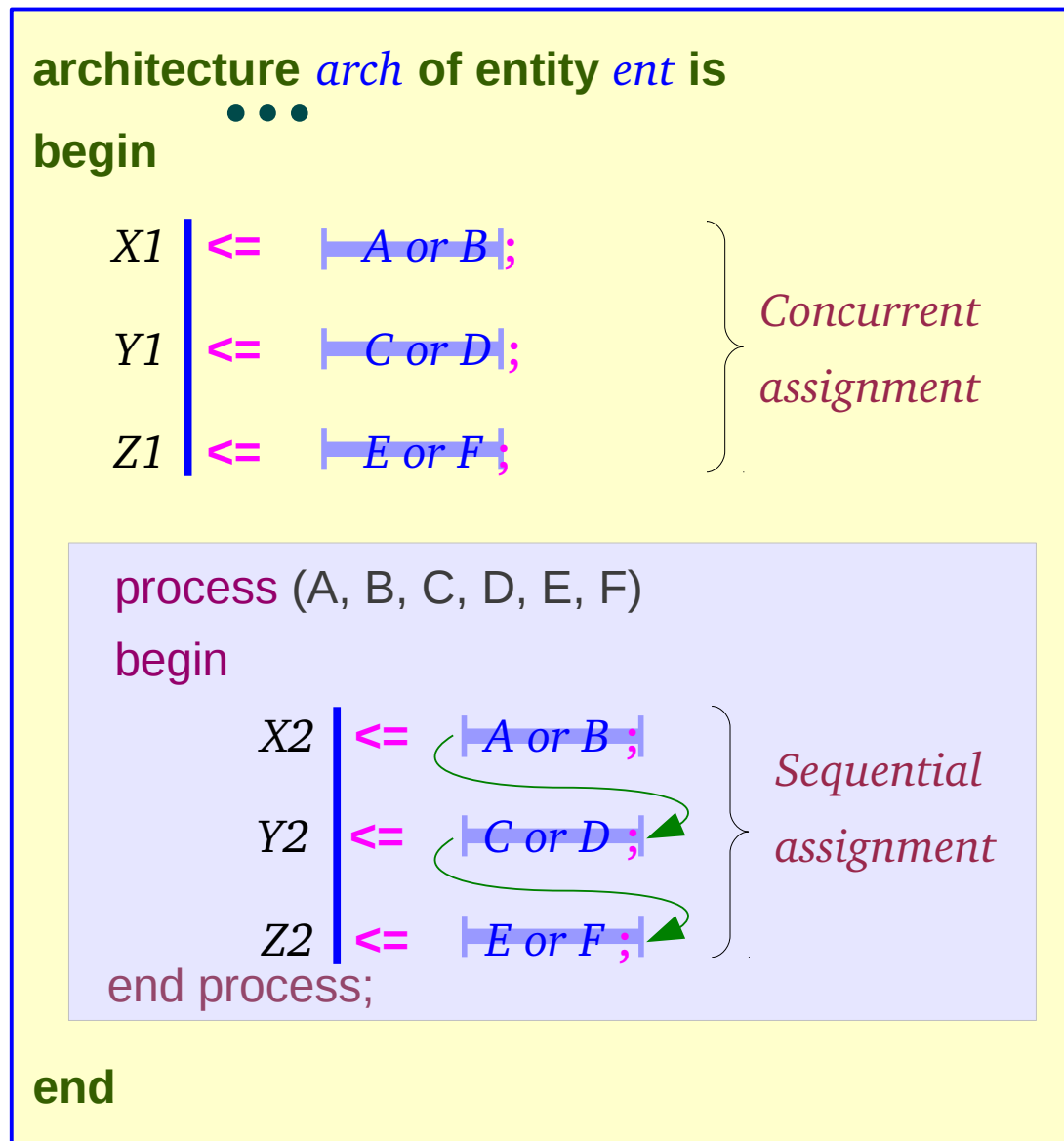
Scheduled Time *Delta Evaluation Time*

Sequential assignments

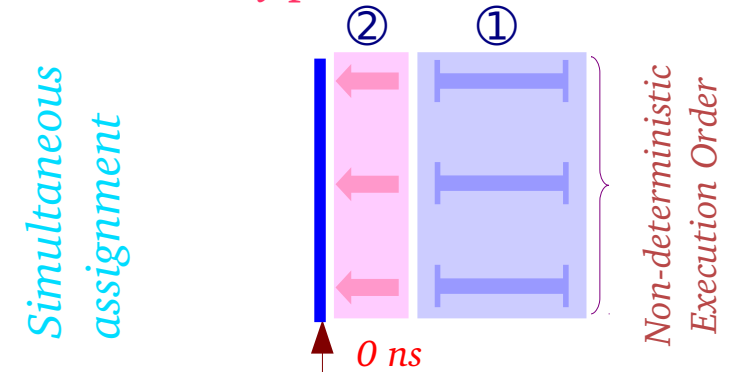


Non-blocking Assignment

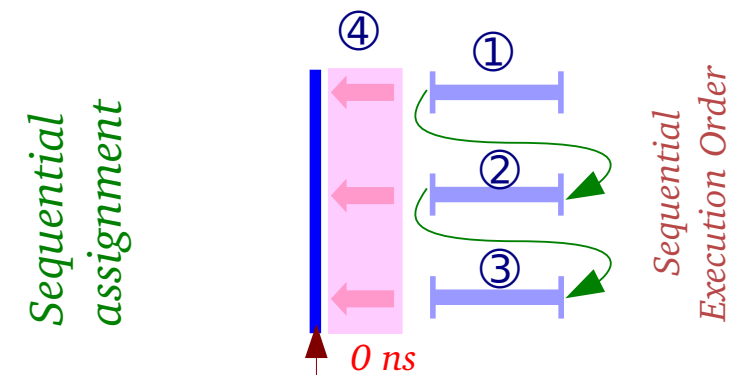
Order of Execution (1)



Simulation of parallel activities

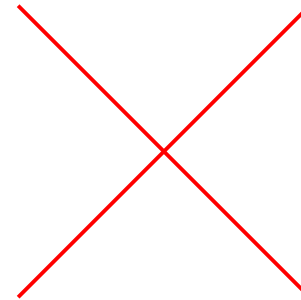
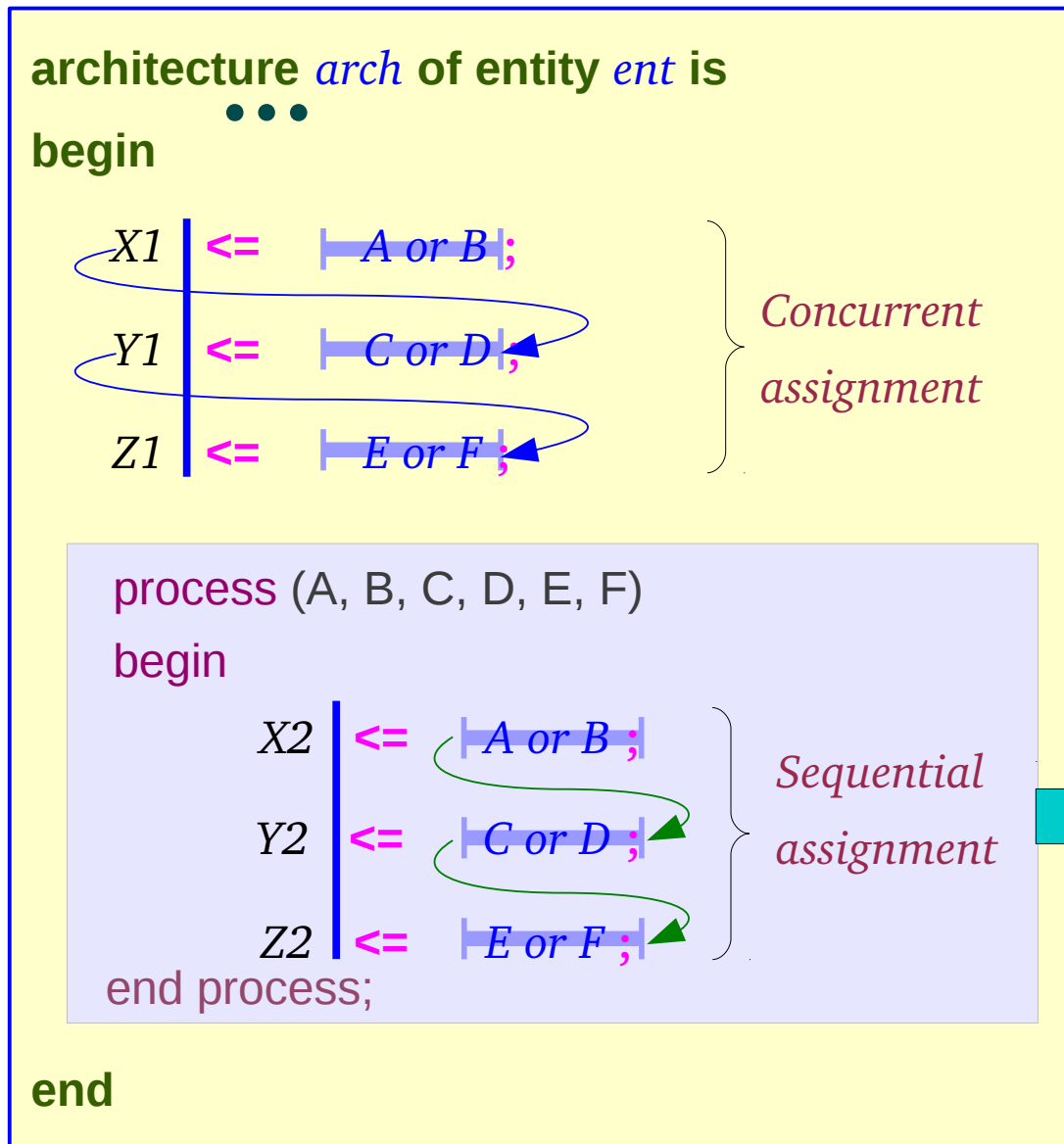


