

Discrete Event Modelling

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2008/11/2



Models of computation considered in this course

Communication/ local computations	Shared memory	Message passing	
		Synchronous	Asynchronous
Communicating finite state machines	StateCharts		SDL
Data flow model \subset	Not useful	Simulink	Kahn process networks, SDF
Computational graphs		Sequence dia- gram, Petri nets	
Von Neumann model	C, C++, Java	C, C++, Java with libraries CSP, ADA	
Discrete event (DE) model	VHDL, ...	Only experimental systems, e.g. distributed DE in Ptolemy	

VHDL

VHDL as a prominent example of discrete event modeling:



VHDL

HDL = hardware description language

Textual HDLs replaced graphical HDLs in the 1980'ies (better description of complex behavior).

In this course:

VHDL = VHSIC hardware description language

VHSIC = very high speed integrated circuit

1980: Def. started by US Dept. of Defense (DoD) in 1980

1984: first version of the language defined, based on ADA (which in turn is based on PASCAL)

1987: revised version became IEEE standard 1076

1992: revised IEEE standard

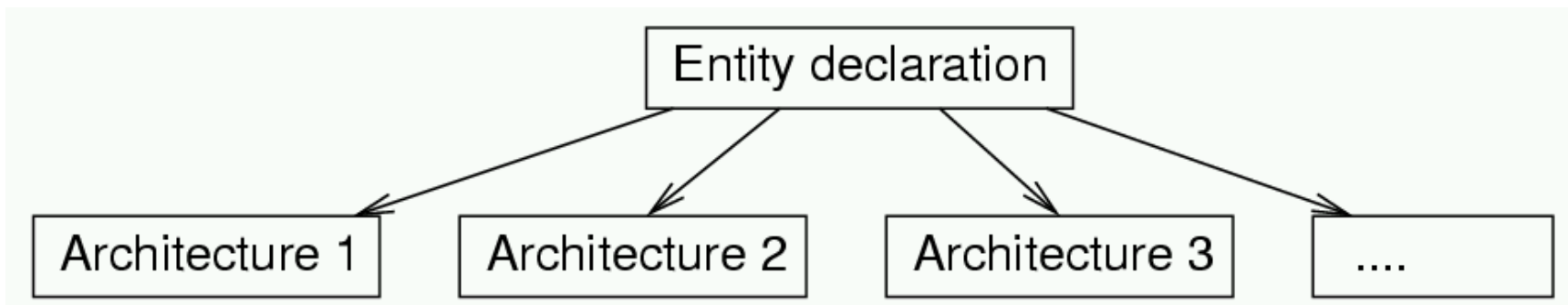
1999: VHDL-AMS: includes analog modeling

2006: Major extensions

Entities and architectures

Each design unit is called an **entity**.

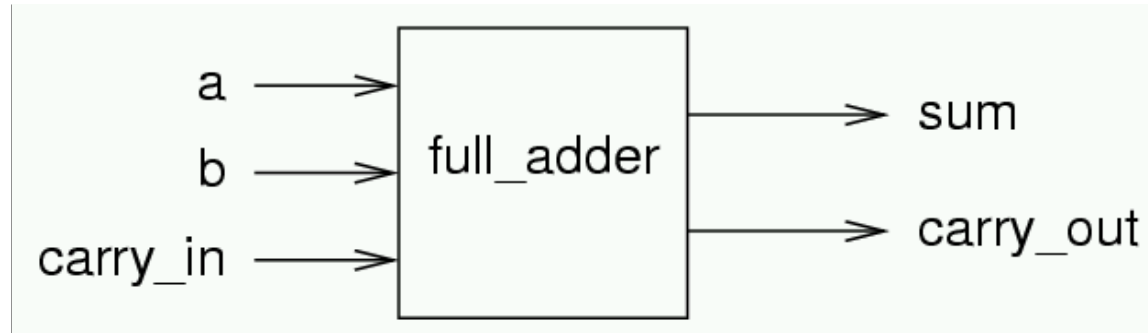
Entities are comprised of **entity declarations** and one or several **architectures**.



Each architecture includes a model of the entity. By default, the most recently analyzed architecture is used. The use of another architecture can be requested in a **configuration**.

The full adder as an example

- Entity declaration -



Entity declaration:

entity full_adder **is**

port(a, b, carry_in: **in** Bit; -- input ports

sum, carry_out: **out** Bit); --output ports

end full_adder;

The full adder as an example

- Architectures -

Architecture = Architecture header + architectural bodies

architecture behavior of full_adder is

begin

sum <= (a xor b) xor carry_in **after** 10 Ns;

carry_out <= (a and b) or (a and carry_in) or
(b and carry_in) **after** 10 Ns;

end behavior;

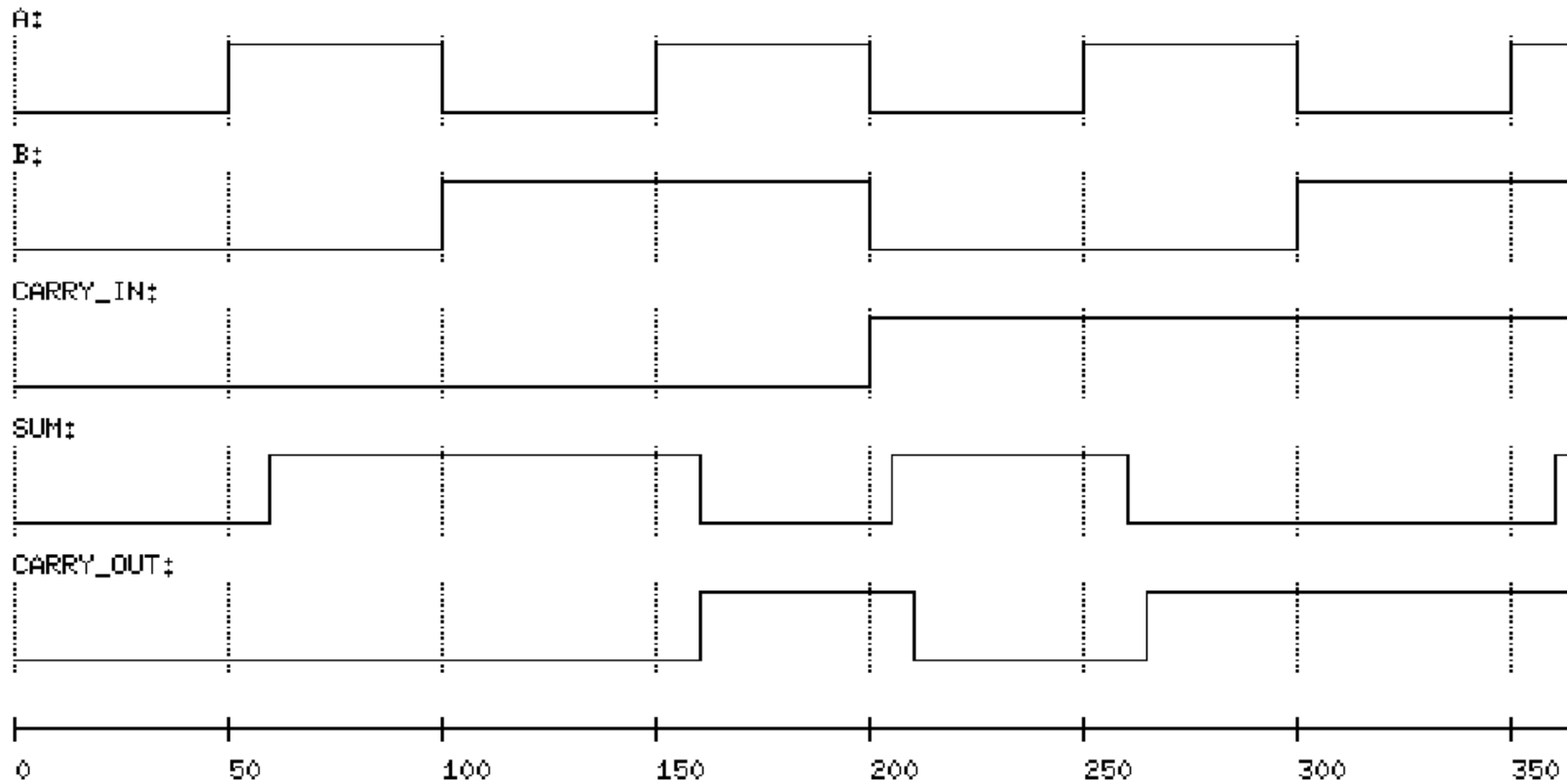
Architectural bodies can be

- **behavioral bodies** or - **structural bodies**.

Bodies not referring to hardware components are called behavioral bodies.

