SystemC AMS and upcoming frameworks for the free design of Analog/Mixed-Signal Systems

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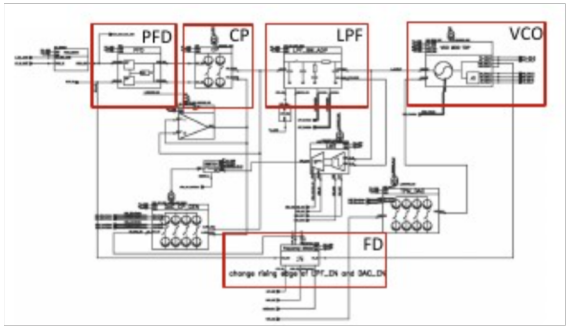
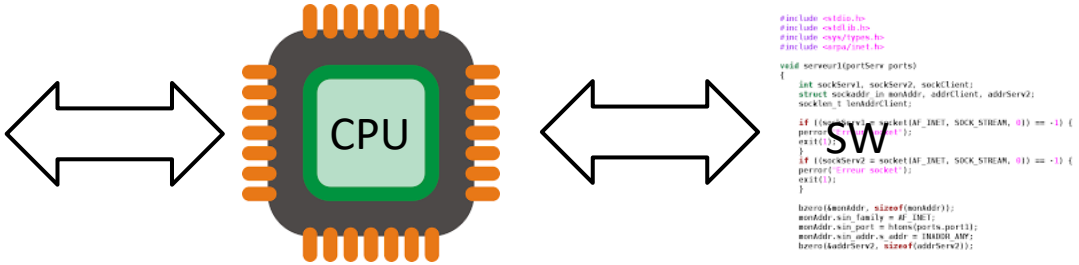
SYSTEMC™: free eco-system for HW/SW/AMS systems





SystemC ; IEEE Std. 1666

- Free simulator for HW/SW Systems; C++ based; C++ based framework
- https://accellera.org/downloads/standards/systemc

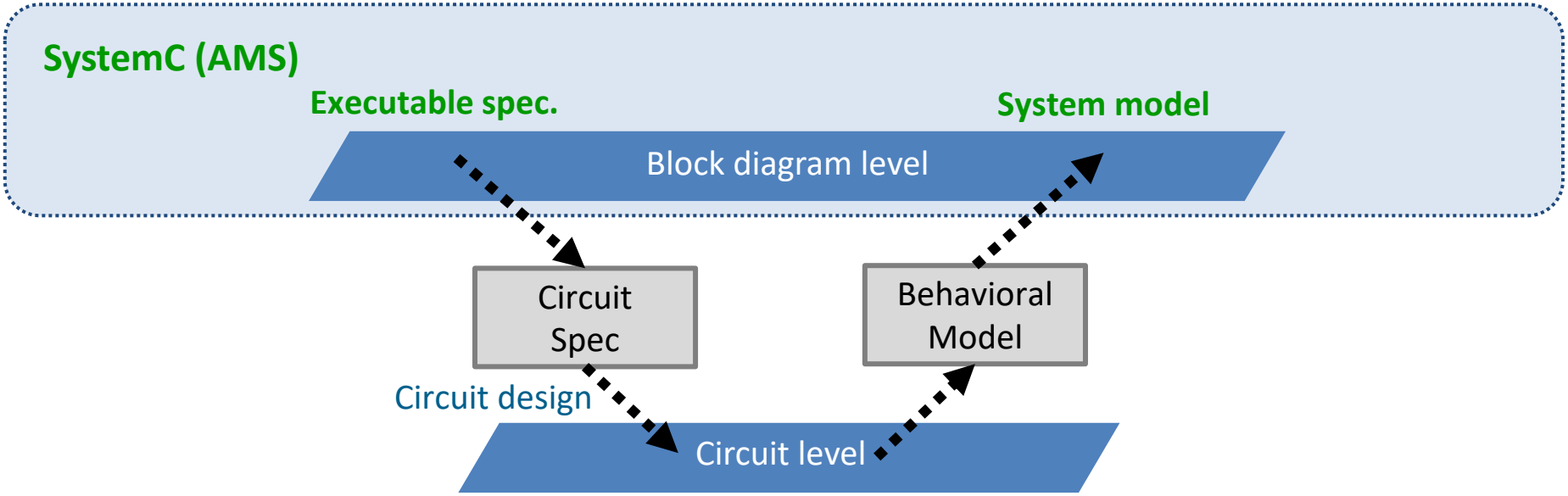
SystemC AMS; IEEE Std. 1666.1-2016

- Support DSP methods, analog
- https://www.coseda-tech.com/systemc-ams-proof-of-concept