Scheduled Time *Delta Evaluation*



The order of statements is important

Order of Execution (2)



1. scheduled after some delta time
2. non-blocking assignment

Order of Execution (3)

```
architecture arch of entity ent is
  ...
begin
```

```

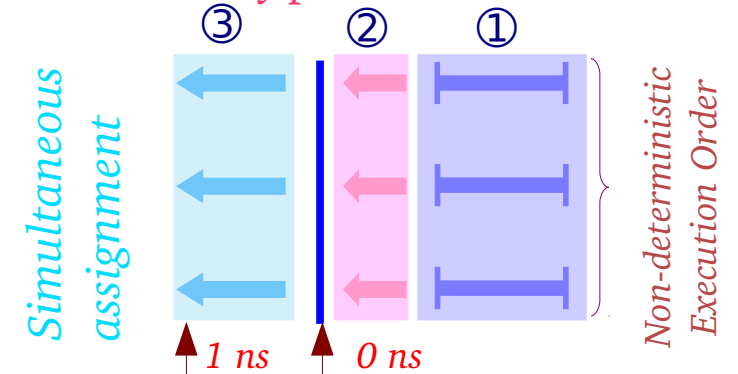
X1 <= A or B after 1 ns;
Y1 <= C or D after 1 ns;
Z1 <= E or F after 1 ns;
```

```

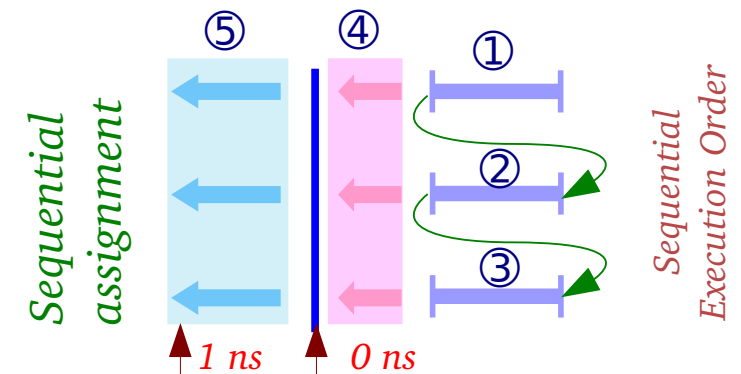
process (A, B, C, D, E, F)
begin
  X2 <= A or B after 1 ns;
  Y2 <= C or D after 1 ns;
  Z2 <= E or F after 1 ns;
end process;
```

```
end
```

Simulation of parallel activities



Scheduled Time *Delta Evaluation*



The order of statements is important
Non-blocking Assignment

Zero Delay Assignment

architecture *arch* of entity *ent* is

begin

X1 <= A or B ;

Y1 <= C or D ;

Z1 <= E or F ;

process (A, B, C, D, E, F)

begin

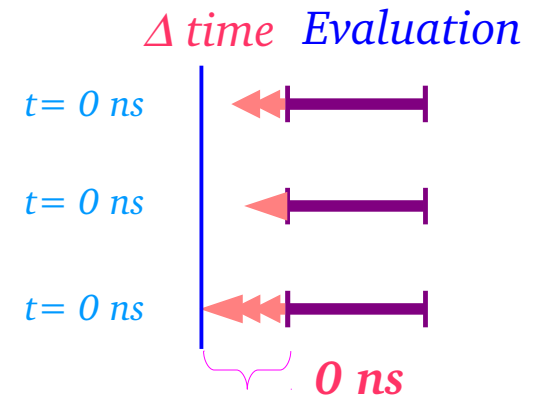
X2 <= A or B ;

Y2 <= C or D ;

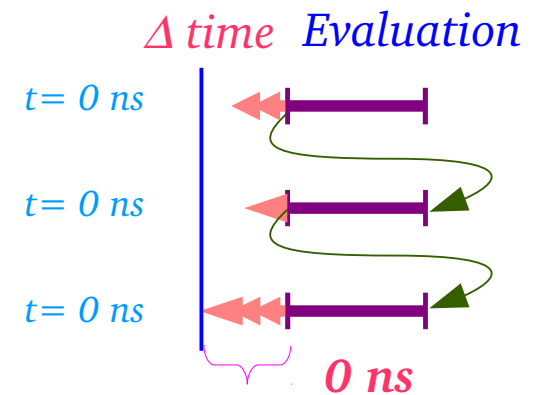
Z2 <= E or F ;

end process;

end



The exact no of delta is determined by the simulator and the context



Updated values

Non-Zero Delay Assignment

```
architecture arch of entity ent is
  ...
begin
```

```

X1 <= A or B after 1 ns;
Y1 <= C or D after 3 ns;
Z1 <= E or F after 2 ns;
```

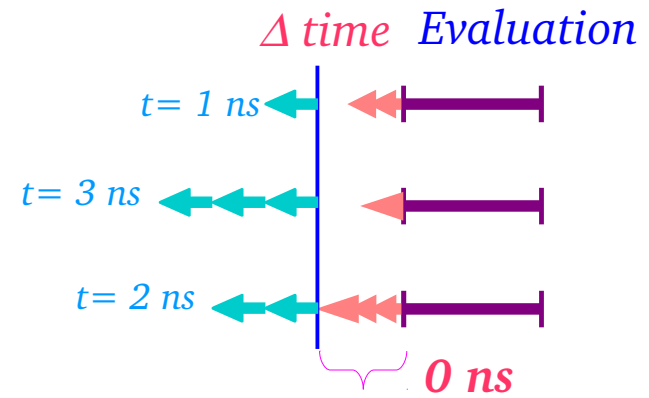
```
process (A, B, C, D, E, F)
```

```
begin
```

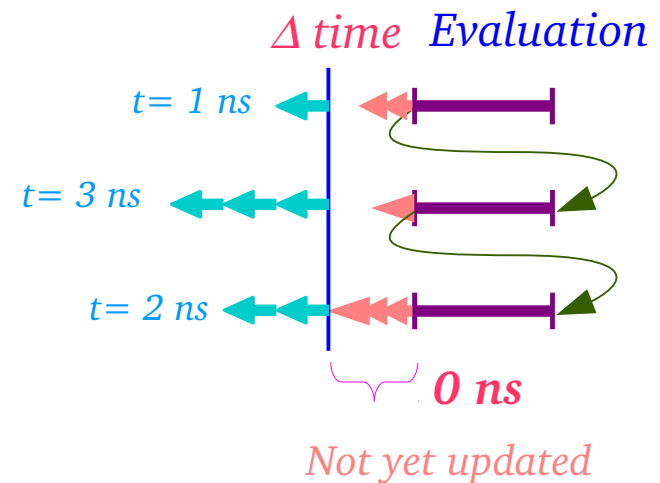
```

X2 <= A or B after 1 ns;
Y2 <= C or D after 1 ns;
Z2 <= E or F after 1 ns;
end process;
```

```
end
```