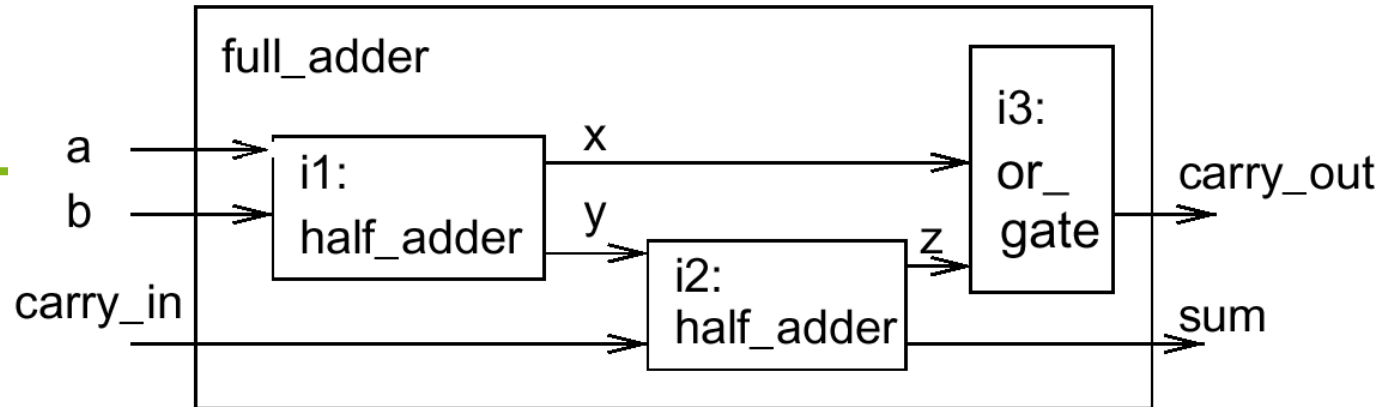
The full adder as an example

- Simulation results -



Behavioral description different from the one shown (includes 5ns delays).

Structural bodies



architecture structure of full_adder is

component half_adder

```
port (in1,in2:in Bit; carry:out Bit; sum:out Bit);
```

```
end component;
```

component or_gate

```
port (in1, in2:in Bit; o:out Bit);
```

```
end component;
```

```
signal x, y, z: Bit;      -- local signals
```

```
begin                    -- port map section
```

```
  i1: half_adder port map (a, b, x, y);
```

```
  i2: half_adder port map (y, carry_in, z, sum);
```

```
  i3: or_gate port map (x, z, carry_out);
```

```
end structure;
```

VHDL processes

Processes model parallelism in hardware

General syntax:

label: --optional

process

declarations --optional

begin

statements --optional

end process

$a \leq b$ **after** 10 ns is equivalent to

process

begin

$a \leq b$ **after** 10 ns

end

Assignments

2 kinds of assignments:

- Variable assignments

Syntax: *variable := expression;*

- Signal assignments

Syntax:

signal <= expression;

*signal <= expression **after** delay;*

*signal <= **transport** expression **after** delay;*

*signal <= **reject** time **inertial** expression **after** delay;*

Possibly several assignments to 1 signal within 1 process.

For each signal there is one **driver** per process.

Driver stores information about the **future** of signal,
the so-called **projected waveform**.

Adding entries in the projected waveform

- Each executed signal assignment will result in **adding** entries in the projected waveform, as indicated by the delay time, e.g.:

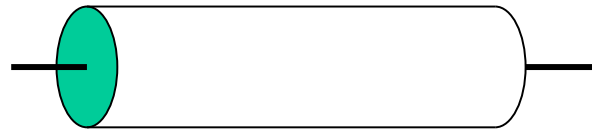
output <= '0' **after** 5 ns, '1' **after** 10 ns;

- Executed signal assignments may also result in **deleting** entries in the projected waveform, according to the following rules:

1. Transport delay

signal <= **transport** expression **after** delay;

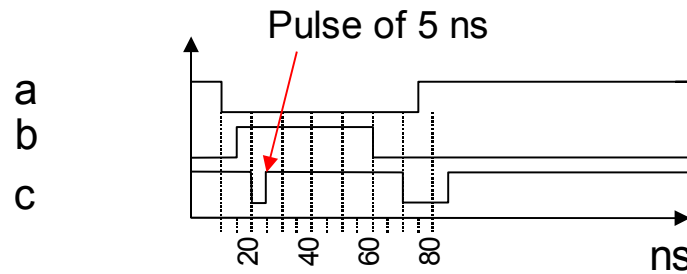
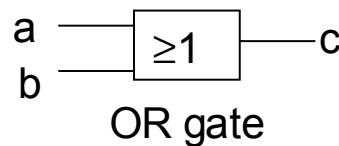
This corresponds to models for *simple wires*



Pulses will be propagated, no matter how short they are.

Example:

c <= **transport** *a* or *b* **after** 10 ns;



1. Transport delay (2)

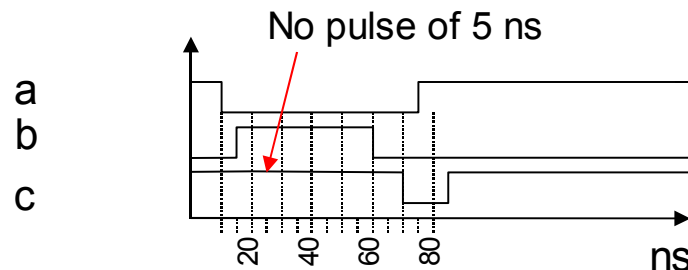
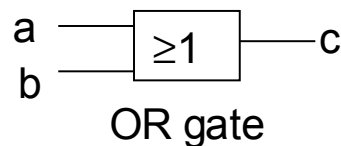
“All old transactions that are projected to occur at or after the time at which the earliest of the new transactions is projected to occur are deleted from the projected output waveform”
[VHDL LRM, chap. 8.4]

2. Inertial delay

- By default, inertial delay is assumed.
- Suppression of all “spikes” shorter than the delay, resp. shorter than the indicated suppression threshold.
- Inertial delay models the behavior of gates.

Example:

$c \leq a \text{ or } b$ **after** 10 ns;



- Tricky rules for removing events from projected waveform (☞)

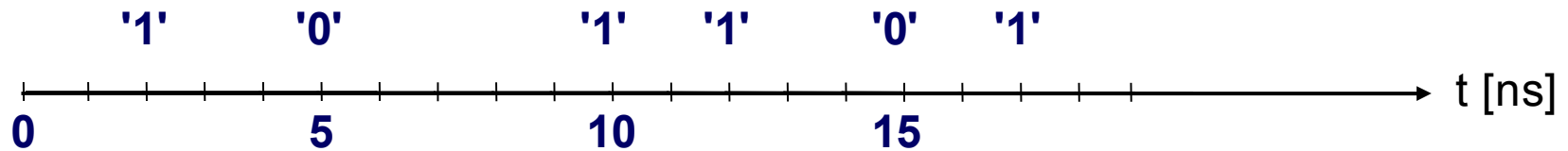
2. Inertial delay (2)

- *“All old transactions that are projected to occur at or after the time at which the earliest of the new transactions is projected to occur are deleted from the projected output waveform”*
- The new transactions are then appended
- *“All of the new transactions are marked*
- *An old transaction is marked if it immediately precedes a marked transaction and its value component is the same as that of the marked transaction;*
- *The transactions that determines the current value of the driver is marked;*
- *All unmarked transactions ... are deleted from the projected output waveform”*

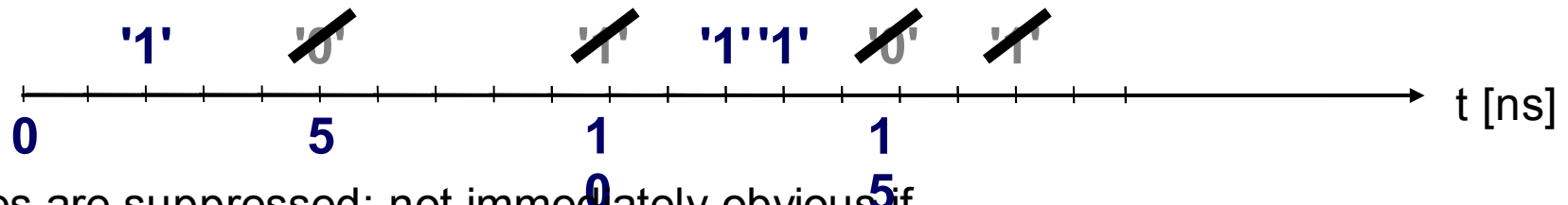
[VHDL LRM, chap. 8.4]

2. Inertial delay (3)

Assume that we are executing a signal assignment
`output <= '1' after 11 ns at time t=2 ns` and the projected waveform is:



- Transactions to occur at or after 13 ns are deleted from the output waveform
- The new transactions are then appended
- All of the new transactions are marked
- Transactions immediately preceding a marked transaction and their value component is the same as that of the marked transaction;
- The transactions that determines the current value of the driver is marked;
- All unmarked transactions ... are deleted from the projected output waveform



Spikes are suppressed; not immediately obvious if
 a) this suppresses all spikes and b) removes all unnecessary transactions.