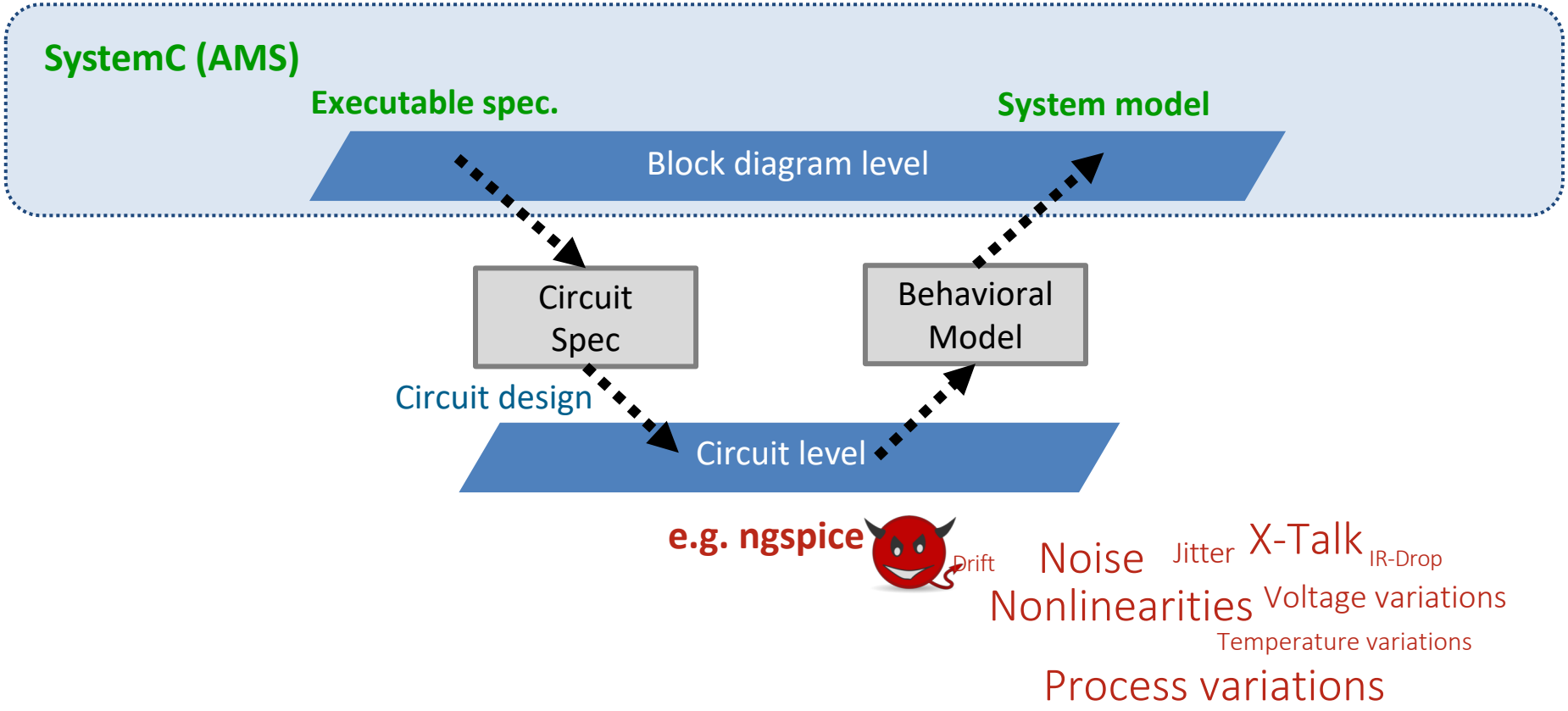
AADDlib

- Symbolic execution/simulation of e.g. C++ 11, SystemC, SystemC AMS
- https://github.com/TUK-CPS/AADD