The exact no of delta is determined by the simulator and the context



Non-blocking Assignment (1)

```
process (A, I0, I1)
begin
    SEL <= A or B;
    if (A='1') then SEL <= SEL + 1; end if;
    case SEL is
        when 0
            Q <= I0;
        when 1
            Q <= I1;
    end case;
end process;
```

end

Non-blocking Assignment (2)

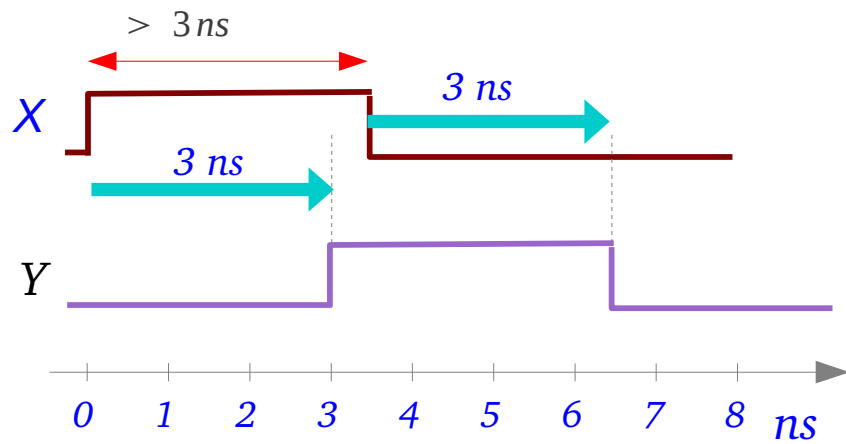
```
process
begin
    SEL <= A or B;
    wait for 0 ns;
    if (A='1') then SEL <= SEL + 1; end if;
    wait for 0 ns;
    case SEL is
        when 0
            Q <= I0;
        when 1
            Q <= I1;
    end case;
    wait on A, I0, I1;
end process;
```

Non-blocking Assignment (3)

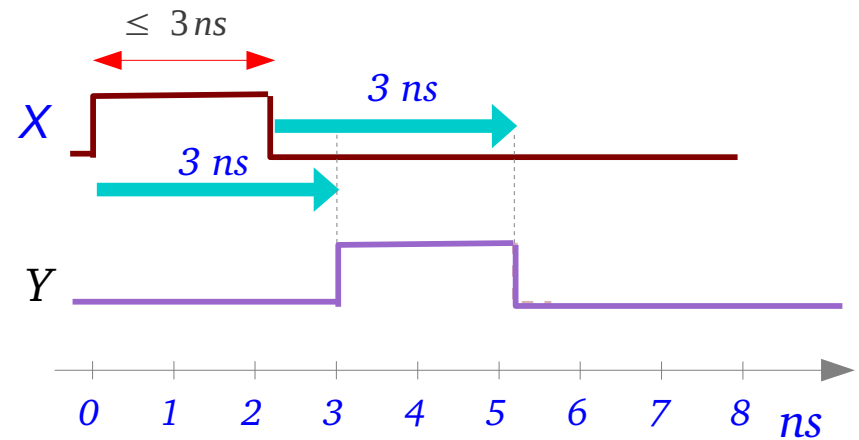
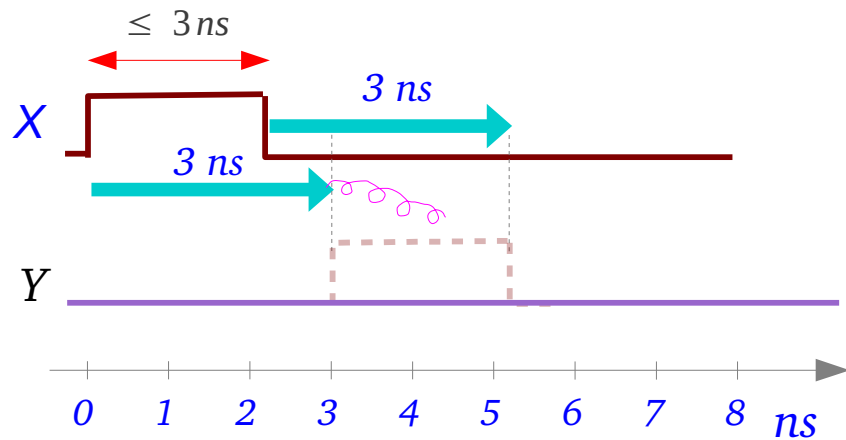
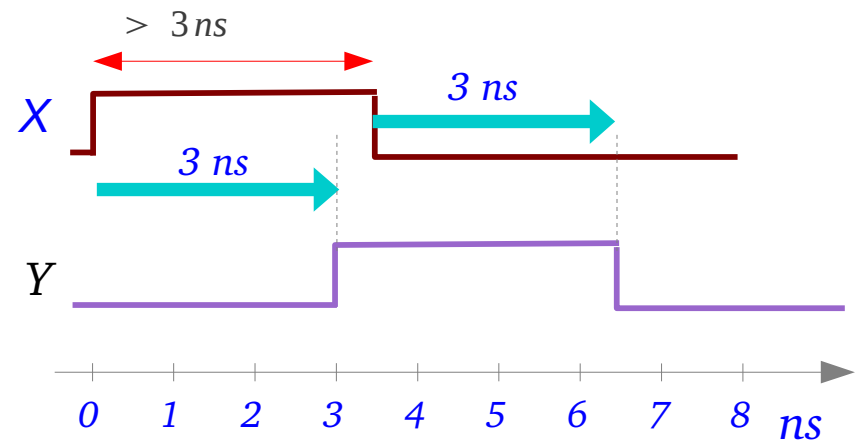
```
process (A, I0, I1)
  variable SEL : integer range 0 to 1;
begin
  SEL := A or B;
  if (A='1') then SEL := SEL + 1; end if;
  case SEL is
    when 0
      Q <= I0;
    when 1
      Q <= I1;
  end case;
end process;
```

Inertial Delay & Transport Delay

```
Y <= X after 3 ns;
```



```
Y <= transport X after 3 ns;
```



Variable Assignment (1)

```
architecture arch of entity ent is
```

•••

```
begin
```

```
  X1 <= A or B after 1 ns;
```

```
  Y1 <= C or D after 3 ns;
```

```
  Z1 := E or F ;
```

```
  process (A, B, C, D, E, F)
```

```
    variable Y2, Z2 : bit;
```

```
  begin
```

```
    X2 <= A or B after 1 ns;
```

```
    Y2 := C or D after 3 ns;
```

```
    Z2 := E or F ;
```

```
  end process;
```

```
end
```

The Variable assignment is a sequential statement and cannot be used outside a process statement.

The variable is **declared** here. They are used for **local storage** in process statement and subprogram body.

The variable assignment has nothing to do with time. It executes immediately. It can not have an **after** clause

Variable Assignment (2)

```
process (A, B, C, D, E, F)
```

```
  variable Z2 : bit;
```

```
begin
```

```
  X2 <= A or B after 1 ns;
```

```
  Y2 <= C or D after 3 ns;
```

```
  Z2 := E or F ;
```

```
end process;
```

```
process (A, B, C, D, E, F)
```

```
  variable Y2 : bit;
```

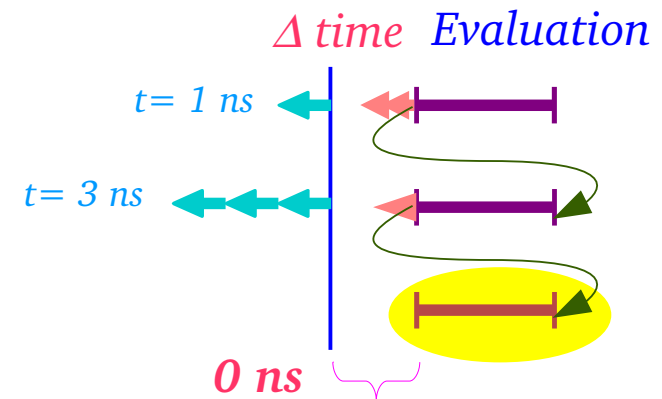
```
begin
```

```
  X2 <= A or B after 1 ns;
```

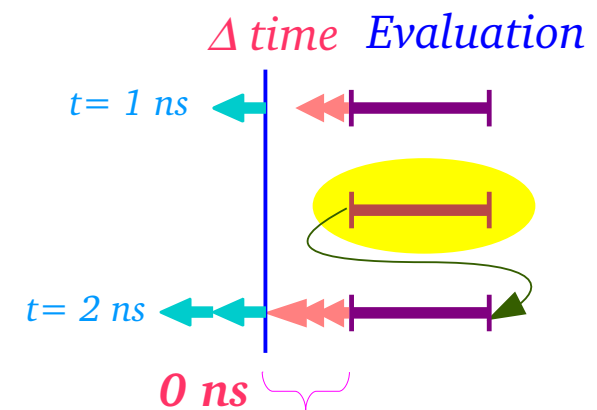
```
  Y2 := C or D ;
```

```
  Z2 <= E or F after 2 ns;
```

```
end process;
```



The variable assignment has nothing to do with time. It executes immediately.