Wait-statements

Four possible kinds of **wait**-statements:

- **wait on** *signal list*;
 - wait until signal changes;
 - Example: **wait on** a;
- **wait until** *condition*;
 - wait until condition is met;
 - Example: **wait until** c='1';
- **wait for** *duration*;
 - wait for specified amount of time;
 - Example: **wait for** 10 ns;
- **wait**;
 - suspend indefinitely

Sensitivity lists

Sensitivity lists are a shorthand for a single **wait on**-statement at the end of the process body:

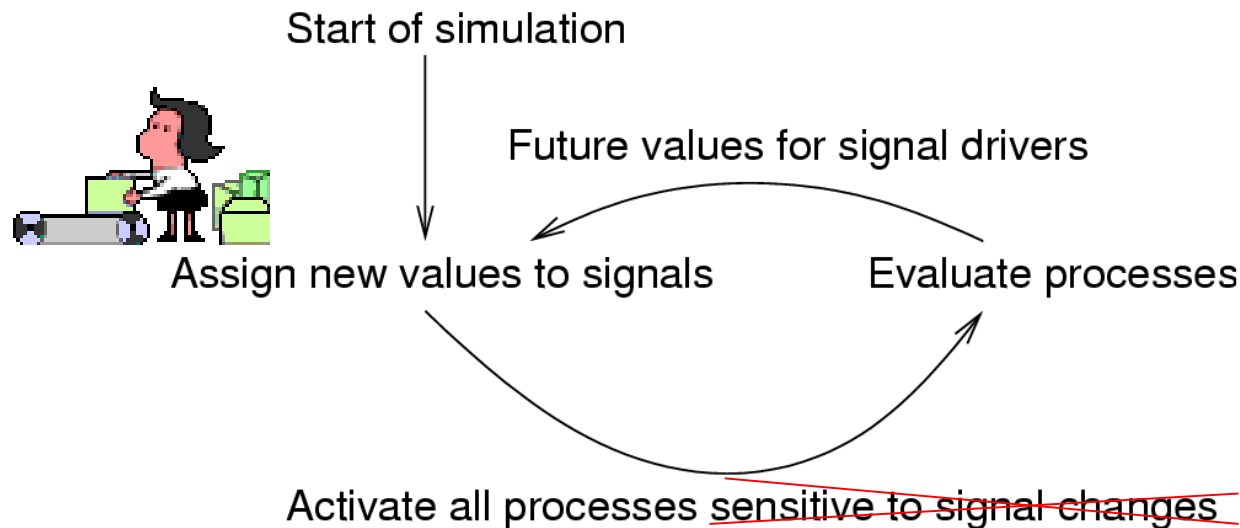
```
process (x, y)
begin
  prod <= x and y ;
end process;
```

is equivalent to

```
process
begin
  prod <= x and y ;
  wait on x,y;
end process;
```

VHDL semantics: global control

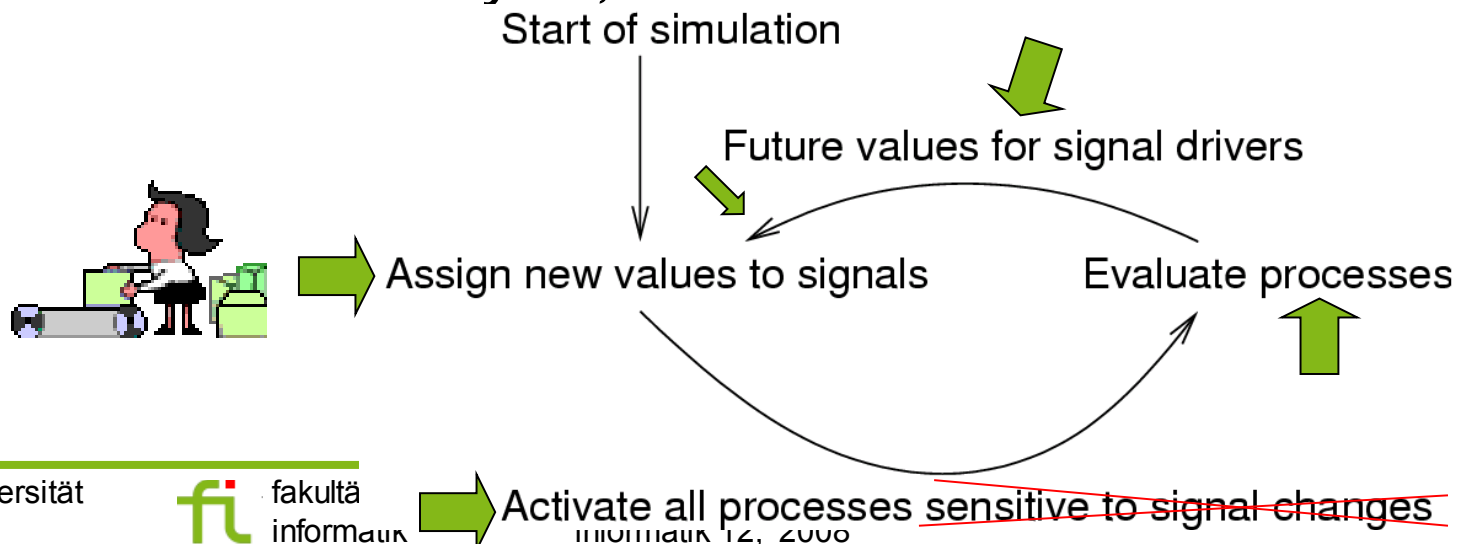
According to the original standards document:
The execution of a model consists of an initialization phase followed by the repetitive execution of process statements in the description of that model.
Initialization phase executes each process once.



VHDL semantics: initialization

At the beginning of initialization, the current time, T_c is 0 ns.

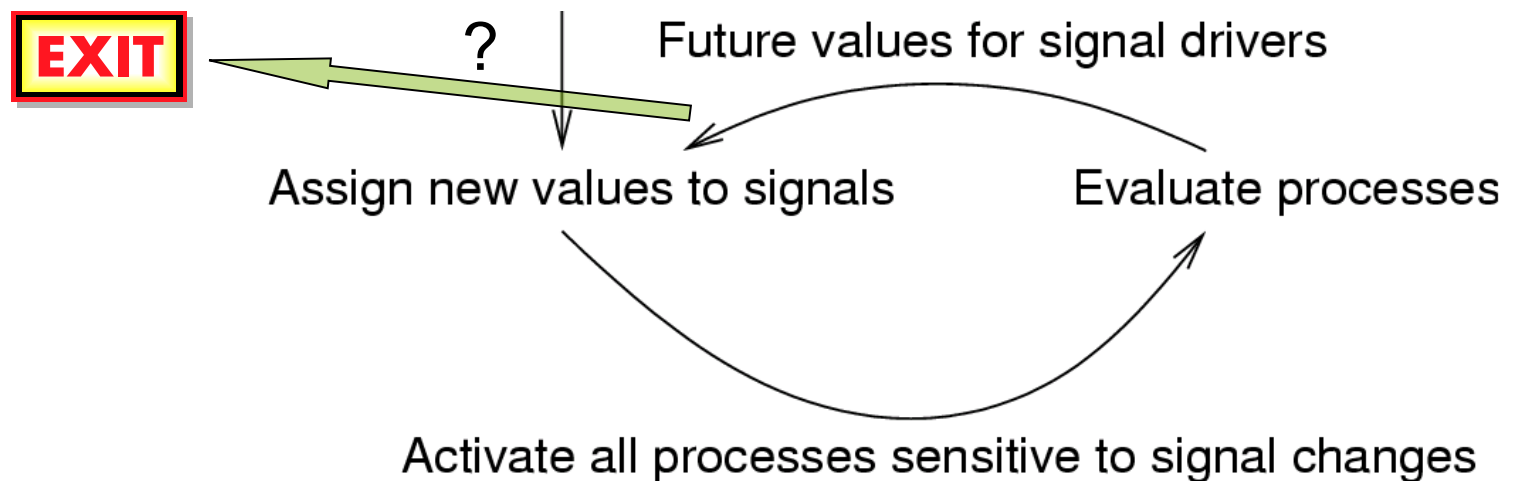
- ➡ *The driving value and the effective value of each explicitly declared signal are computed, and the current value of the signal is set to the effective value. ...*
- ➡ *Each ... process ... is executed until it suspends.*
- ➡ *The time of the next simulation cycle (... in this case ... the 1st cycle), T_n is calculated according to the rules of step f of the simulation cycle, below.*



VHDL semantics: The simulation cycle (1)

Each simulation cycle starts with setting T_c to T_n . T_n was either computed during the initialization or during the last execution of the simulation cycle. Simulation terminates when the current time reaches its maximum, TIME'HIGH. According to the standard, the simulation cycle is as follows:

- a) The current time, T_c is set to T_n . Stop if $T_n = \text{TIME'HIGH}$ and not \exists active drivers or process resumptions at T_n .