SystemC (AMS), SPICE and AADDlib in Development Process



SystemC (AMS), SPICE and AADDlib in Development Process



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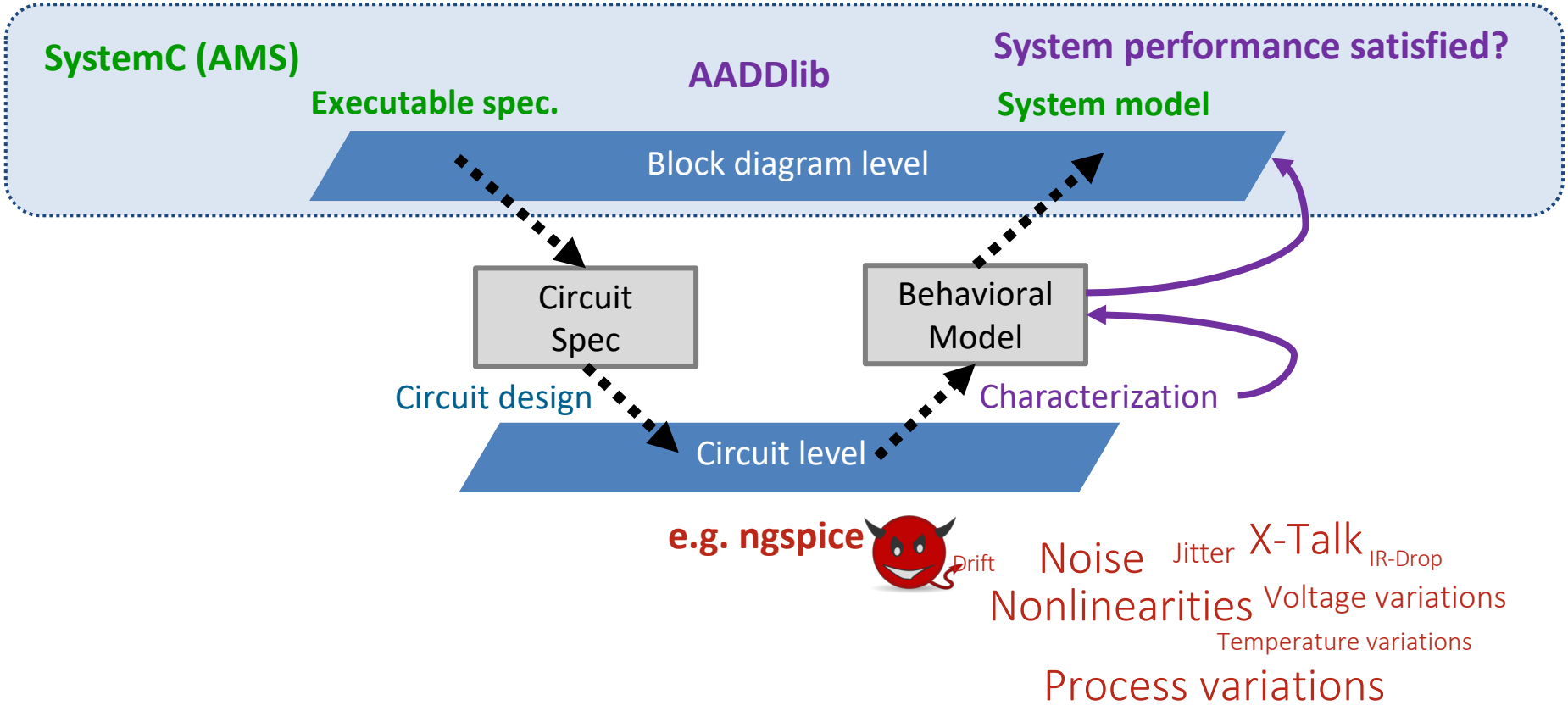
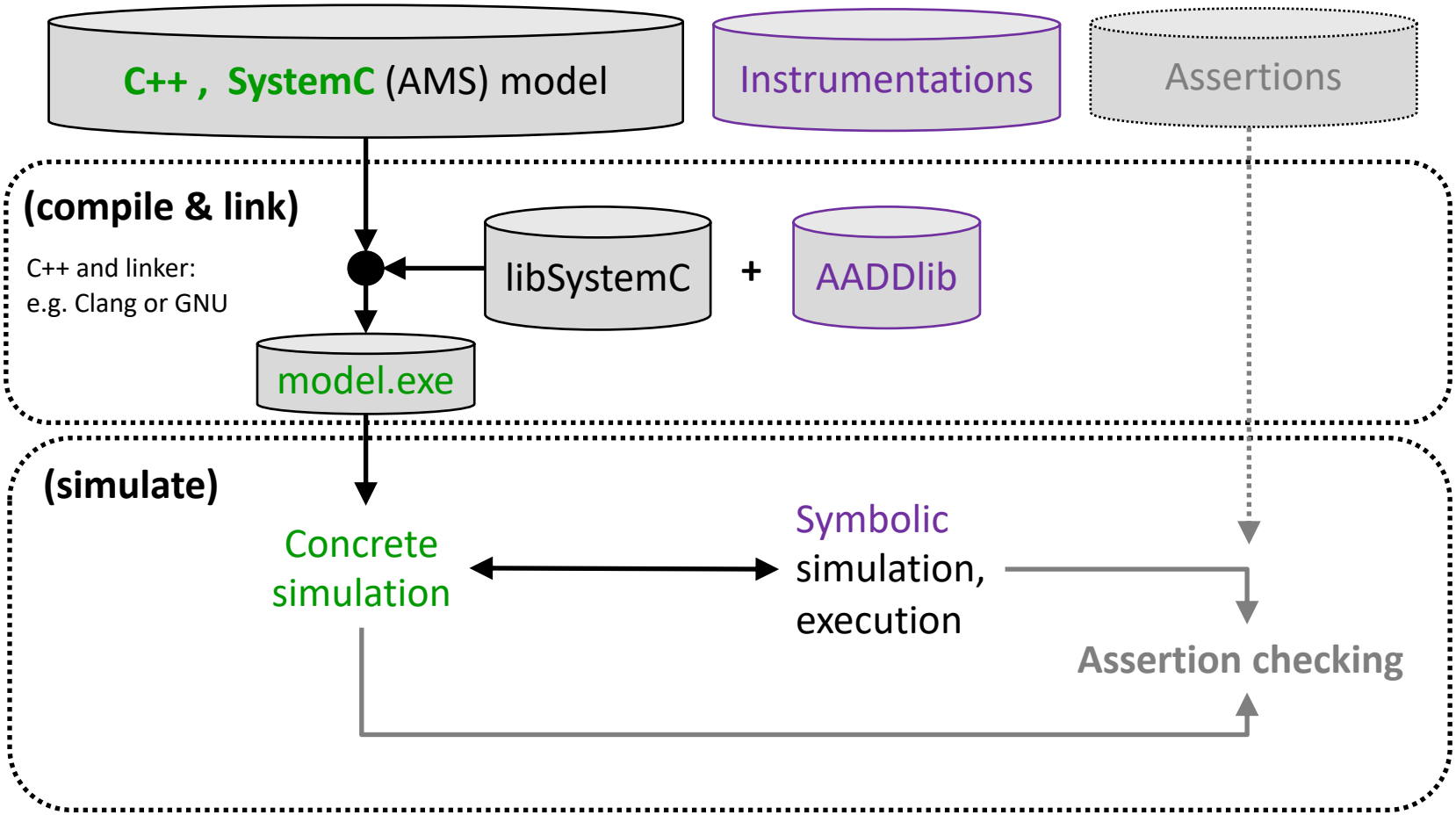