Multiple Assignments to the Same Target

```
architecture arch of entity ent is
  ...
begin
  X1 <= A or B ;
  X1 <= C or D ;

  process (A, B, C, D, E, F)
    variable Z2 : bit;
  begin
    Y2 <= A or B ;
    Y2 <= C or D ;

    Z2 := A or B ;
    Z2 := C or D ;
  end process;
end
```

Multiple Concurrent Assignments

Multiple Concurrent Assignment is legal only when a resolution function is defined.

(wire-and, wire-or)

Multiple Sequential Assignments

- Overwrite
- Append
- Keep

Multiple Variable Assignments

Variable Z2 has the result of the latest assignments (The new assignment overwrites the old one)

Multiple Sequential Assignments

```
architecture arch of entity ent is
```

```
    .....
```

```
begin
```

```
    X1 <= A or B ;
```

```
    X1 <= C or D ;
```

```
    process (A, B, C, D, E, F)
```

```
        variable Z2 : bit;
```

```
    begin
```

```
        Y2 <= A or B ;
```

```
        Y2 <= C or D ;
```

```
        Z2 := A or B ;
```

```
        Z2 := C or D ;
```

```
    end process;
```

```
end
```

Multiple Concurrent Assignments

Multiple Concurrent Assignment is legal only when a resolution function is defined.

(wire-and, wire-or)

Multiple Sequential Assignments

- *Overwrite*
- *Append*
- *Keep*

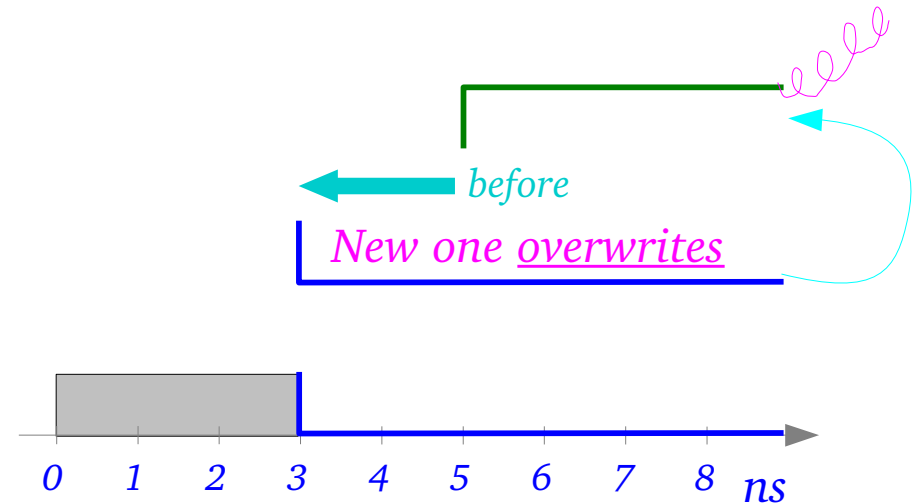
Multiple Variable Assignments

Variable Z2 has the result of the latest assignments (The new assignment overwrites the old one)

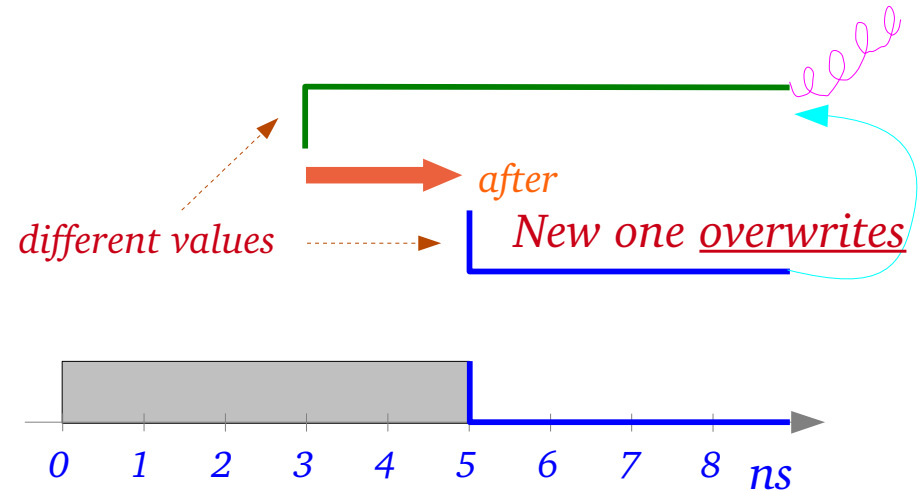
Inertial Delay (1)

Multiple Sequential Assignments

```
process (...)  
begin  
  
    X2 <= '1' after 5 ns;  
    X2 <= '0' after 3 ns;  
  
end process;
```



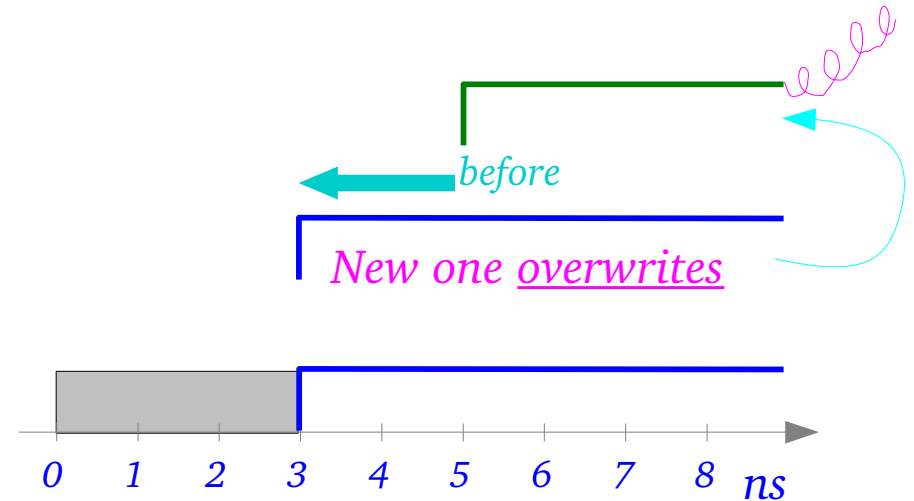
```
process (...)  
begin  
  
    X2 <= '1' after 3 ns;  
    X2 <= '0' after 5 ns;  
  
end process;
```



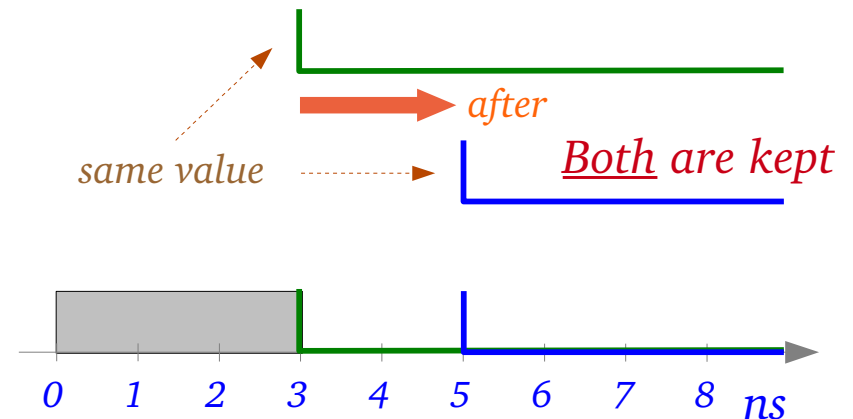
Inertial Delay (2)

Multiple Sequential Assignments

```
process (...)  
begin  
  
    X2 <= '1' after 5 ns;  
    X2 <= '1' after 3 ns;  
  
end process;
```