VHDL semantics: The simulation cycle (2)

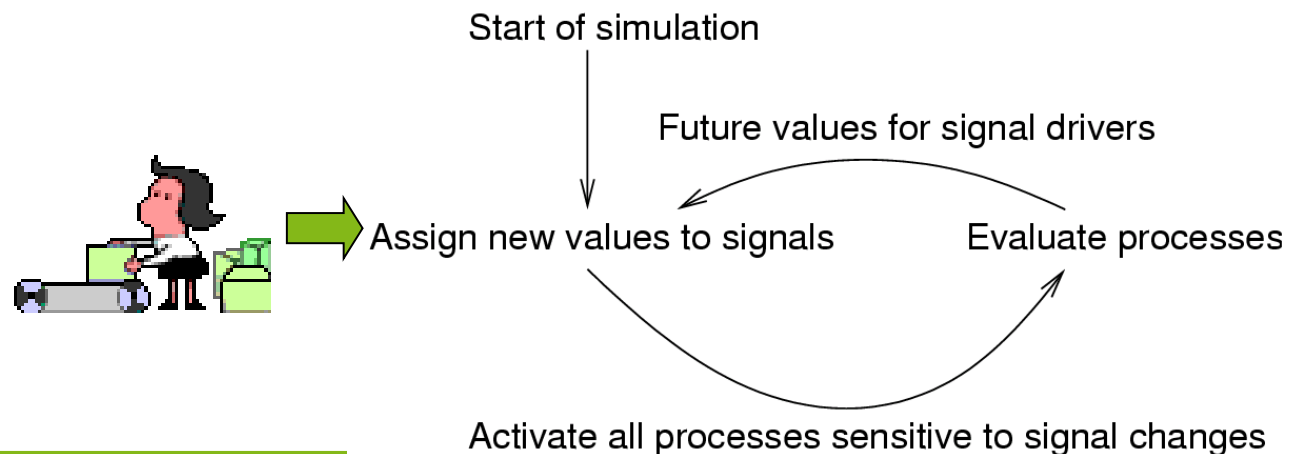
- a) **Each active explicit signal in the model is updated. (Events may occur as a result.)**

Previously computed entries in the queue are now assigned if their time corresponds to the current time T_c .

New values of signals are not assigned before the next simulation cycle, at the earliest.

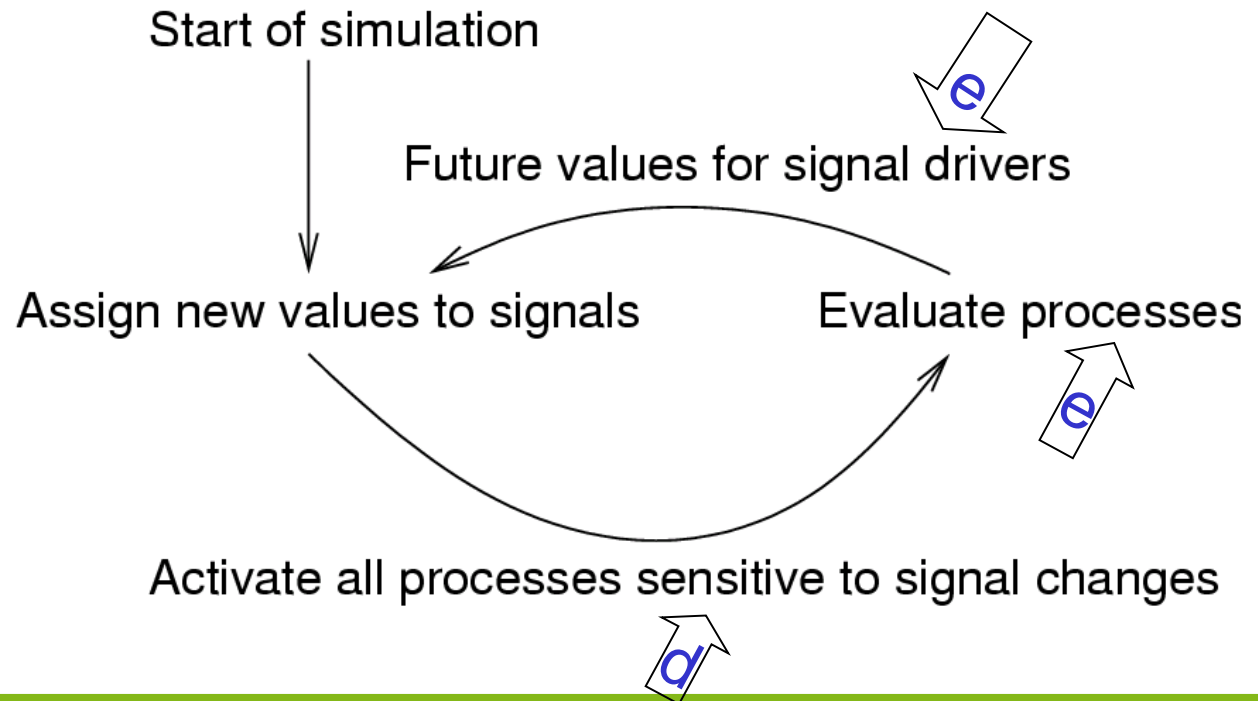
Signal value changes result in events  enable the execution of processes that are sensitive to that signal.

- b) ..

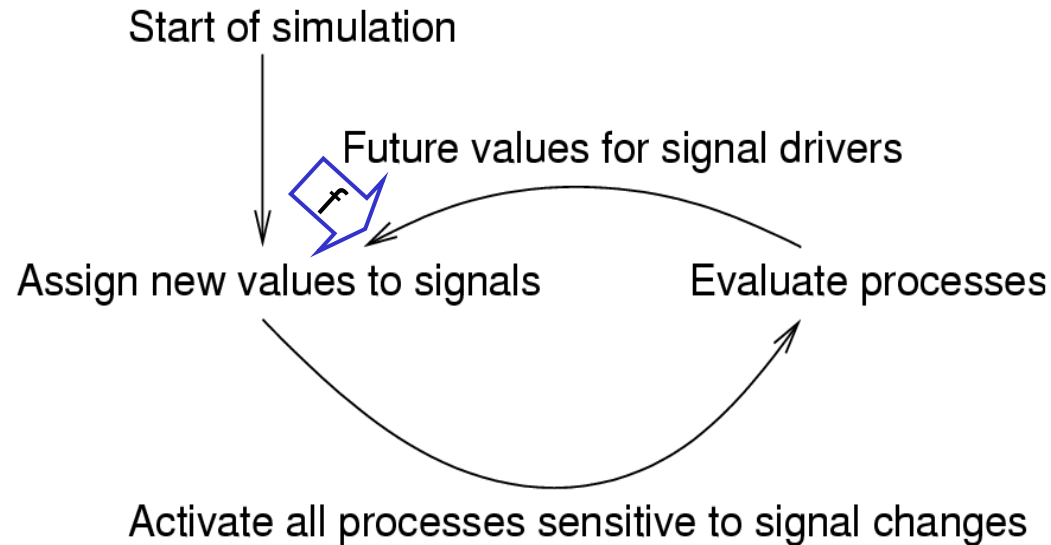


VHDL semantics: The simulation cycle (3)

- α) \forall P sensitive to s: if event on s in current cycle: P resumes.
 - b) Each ... process that has resumed in the current simulation cycle is executed until it suspends*.
- *Generates future values for signal drivers.



VHDL semantics: The simulation cycle (4)

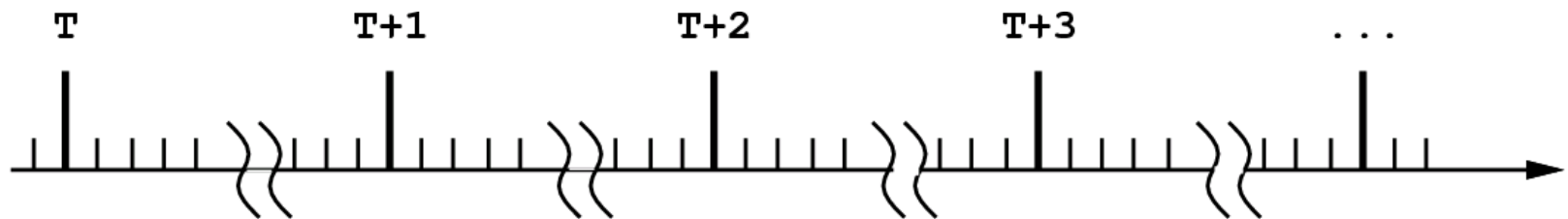


- a) Time T_n of the next simulation cycle = earliest of
1. TIME'HIGH (end of simulation time).
 2. The next time at which a driver becomes active
 3. The next time at which a process resumes (determined by **wait for** statements).

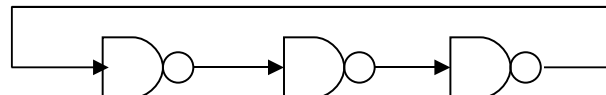
Next simulation cycle (if any) will be a delta cycle if $T_n = T_c$.

δ -simulation cycles

...
Next simulation cycle (if any) will be a delta cycle if $T_n = T_c$.
Delta cycles are generated for delay-less models.
There is an arbitrary number of δ cycles between any 2 physical time instants:

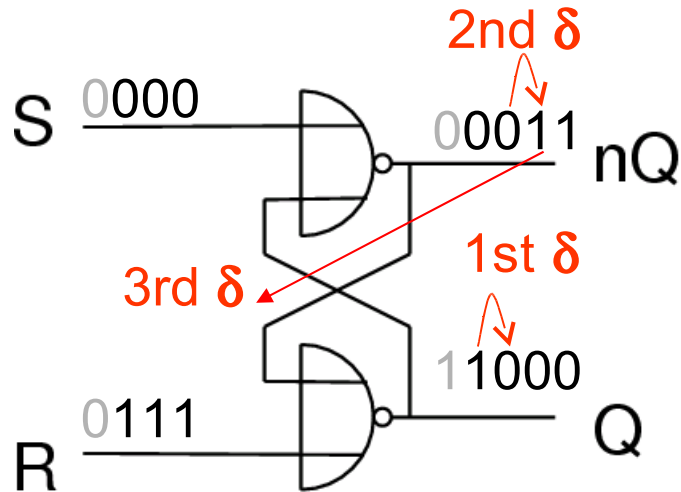


In fact, simulation of delay-less hardware loops might not terminate (don't even advance T_c).