Overview of Tool Integration



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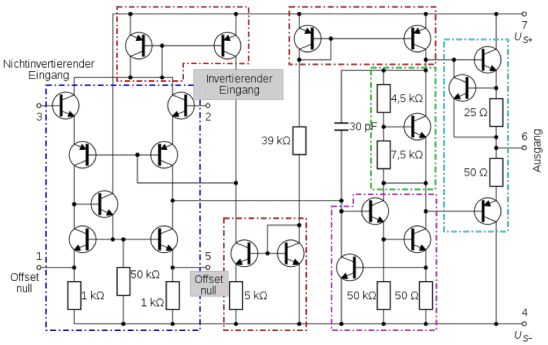
1) SystemC AMS

2) Performance verification with AADDlib

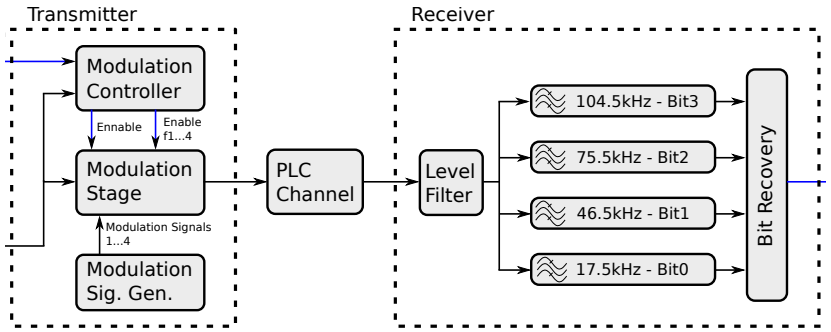
3) Case study

4) Outlook

SystemC AMS: Block Diagram Level, but not Circuit Level



Circuit schematic, e.g. ***SPICE***



Block diagram, e.g. ***Matlab/Simulink, SystemC AMS***

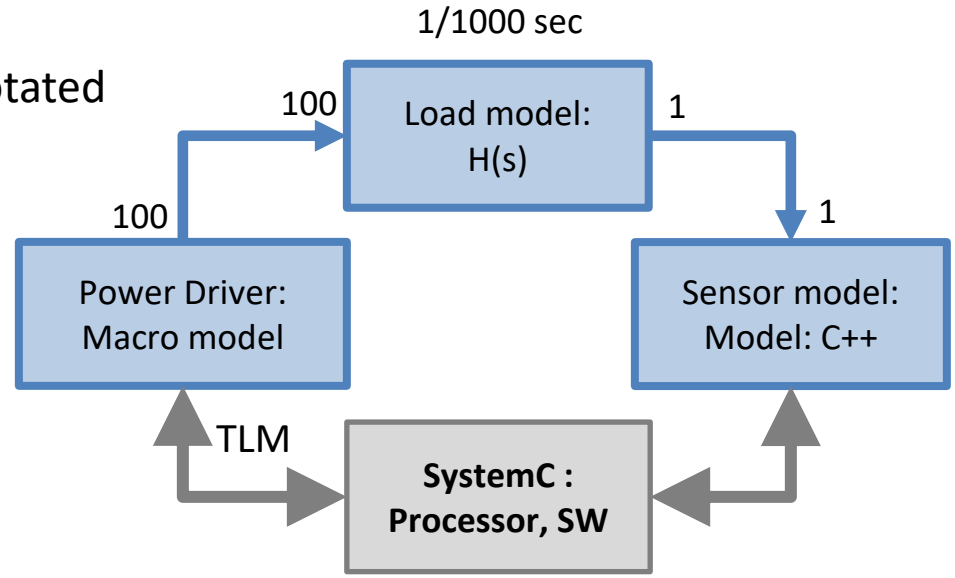
SystemC AMS: simulation of AMS systems at **functional** and **block diagram level**

- **Directed interaction** of functional blocks
- Blocks are either **ideal functions** or **behavioral models**, no circuit-level models

Block Diagrams in SystemC AMS

TIMED DATA FLOW (TDF):