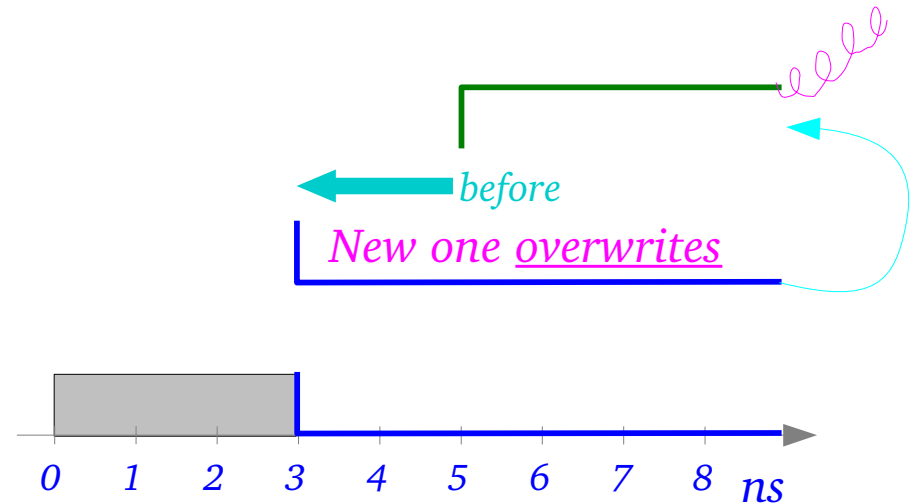
```
process (...)  
begin  
  
    X2 <= '0' after 3 ns;  
    X2 <= '0' after 5 ns;  
  
end process;
```



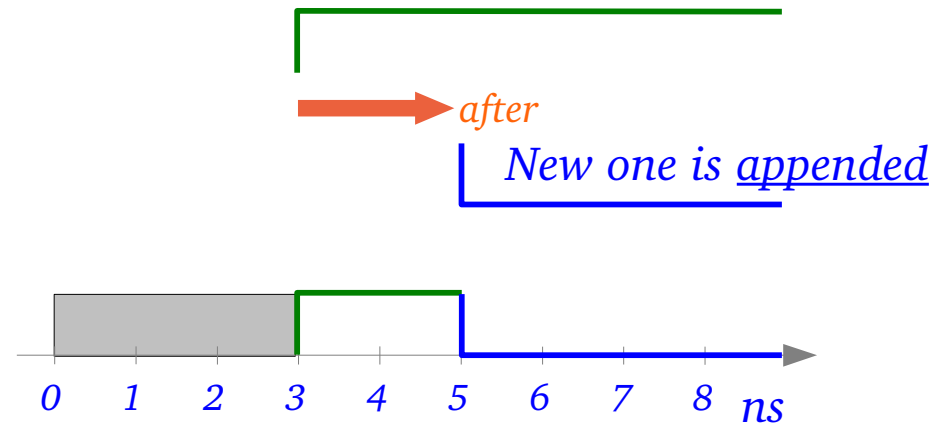
Transport Delay (1)

Multiple Sequential Assignments

```
process (...)  
begin  
  
    X2 <= transport '1' after 5 ns;  
    X2 <= transport '0' after 3 ns;  
  
end process;
```



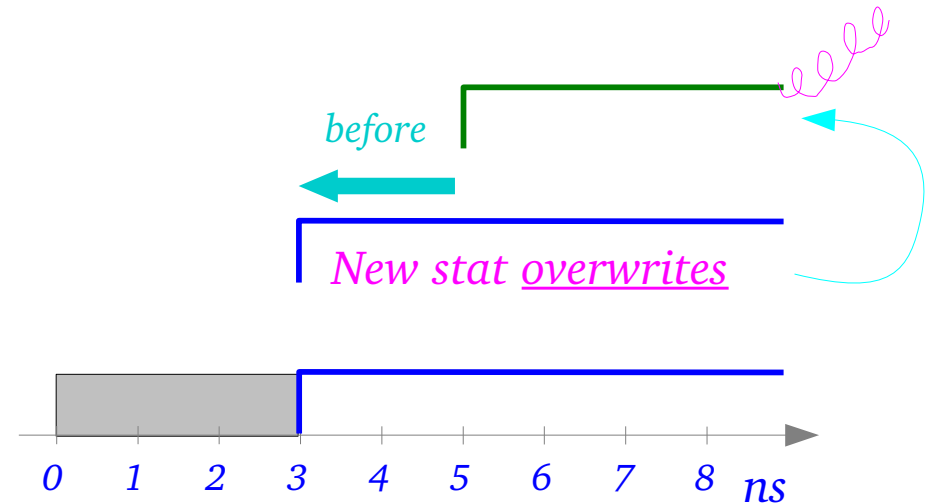
```
process (...)  
begin  
  
    X2 <= transport '1' after 3 ns;  
    X2 <= transport '0' after 5 ns;  
  
end process;
```



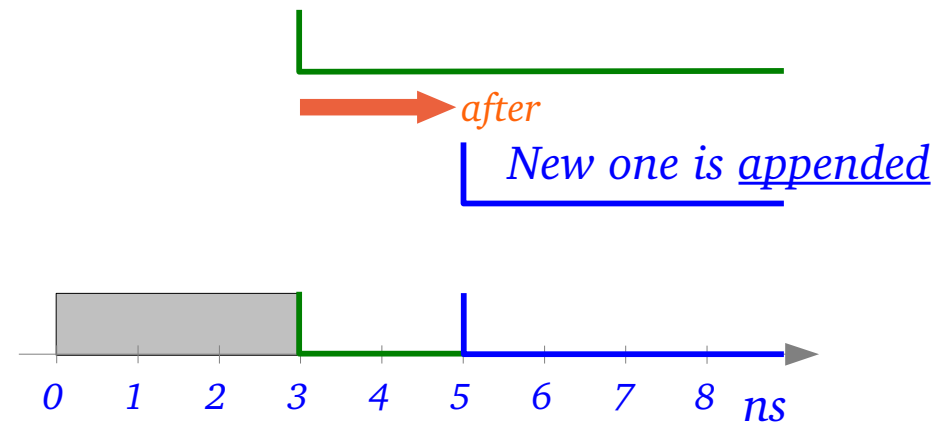
Transport Delay (2)

Multiple Sequential Assignments

```
process (...)  
begin  
  
    X2 <= transport '1' after 5 ns;  
    X2 <= transport '1' after 3 ns;  
  
end process;
```



```
process (...)  
begin  
  
    X2 <= transport '0' after 3 ns;  
    X2 <= transport '0' after 5 ns;  
  
end process;
```



Inertial Delay

Multiple Sequential Assignments - Inertial Delay

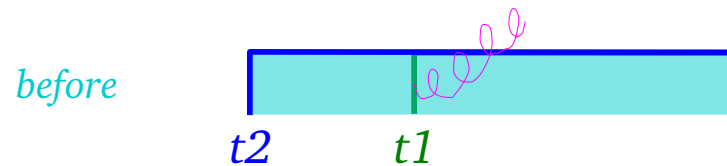
```
process (...)  
begin  
  
    X2 <= v1 after t1 ns;  
    X2 <= v2 after t2 ns;  
  
end process;
```

$t2 < t1$ $v2 = v1$ *New one overwrites*

$v2 \neq v1$ *New one overwrites*

$t1 < t2$ $v1 = v2$ *Both are kept*

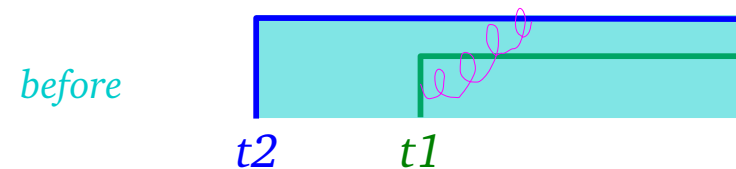
$v1 \neq v2$ *New one overwrites*



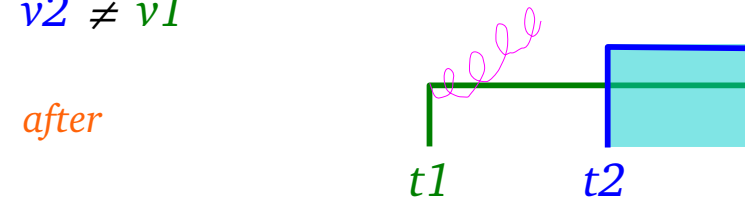
$t2 < t1$ *New one overwrites*
 $v2 = v1$