δ -simulation cycles

Simulation of an RS-Flipflop



	$0ns$	$0ns+\delta$	$0ns+2\delta$	$0ns+3\delta$
R	1	1	1	1
S	0	0	0	0
Q	1	0	0	0
nQ	0	0	1	1

**architecture one
of RS_Flipflop is
begin**

process: (R,S,Q,nQ)

begin

$Q \leq R \text{ nor } nQ;$

$nQ \leq S \text{ nor } Q;$

end process;

end one;

**δ cycles reflect the fact that no
real gate comes with zero delay.**

**☞ should delay-less signal
assignments be allowed at all?**

δ -simulation cycles and deterministic simulation semantics

Semantics of

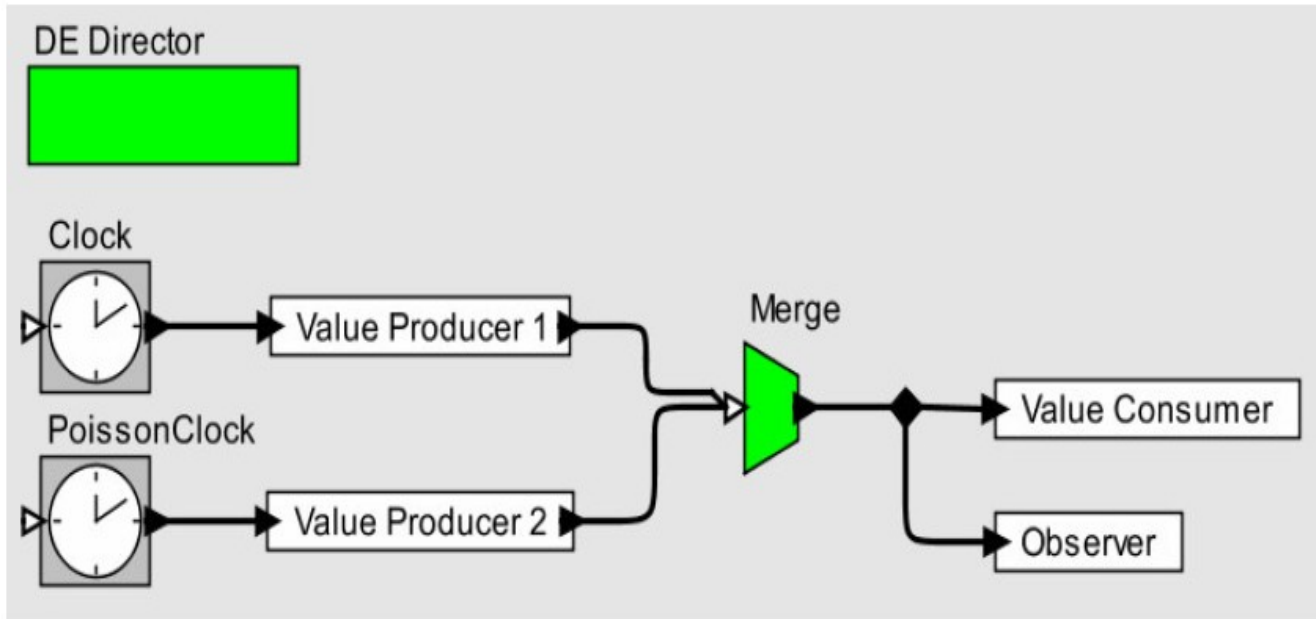
$a \leq b$;

$b \leq a$; ?

Separation into 2 simulation phases
results in deterministic semantics

( StateMate).

Observer Pattern using Discrete Events



Messages have a (semantic) time, and actors react to messages chronologically. Merge now becomes deterministic.

Multi-valued logic and standard IEEE 1164

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How many logic values for modeling ?

Two ('0' and '1') or more?

If real circuits have to be described, some abstraction of the resistance (inversely-related to the strength) is required.

☞ We introduce the distinction between:

- the **logic level** (as an abstraction of the voltage) and
- the **strength** (as an abstraction of the current drive capability) of a signal.

The two are encoded in **logic values**.

☞ CSA (connector, switch, attenuator) - theory [Hayes]

1 signal strength

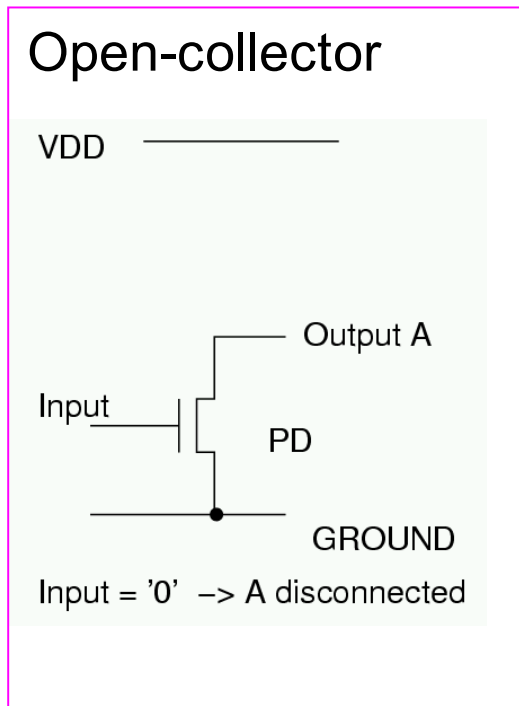
Logic values '0' and '1'.

Both of the same strength.

Encoding false and true, respectively.

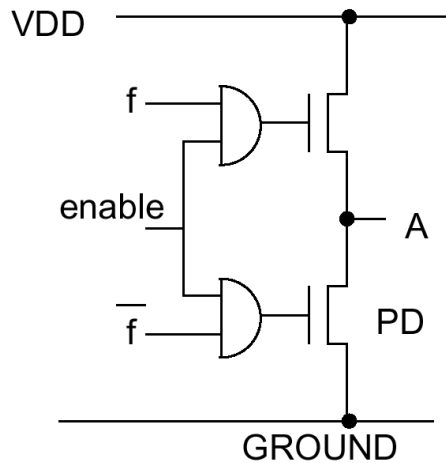
2 signal strengths

Many subcircuits can effectively disconnect themselves from the rest of the circuit (they provide „high impedance“ values to the rest of the circuit). Example: subcircuits with open collector or tri-state outputs.



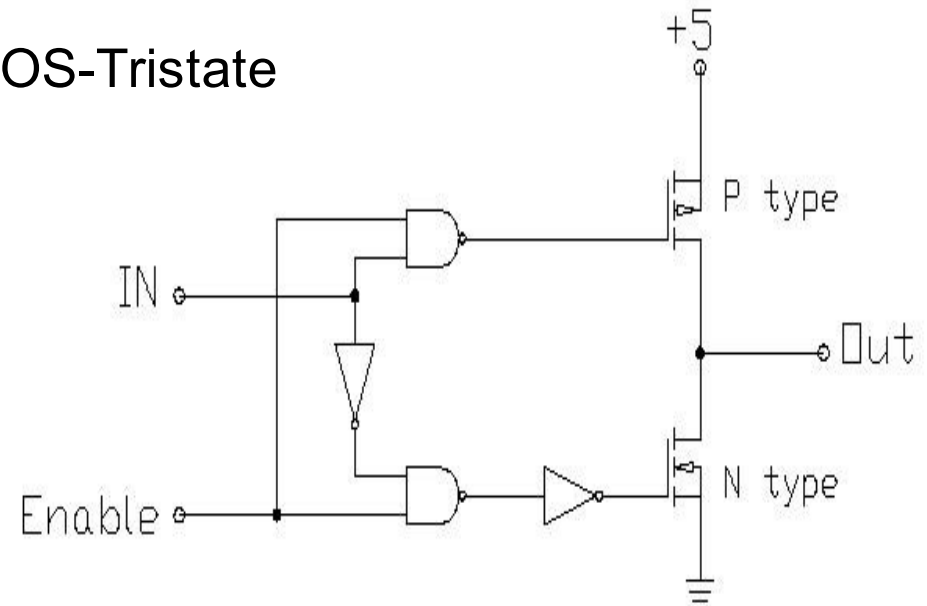
TriState circuits

nMOS-Tristate



enable = '0' -> A disconnected

CMOS-Tristate

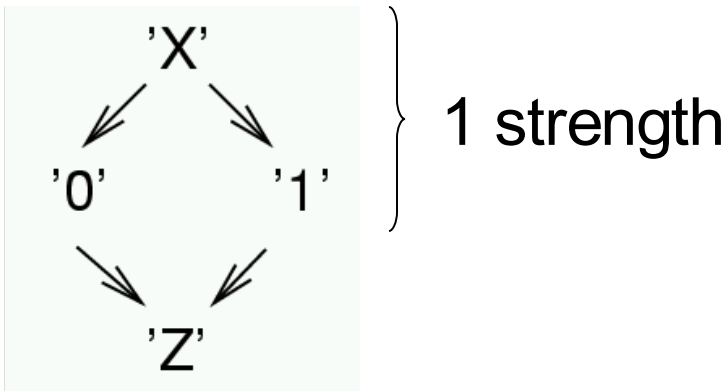


Source: <http://www-unix.oit.umass.edu/~phys532/lecture3.pdf>

☞ We introduce signal value 'Z', meaning „high impedance“

2 signal strengths (cont'ed)