- Functions of blocks in block diagrams are processed **in data flow's direction**.
- Ports may have different rates
  - Static data-flow + timing annotated
  - Scheduling before simulation



LINEAR SIGNAL FLOW (LSF)

- Structure sets up system of linear equations

Specification of a Block's Function

By a (static) function (TDF only)

- E.g. mixer:

```
y = rf_in*carrier;
```

By a transfer function

- E.g. filter:

```
y = ltf_1(nom, denom, x);
```

By a macro model (ELN)

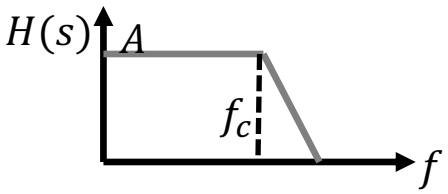
- E.g. power driver

```
(SPICE-like Structure of switches,
controlled sources, R L C)
```

… or by arbitrary C++ code, maybe mixing all the above options.

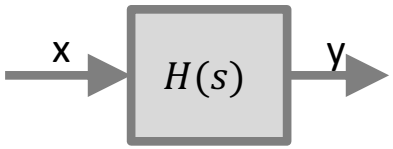
Simple Example: Executable Specification of a Filter

Function of a "filter" is described by a **transfer function, e.g.**



$$H(s) = \frac{A}{1 + 1/(2\pi f_c)s}$$

SystemC AMS allows us to specify the behavior of a block by C++ -Code




```
sca_module("LP") {
  sca_in<double> x;
  sca_out<double> y;
  (…)
  void sca_processing() {
    A(0) = 1.0;
    denom(0)=1.0; denom(1)=r2pi/fc;
    y = ltf_block(A, denom, x);
  }
}
```

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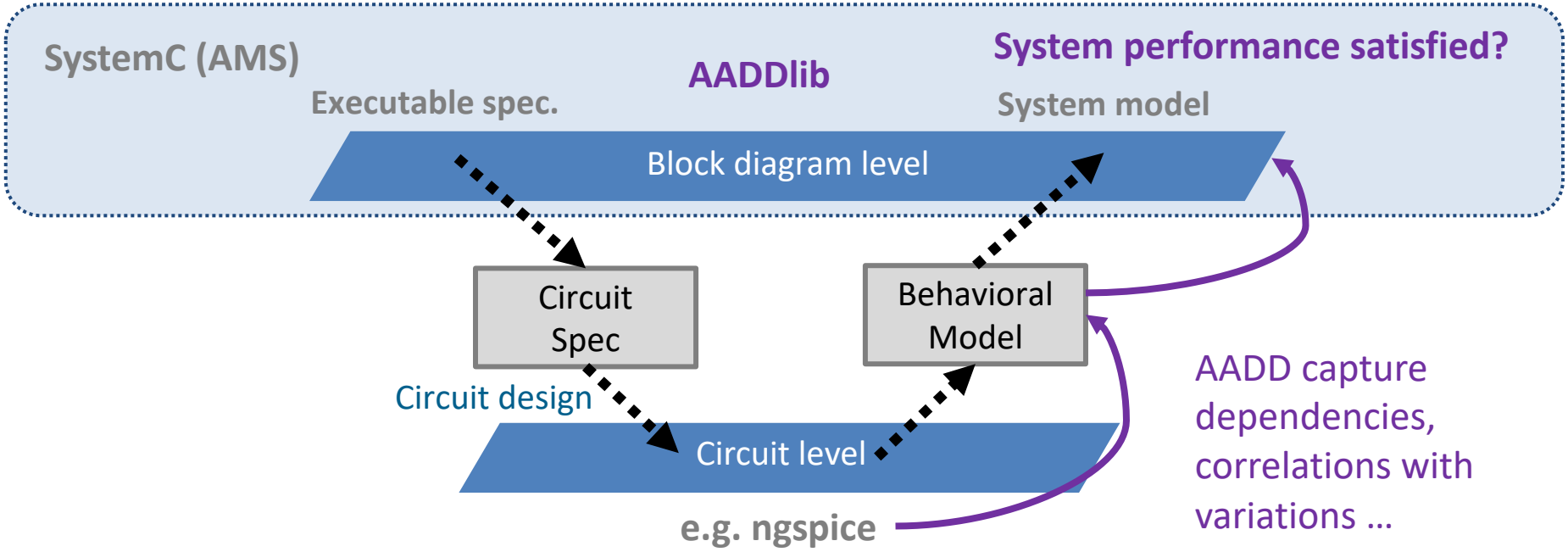


Drift Noise Jitter X-Talk IR-Drop
Nonlinearities Voltage variations
Temperature variations
Process variations

Refined model of a filter … more realistic!