$t1 < t2$ *Both are kept*
 $v1 = v2$



$t2 < t1$ *New one overwrites*
 $v2 \neq v1$



$t1 < t2$ *New one overwrites*
 $v1 \neq v2$

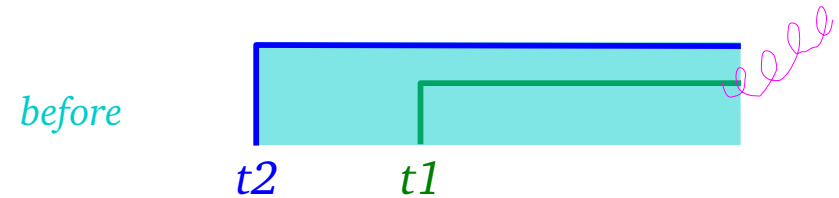
Transport Delay

Multiple Sequential Assignments - Transport Delay

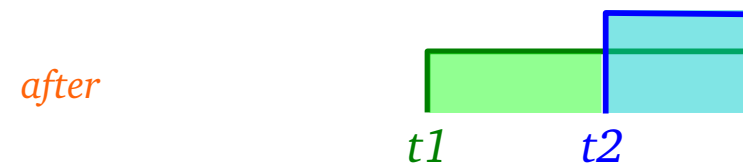
```
process (...)  
begin  
  
    X2 <= transport v1 after t1 ns;  
    X2 <= transport v2 after t2 ns;  
  
end process;
```

$t2 < t1$ *New stat overwrites*

$t1 < t2$ *New stat is appended*



$t2 < t1$ *New one overwrites*



$t1 < t2$ *New one is appended*

Inertial & Transport Delay Model (1)

Inertial Delay

The simulation time of a new event	
Before the time of an old one	
New one <u>overwrites</u>	
After the time of an old one	
For the same value	Both are kept
For different values	New one overwrites

$t2 < t1$	$v2 = v1$	New one overwrites
	$v2 \neq v1$	New one overwrites
$t1 < t2$	$v1 = v2$	Both are kept
	$v1 \neq v2$	New one overwrites

Transport Delay

The simulation time of a new event	
Before the time of an old one	
New one <u>overwrites</u>	
After the time of an old one	
New stat is <u>appended</u>	

$t2 < t1$	New stat <u>overwrites</u>
$t1 < t2$	New stat is <u>appended</u>

Inertial & Transport Delay Model (2)

Inertial Delay

The simulation time of a new event

Before the time of an old one

New one overwrites

After the time of an old one

For the **same** value

Both are kept

For **different** values

New one overwrites

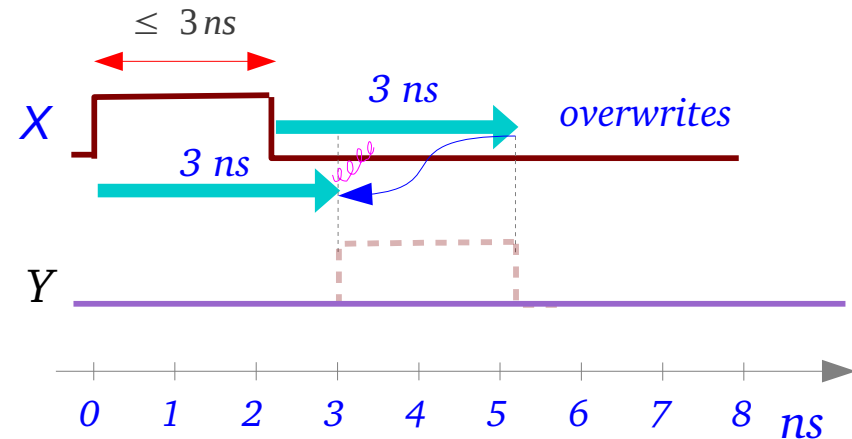
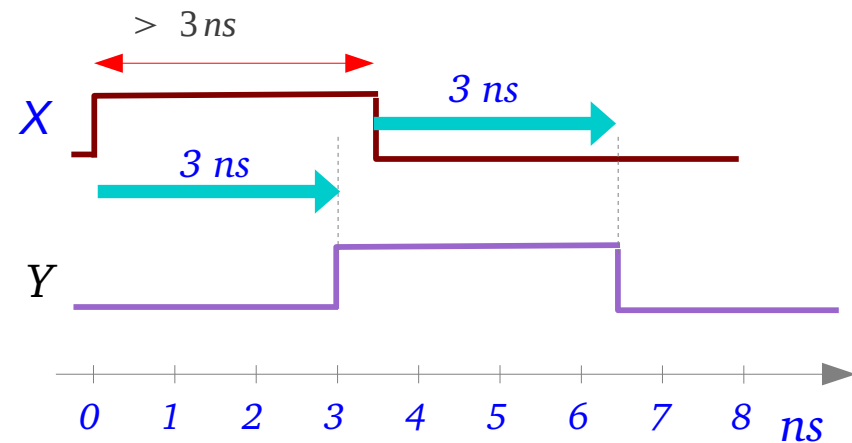
$t2 < t1$ $v2 = v1$ New one overwrites

$v2 \neq v1$ New one overwrites

$t1 < t2$ $v1 = v2$ Both are kept

$v1 \neq v2$ New one overwrites

$Y \leq X$ after 3 ns;



Inertial & Transport Delay Model (3)

Transport Delay

The simulation time of a new event

Before the time of an old one

New one overwrites

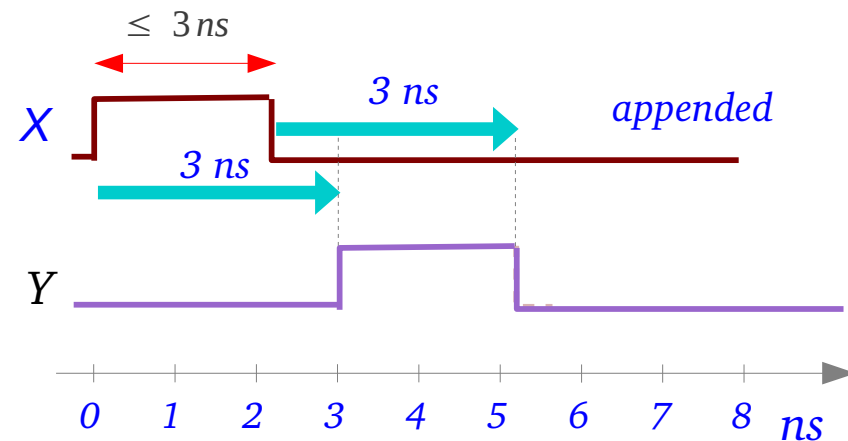
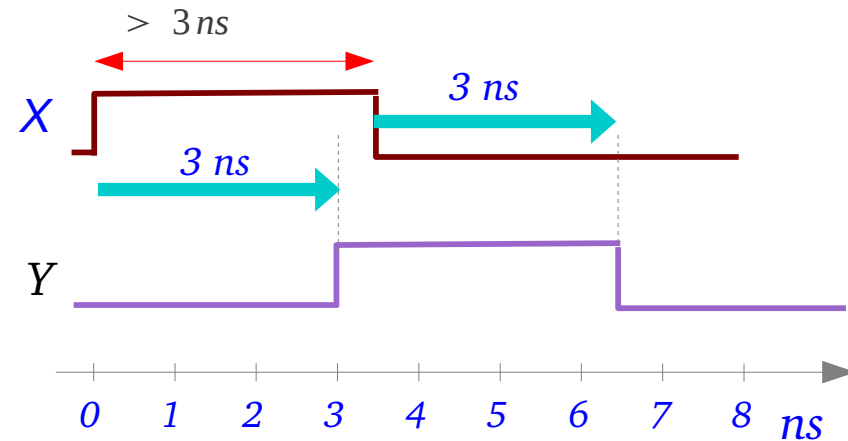
After the time of an old one

New stat is appended

$t_2 < t_1$ New stat overwrites

$t_1 < t_2$ New stat is appended

```
Y <= transport X after 3 ns;
```



Multiple Concurrent Assignments

```
architecture arch of entity ent is
```

```
    ...
```

```
begin
```

```
    X1 <= A or B ;
```

```
    X1 <= C or D ;
```

```
    process (A, B, C, D, E, F)
```

```
        variable Z2 : bit;
```

```
    begin
```

```
        Y2 <= A or B ;
```

```
        Y2 <= C or D ;
```

```
        Z2 := A or B ;
```

```
        Z2 := C or D ;
```

```
    end process;
```

```
end
```

Multiple Concurrent Assignments

Multiple Concurrent Assignment is legal only when a resolution function is defined.