We introduce an operation $\#$, which generates the effective signal value whenever two signals are connected by a wire.
 $\#('0','Z')='0'$; $\#('1','Z')='1'$; '0' and '1' are „stronger“ than 'Z'

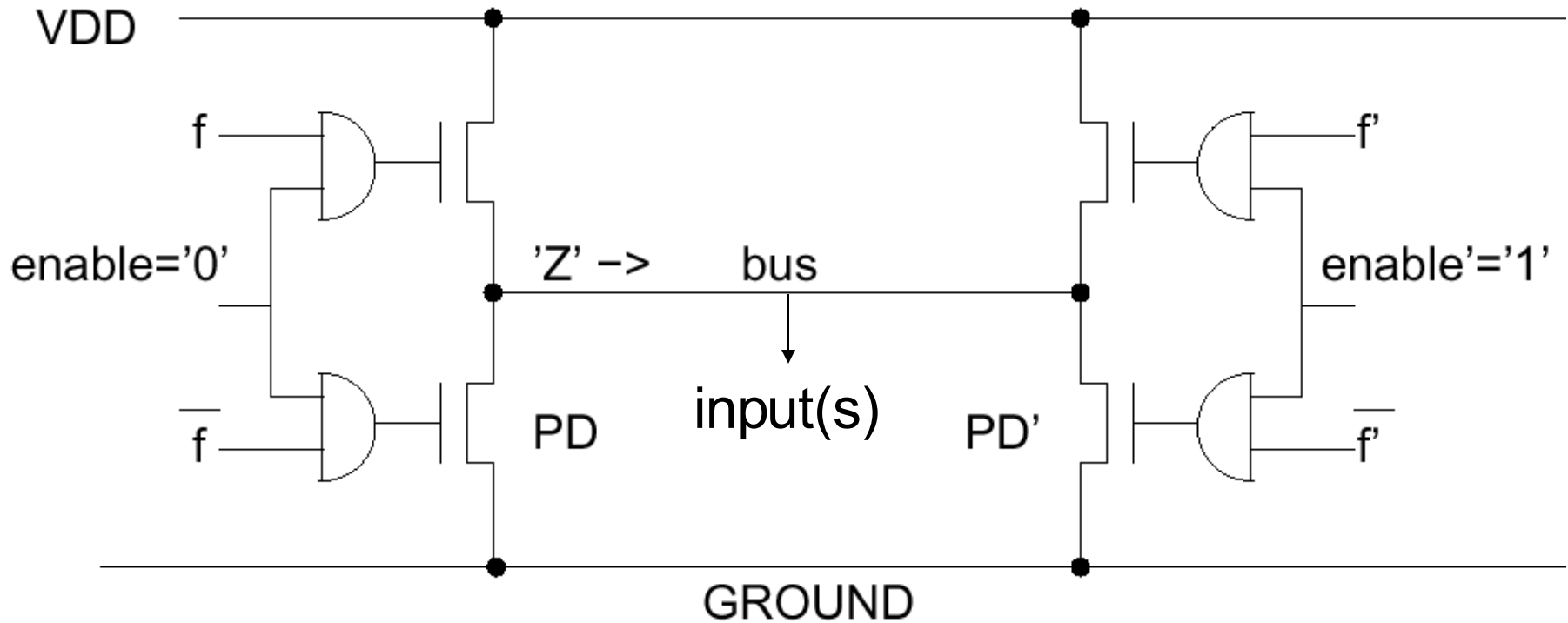


According to the partial order in the diagram, $\#$ returns the *larger of the two arguments*.

In order to define $\#('0','1')$, we introduce 'X', denoting an undefined signal level.

'X' has the same strength as '0' and '1'.

Application example

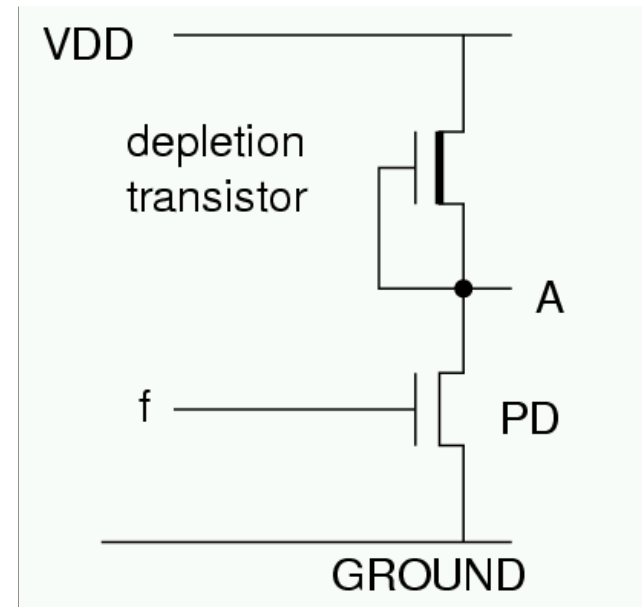


signal value on bus = $\#(\text{value from left subcircuit, value from right subcircuit})$
 $\#('Z', \text{value from right subcircuit})$
 value from right subcircuit

„as if left circuit were not there“.

3 signal strengths

Current values insufficient for describing real circuits:



Depletion transistor contributes a weak value to be considered in the #-operation for signal A

☞ Introduction of 'H', denoting a weak signal of the same level as '1'.

$\#('H', '0') = '0'$; $\#('H', 'Z') = 'H'$

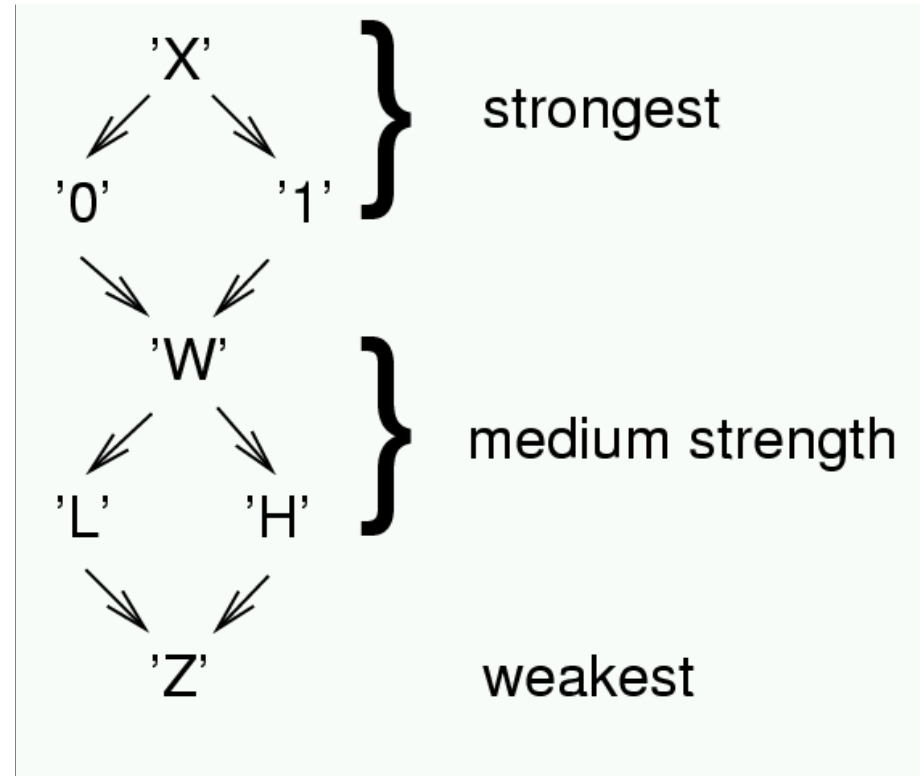
3 signal strengths

There may also be weak signals of the same level as '0'

☞ Introduction of 'L', denoting a weak signal of the same level as '0': $\#('L', '0') = '0'$; $\#('L', 'Z') = 'L'$;

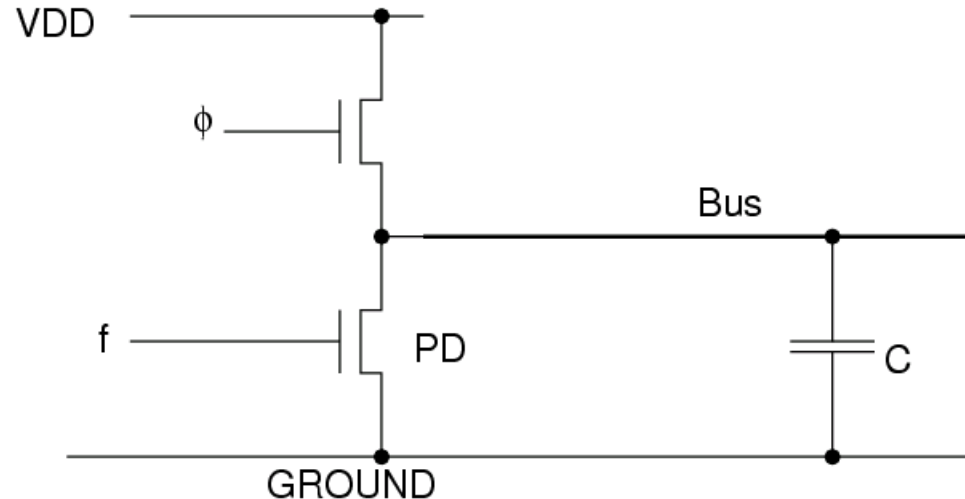
☞ Introduction of 'W', denoting a weak signal of the same level as 'X': $\#('L', 'H') = 'W'$; $\#('L', 'W') = 'W'$;

reflected by the partial order shown.