Relevant properties of filter for the system are amplification, corner frequency, noise, limitation, …

- E.g. corner frequency f_c, amplification A can be modeled by a range
- In specification: means allowed range
- In behavioral model: models uncertainties, impact of PVT variations

```
void processing()
  (...)
  A(0) = 1.0 + dA;            // Range of possible A
  denom(0)=1.0;
  denom(1)=r2pi/(fc + df);    // Range of possible fc

  if (x > 5.0) then x = 5.0; // limitation at input
  x += noise(3);              // assume some noise

  y = ltf_block(A, denom, x);

  if y > 5.0 then y = 5.0;    // limitation at output
```

Affine forms, affine arithmetic [Andrade, Stolfi, 1997]

```
A(0) = 1.0 +/- dA;        // Range of possible A
     = 1.0 +   dA * ε_i   // By affine form
```

Affine forms represent linear dependencies in symbolic way:

$$\tilde{x} := x_0 + \sum_{i=1}^{n} x_i \varepsilon_i \quad \text{with noise symbols } \varepsilon_i \in [-1,1]$$

- x_0 is *center value*,
- x_i are *partial deviations*, models sensitivity to variations e.g. P, V or T.
- Nonlinear dependencies handled by safe inclusion with x_i not used otherwise. *e.g. Chebychev approximation*

Limitations:

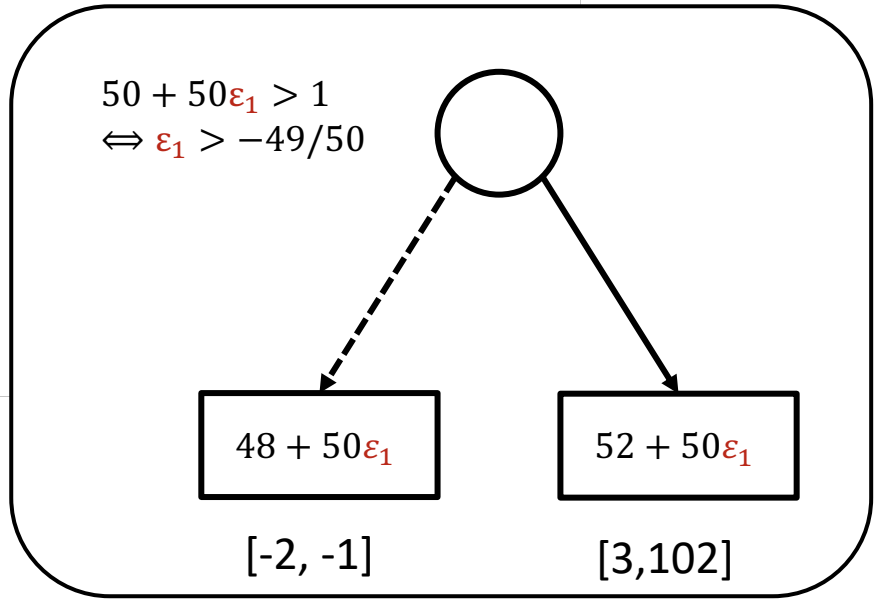
- *Functions with local extrema, discontinuous functions, e.g.*

```
if y > 5.0 then y = 5.0;   // limitation at output
```

Basic Example: Use of libAADD in C++ 11

```
if y > 5.0 then y = 5.0;   // limitation at output
```

```
#include "aadd.h"

doubleS a;  // Data types with S are computed symbolically.

int main()
{
    a = doubleS(0,100); // a takes double value from range [0,100]

    ifS(a > 1)          // symbolic cond. and iteration statements
       a = a + 2;
    elseS
       a = a - 2;
    endS;

    cout << "a is: " << endl;
    cout << a;

}
```



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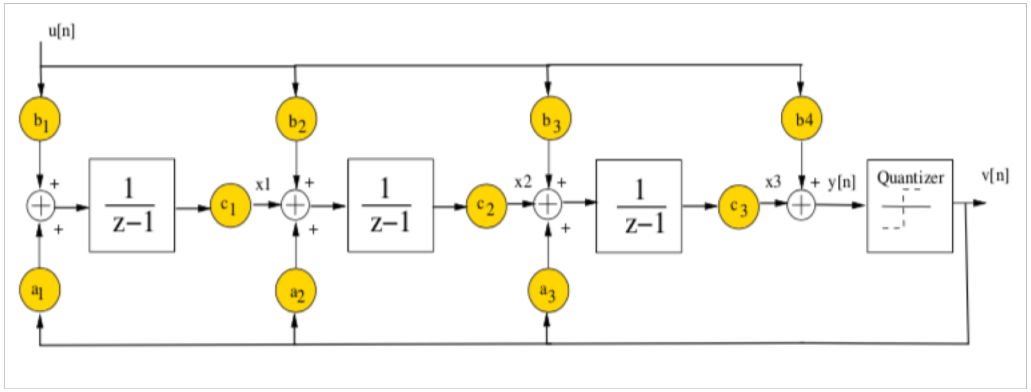
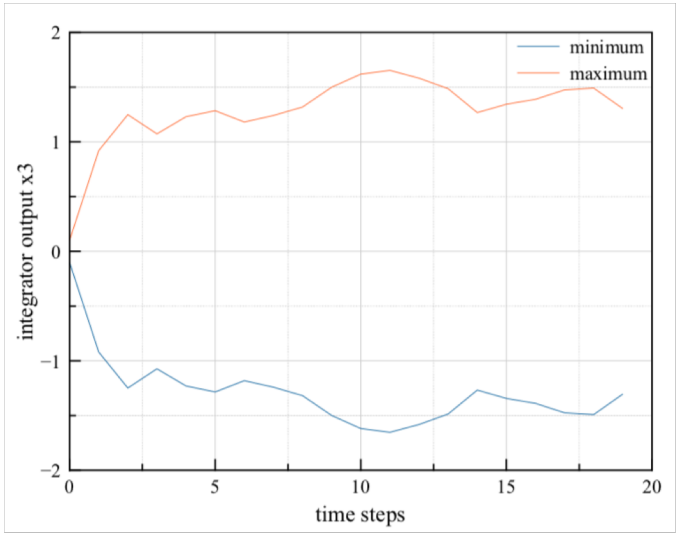
Benchmark: 3rd order sigma-delta modulator