(wire-and, wire-or)

Multiple Sequential Assignments

- Overwrite
- Append
- Keep

Multiple Variable Assignments

Variable Z2 has the result of the latest assignments (The new assignment overwrites the old one)

Resolution Function

architecture *arch* of entity *ent* is

```
FUNCTION w_and (drivers : bit_vector) RETURN bit is  
BEGIN
```

...

```
END w_and;
```

```
SIGNAL X1 : w_and bit;
```

...

begin

```
X1 <= A or B ;
```

```
X1 <= C or D ;
```

```
process (A, B, C, D, E, F)
```

```
begin
```

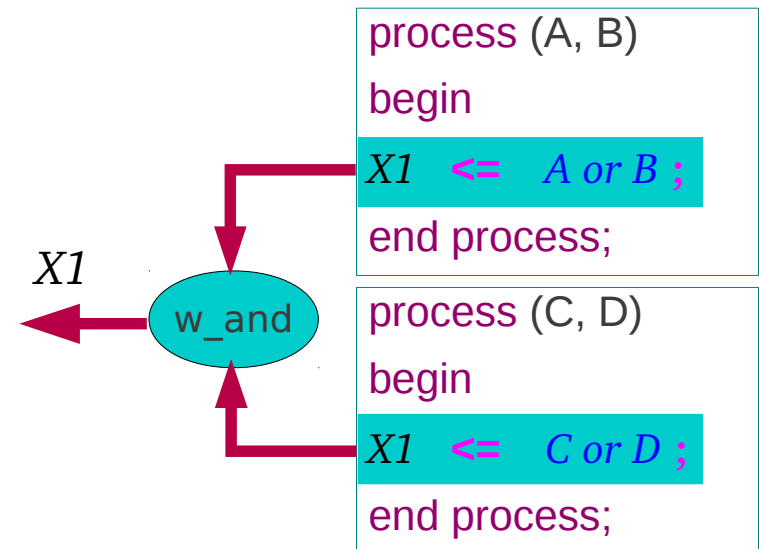
...

```
end process;
```

```
end
```

Multiple Concurrent Assignment is legal only when a resolution function is defined.


(wire-and, wire-or)



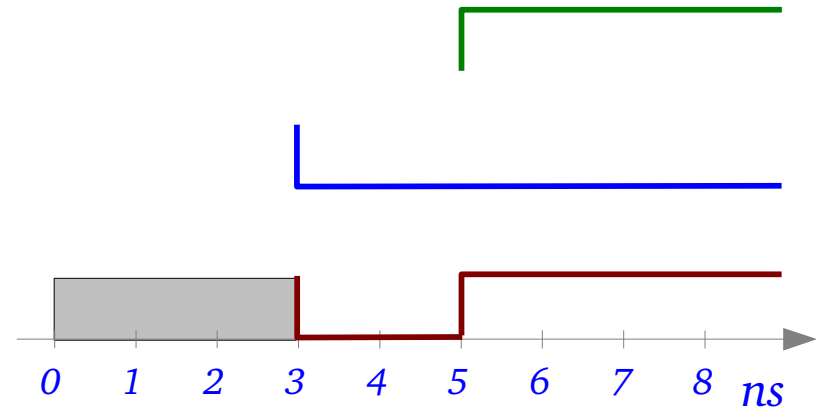
```
X1 <= w_and (A or B, C or D) ;
```


Inertial Delay

Multiple Concurrent Assignments

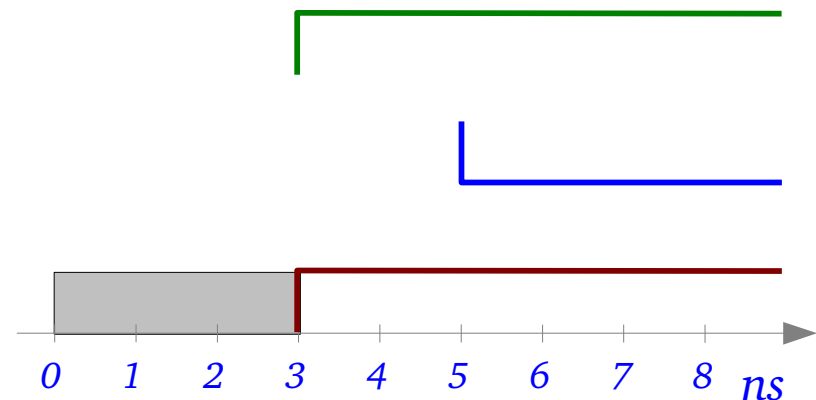
 X2 <= '1' after 5 ns; Wire-or resolution function
X2 <= '0' after 3 ns; resolution function

```
process (...)  
begin  
    ...  
end process;
```



 X2 <= '1' after 3 ns; Wire-or resolution function
X2 <= '0' after 5 ns; resolution function

```
process (...)  
begin  
    ...  
end process;
```

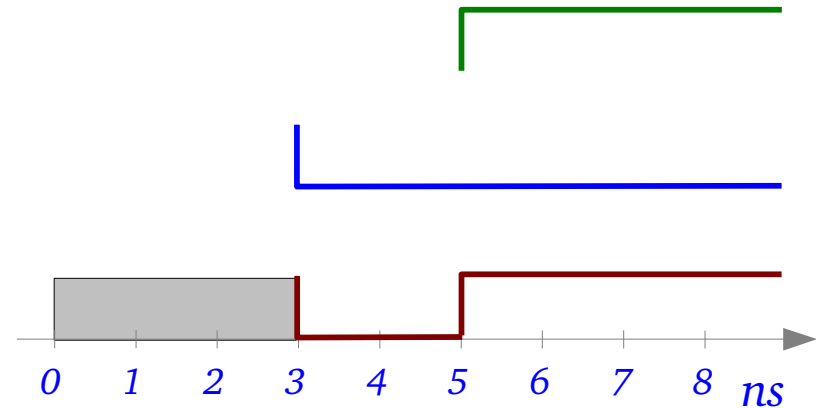


Transport Delay

Multiple Concurrent Assignments

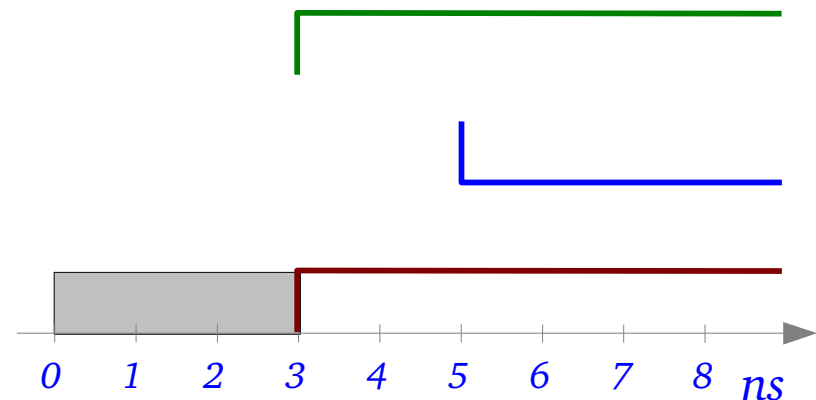
```
X2 <= transport '1' after 5 ns;  
X2 <= transport '0' after 3 ns;  
  
process (...)  
begin  
    ...  
end process;
```

Wire-or resolution function




```
X2 <= transport '1' after 3 ns;  
X2 <= transport '0' after 5 ns;  
  
process (...)  
begin  
    ...  
end process;
```

Wire-or resolution function



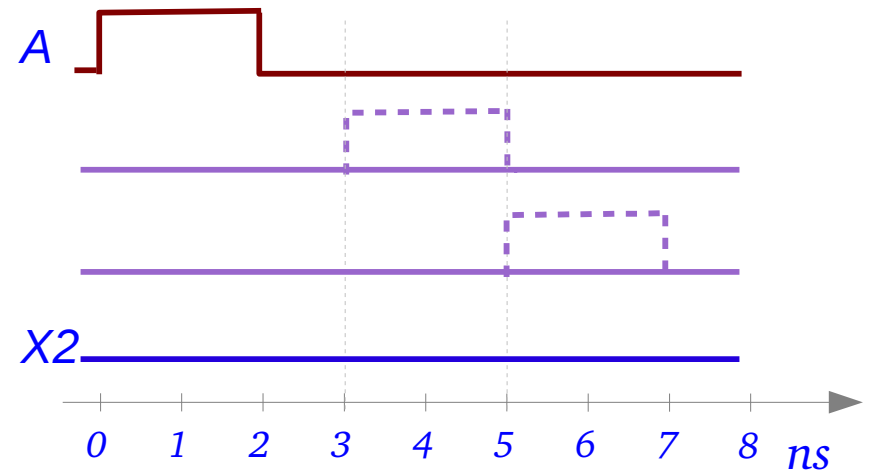
Inertial Delay


Multiple Concurrent Assignments

 `X2 <= A after 5 ns;` *Wire-or resolution function*

`X2 <= A after 3 ns;` *resolution function*

```
process (...)  
begin  
    ...  
end process;
```