4 signal strengths (1)

Current values insufficient for describing pre-charging:



Pre-charged '1'-levels weaker than any of the values considered so far, except 'Z'.

☞ Introduction of 'h', denoting a very weak signal of the same level as '1'.

$\#('h', '0') = '0'$; $\#('h', 'Z') = 'h'$

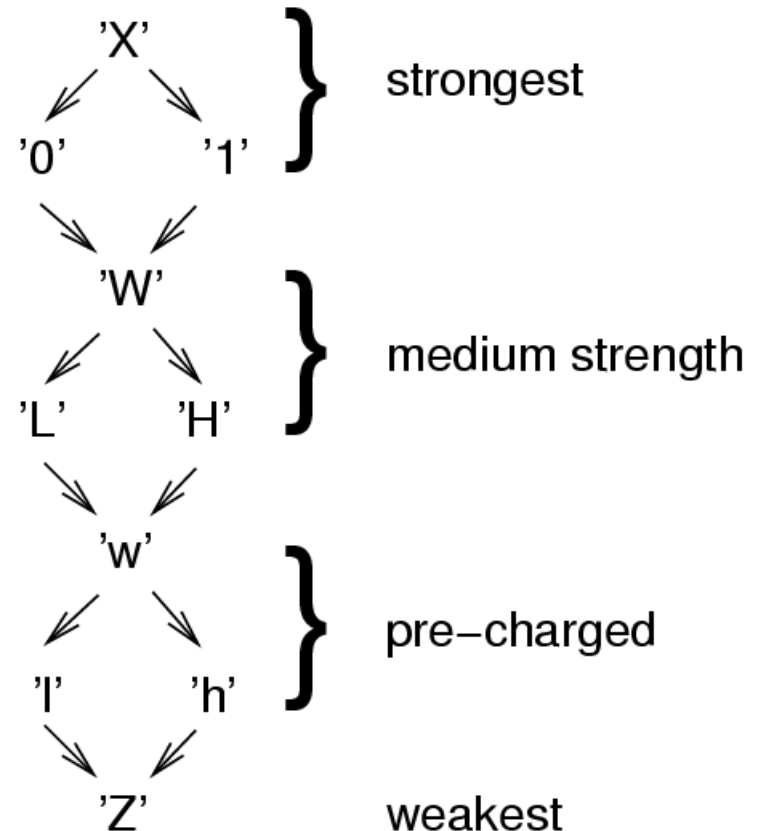
4 signal strengths (2)

There may also be weak signals of the same level as '0'

☞ Introduction of 'l', denoting a very weak signal of the same level as '0':
 $\#('l', '0') = '0'$;
 $\#('l', 'Z') = 'l'$;

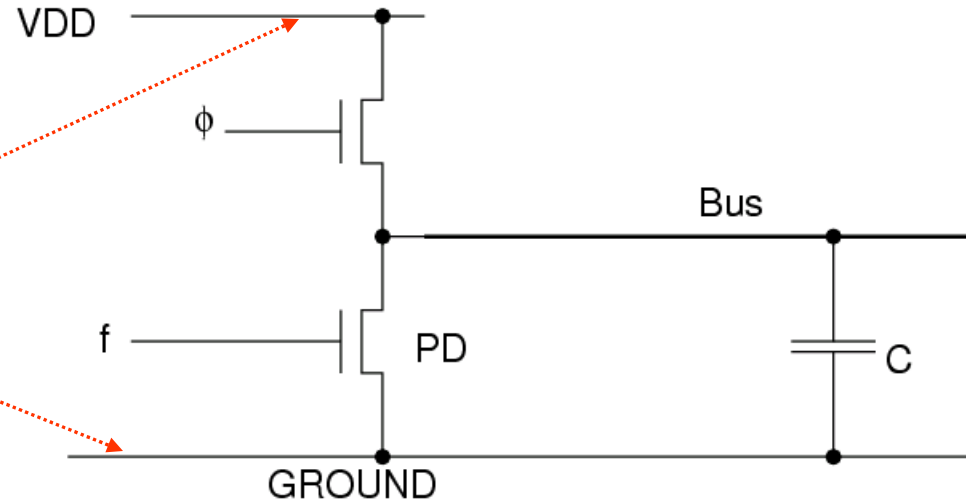
☞ Introduction of 'w', denoting a very weak signal of the same level as 'W':
 $\#('l', 'h') = 'w'$;
 $\#('h', 'w') = 'w'$; ...

reflected by the partial order shown.



5 signal strengths

Current values insufficient for describing strength of supply voltage



Supply voltage stronger than any voltage considered so far.

➡ Introduction of 'F0' and 'F1', denoting a very strong signal of the same level as '0' and '1'.

➡ Definition of 46-valued logic, also modeling uncertainty (Coelho); initially popular, now hardly used.

IEEE 1164

VHDL allows user-defined value sets.

- Each model could use different value sets (unpractical)
- Definition of standard value set according to standard IEEE 1164:

{'0', '1', 'Z', 'X', 'H', 'L', 'W', 'U', '-'}

First seven values as discussed previously.

- : Everything said about 7-valued logic applies.
 - : Combination of pre-charging and depletion transistors cannot be described in IEEE 1164.
- 'U': un-initialized signal; used by simulator to initialize all not explicitly initialized signals.

Input don't care

' - ' denotes **input don't care**.

Suppose:

$f(a,b,c) = a\bar{b} + bc$ except for $a=b=c='0'$ where f is undefined

Then, we could like specifying this in VHDL as

```
f <= select a & b & c
```

```
    '1' when "10-" -- first term
```

```
    '1' when "-11" -- second term
```

```
    'X' when "000" -- 'X'  $\triangleq$  ('0' or '1') here (output don't care)
```

```
    '0' otherwise;
```

Simulator would check if $a \& b \& c = "10-"$, i.e. if $c='-'$.

Since c is never assigned a value of '-', this test would always fail. Simulator does not know that '-' means either '1' or '0', since it does not include any special handling for '-', (at least not for pre-VHDL'2006).

Function std_match

Special meaning of ' - ' can be used in special function std_match.

if std_match(a&b&c,"10-")

is true for any value of **c**, but this does not enable the use of the compact **select** statement.

-  The flexibility of VHDL comes at the price of less convenient specifications of Boolean functions.

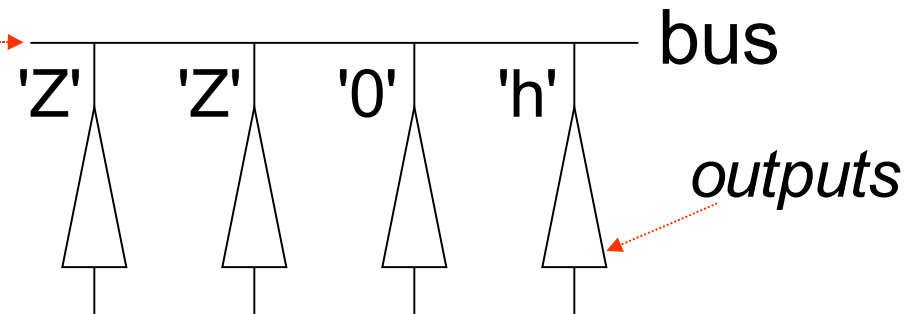
VHDL'2006 has changed this: ' - ' can be used in the “intended” way in case selectors

Outputs tied together

In hardware, connected outputs can be used:

Resolution function

used for assignments to bus, if bus is declared as `std_logic`.