Initial input and integrator values
$x_1 \in [-0.1, 0.1]$
$x_2 \in [-0.1, 0.1]$
$x_3 \in [-0.1, 0.1]$
$u \in [-0.5, 0.5]$

```
SCA_TDF_MODULE(quantizer) {
  sca_tdf::sca_in<doubleS> y;
  sca_tdf::sca_out<doubleS> v;
  void processing() {
    ifS(y>0) v=1; elseS v=-1; endS
  }
  quantizer(sc_module_name nm){}
}
```



Comparison with State of the Art

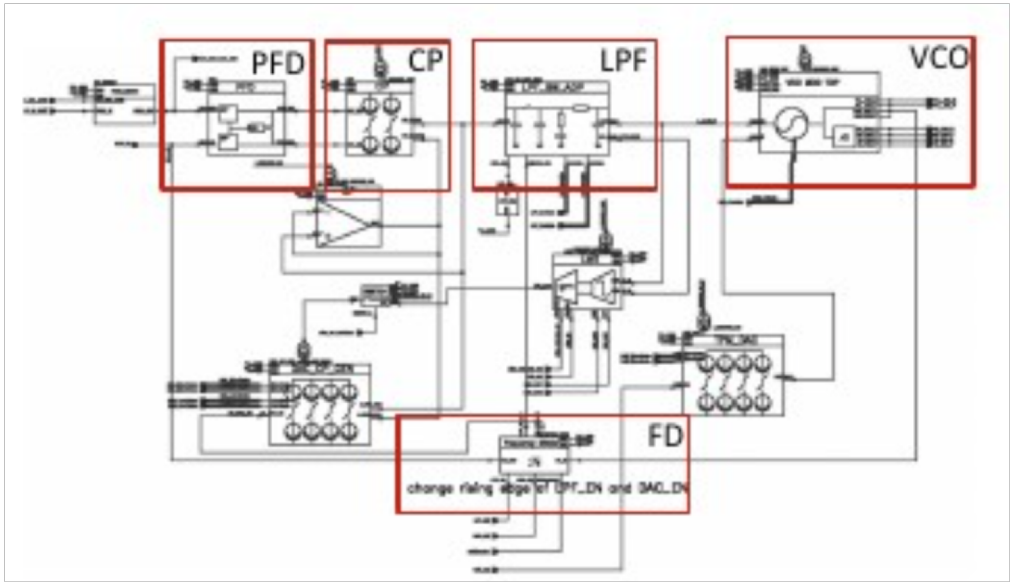
Initial input and integrator values	[Sammane 2007] d/dt [Dang 2004]	AADDlib incl. Property 1	Speedup
$x_1 \in [0.012, 0.013]$ $x_2 \in [0.01, 0.02]$ $x_3 \in [0.8, 0.82]$ u=0.54=const	**31 s** for N=38 time steps [Sammane 2007]	**1.93 s** for 100 time steps	> 16
$x_1 \in [-0.1\ 0.1]$ $x_2 \in [-0.1, 0.1]$ $x_3 \in [-0.1, 0.1]$ u=[-0.5, 0.5]	**2 h** for N=30 time steps (d/dt tool) [Dang 2004]	**525 s** for 30 time steps	> 13

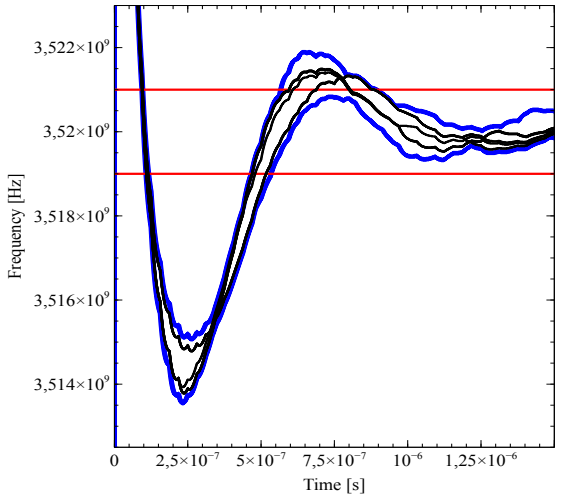
Property 1: $\mathrm{G}(x_i, -2, 2)$ with $i \in \{1, 2, 3\}$ for x_3 was satisfied in both cases.
Property 2: $\mathrm{G}(y, -2, 2)$ failed for second set of initial conditions, simulation was stopped.