 `X2 <= A after 3 ns;` *Wire-or resolution function*

`X2 <= A after 5 ns;` *resolution function*

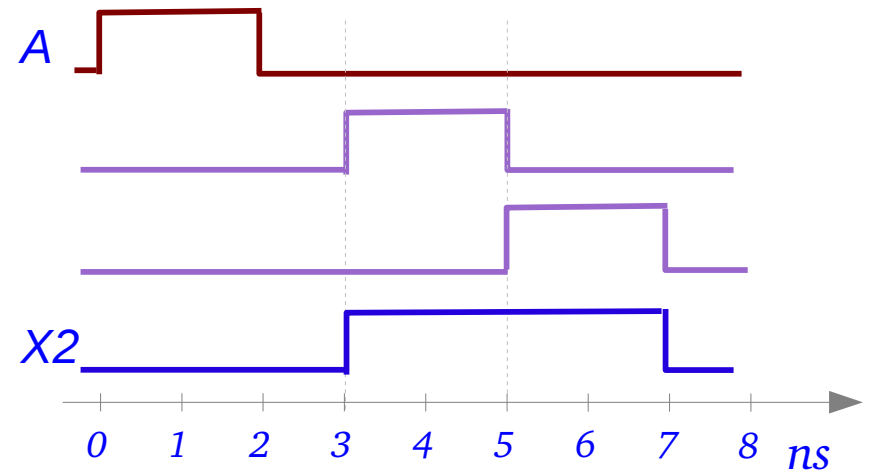
```
process (...)  
begin  
    ...  
end process;
```



Transport Delay

Multiple Concurrent Assignments

 `X2 <= A after 5 ns;` *Wire-or resolution function*
`X2 <= B after 3 ns;` *resolution function*

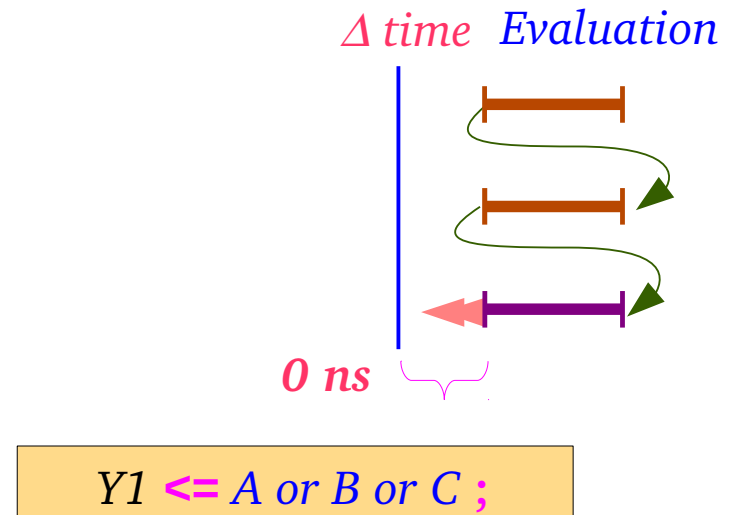
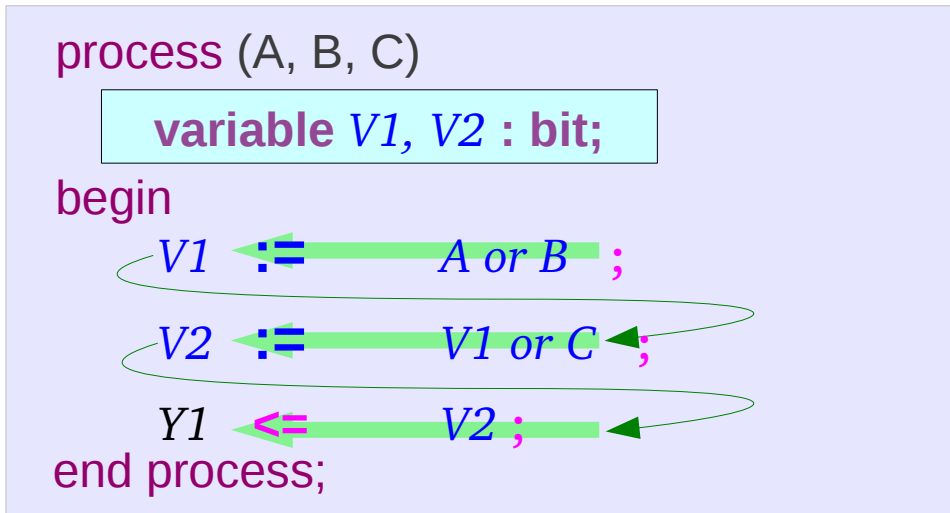
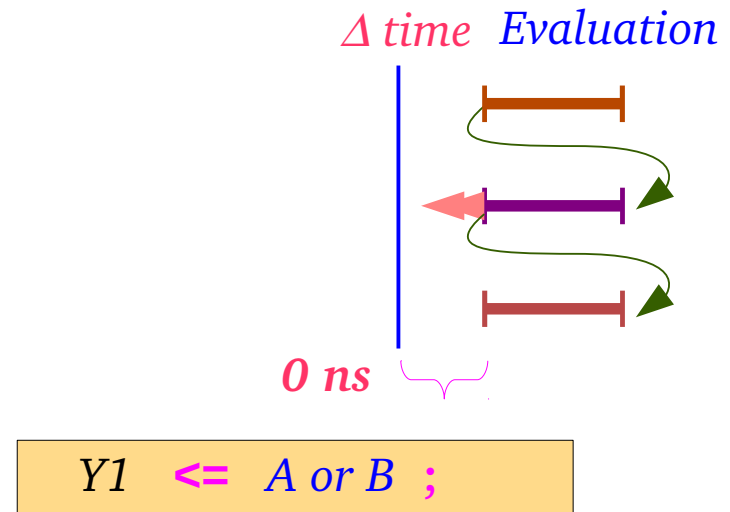
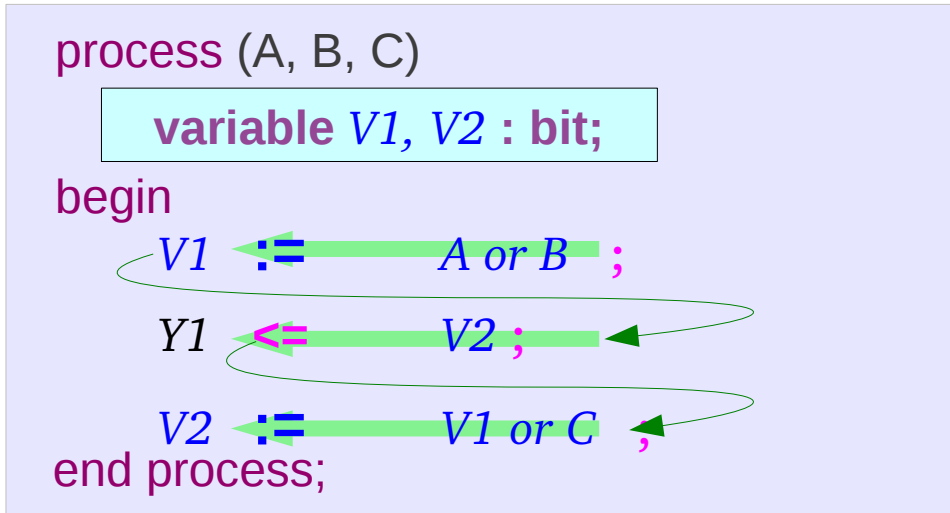
```
process (...)  
begin  
    ...  
end process;
```



 `X2 <= A after 3 ns;` *Wire-or resolution function*
`X2 <= B after 5 ns;` *resolution function*

```
process (...)  
begin  
    ...  
end process;
```

Signals & Variable Assignment Example 1



References

- [1] <http://en.wikipedia.org/>
- [2] J. V. Spiegel, VHDL Tutorial,
http://www.seas.upenn.edu/~ese171/vhdl/vhdl_primer.html
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