Modeling in VHDL: resolution functions

```
type std_ulogic is ('U', 'X', '0', '1', 'Z', 'W', 'I', 'h', '-');
```

```
subtype std_logic is resolved std_ulogic;
```

```
-- involve function resolved for assignments to std_logic
```

Resolution function for IEEE 1164

```
type std_ulogic_vector is array(natural range<>)of std_ulogic;
```

```
function resolved (s:std_ulogic_vector) return std_ulogic is  
variable result: std_ulogic:='Z'; --weakest value is default  
begin
```

```
  if (s'length=1) then return s(s'low) --no resolution
```

```
  else for i in s'range loop
```

```
    result:=resolution_table(result,s(i))
```

```
  end loop
```

```
  end if;
```

```
  return result;
```

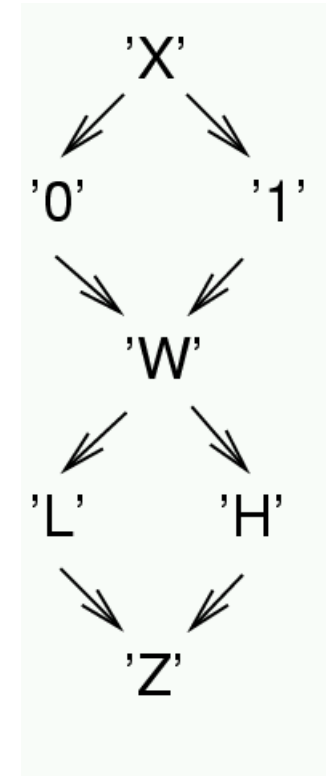
```
end resolved;
```

Using # (=sup) in resolution functions

```

constant resolution_table : stdlogic_table := (
--U  X  0  1  Z  W  L  H  -
('U', 'U', 'U', 'U', 'U', 'U', 'U', 'U', 'U'), --| U |
('U', 'X', 'X', 'X', 'X', 'X', 'X', 'X', 'X'), --| X |
('U', 'X', '0', 'X', '0', '0', '0', '0', 'X'), --| 0 |
('U', 'X', 'X', '1', '1', '1', '1', '1', 'X'), --| 1 |
('U', 'X', '0', '1', 'Z', 'W', 'L', 'H', 'X'), --| Z |
('U', 'X', '0', '1', 'W', 'W', 'W', 'H', 'X'), --| W |
('U', 'X', '0', '1', 'L', 'W', 'L', 'W', 'X'), --| L |
('U', 'X', '0', '1', 'H', 'W', 'W', 'H', 'X'), --| H |
('U', 'X', 'X', 'X', 'X', 'X', 'X', 'X', 'X') --| - |
);

```



This table would be difficult to understand without the partial order

VHDL: Evaluation



- Behavioral hierarchy (procedures and functions),
- Structural hierarchy: through structural architectures, but no nested processes,
- No specification of non-functional properties,
- No object-orientation,
- Static number of processes,
- Complicated simulation semantics,
- Too low level for initial specification,
- Good as an intermediate “Esperanto“ or ”assembly“ language for hardware generation.

Summary

VHDL:

- Entities and (behavioral/structural) architectures
- Modeling hardware parallelism by processes
 - Wait statements and sensitivity lists
- VHDL semantics: the simulation cycle
 - ▽ δ cycles, deterministic simulation
- Multiple-valued logic
 - General CSA approach
 - Application to IEEE 1164
- Evaluation

Verilog

HW description language competing with VHDL

Standardized:

- IEEE 1364-1995 (Verilog version 1.0)
- IEEE 1364-2001 (Verilog version 2.0)
- Features similar to VHDL:
 - Designs described as connected entities
 - Bitvectors and time units are supported
- Features that are different:
 - Built-in support for 4-value logic and for logic with 8 strength levels encoded in two bytes per signal.
 - More features for transistor-level descriptions
 - Less flexible than VHDL.
 - More popular in the US (VHDL common in Europe)

SystemVerilog

Corresponds to Verilog versions 3.0 and 3.1. Includes:

- Additional language elements for modeling behavior
- C data types such as `int`
- Type definition facilities
- Definition of interfaces of HW components as entities
- Mechanism for calling C/C++-functions from Verilog
- Limited mechanism for calling Verilog functions from C.
- Enhanced features for describing the testbench
- Dynamic process creation.
- Interprocess communication and synchronization
- Automatic memory allocation and deallocation.
- Interface for formal verification.

Using C for ES Design: Motivation

- Many standards (e.g. the GSM and MPEG-standards) are published as C programs
 - ☞ Standards have to be translated if special hardware description languages have to be used
- The functionality of many systems is provided by a mix of hardware and software components
 - ☞ Simulations require an interface between hardware and software simulators unless the same language is used for the description of hardware and software
- ☞ Attempts to describe software and hardware in the same language. Easier said than implemented.
Various C dialects used for hardware description.

Drawbacks of a C/C++ Design Flow

- C/C++ is *not* created to design hardware !
- C/C++ does not support
 - Hardware style communication - Signals, protocols
 - Notion of time - Clocks, time sequenced operations
 - Concurrency - Hardware is concurrent, operates in ||
 - Reactivity - Hardware is reactive, responds to stimuli, interacts with its environment (requires handling of exceptions)
 - Hardware data types - Bit type, bit-vector type, multi-valued logic types, signed and unsigned integer types, fixed-point types
- Missing links to hardware during debugging



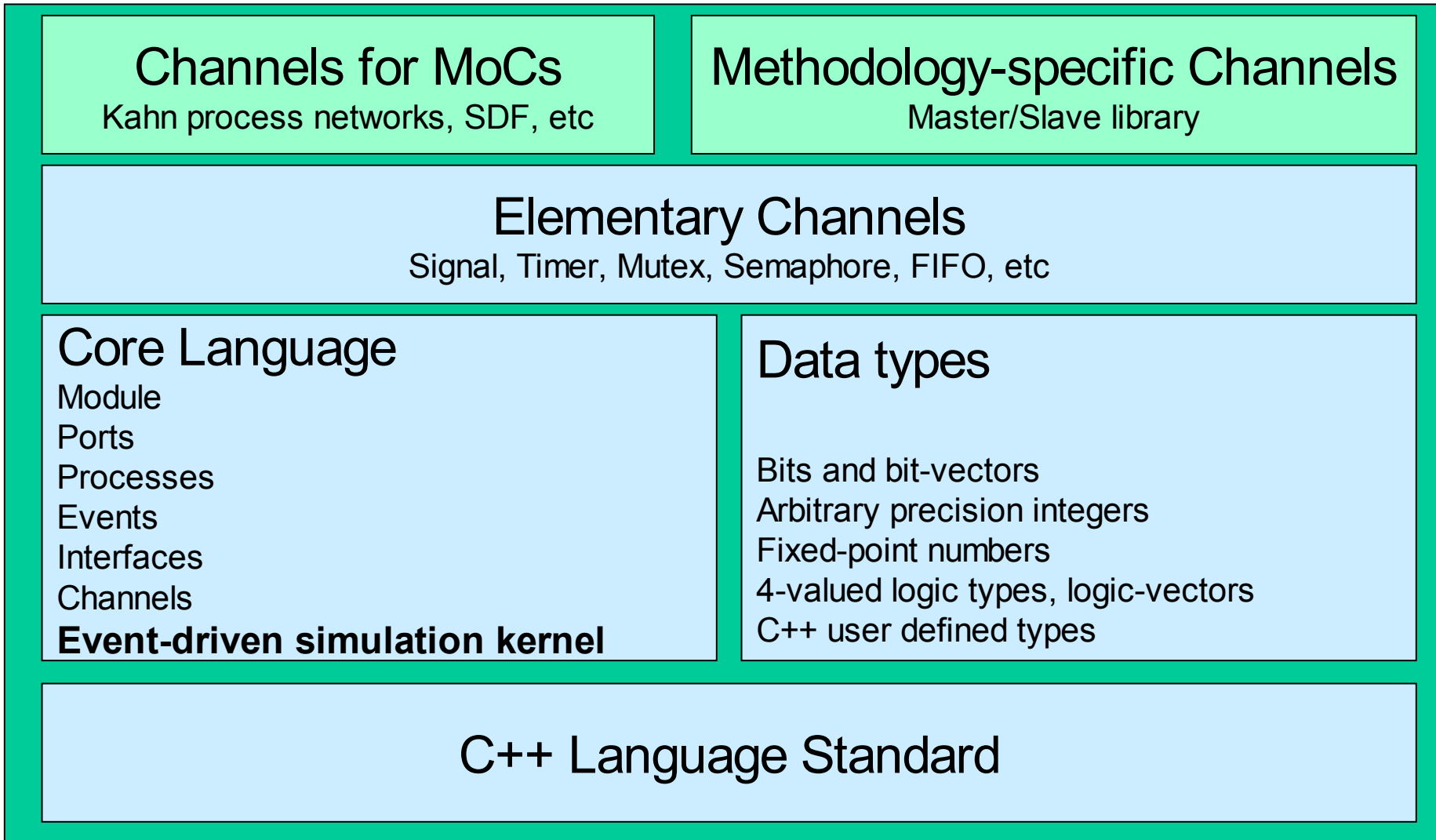
SystemC: Required features

Requirements, solutions for modeling HW in a SW language:

- **C++ class library including required functions.**
- **Concurrency:** via processes, controlled by sensitivity lists* and calls to wait primitives.
- **Time:** Floating point numbers in SystemC 1.0.
Integer values in SystemC 2.0;
Includes units such as ps, ns, μ s etc*.
- **Support of bit-datatypes:** bitvectors of different lengths;
2- and 4-valued logic; built-in resolution*)
- **Communication:** plug-and-play (pnp) channel model,
allowing easy replacement of intellectual property (IP)
- Deterministic behavior not guaranteed.

* Good to know
VHDL ☺

SystemC language architecture



Summary

- VHDL
 - Verilog
 - SystemC
- } Discrete event models