Does it scale for “real” designs?
Larger case study …

Cadence-design of dual-charge-pump PLL of ZigBee transceiver

- 8434 lines of C++ Code in SystemC by netlister
- 7-12 parameters with symbolic variations
- 40.000-120.000 time steps
- 4-11 min. for symbolic simulation, assertion checking





Blue: bounds of AADD stream

Black: corner case simulations

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Conclusion

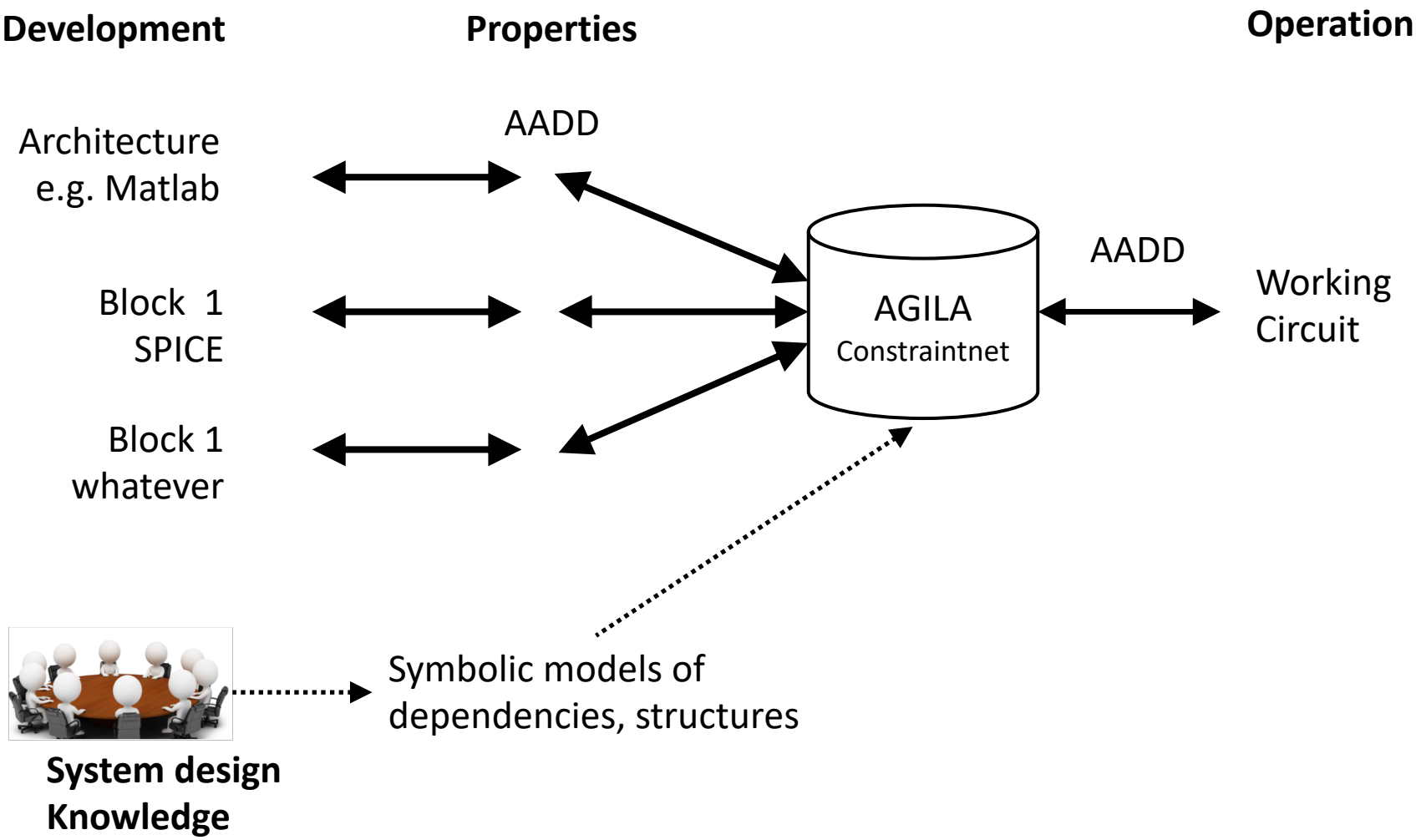
- Combination of SystemC (AMS), AADDLib, SPICE provides a seamless flow, linking circuit-level design and system-level design

- **Interesting observation**: Tool flow used in Automotive / Microelectronics companies for analysis of power train, ECU software, impact on emissions, …

  - Collaboration: Funding for 3-4 PhD or Postdoc from industry
  - Collaboration: AADDlib + VHDL?

- Next major version of AADDlib in preparation
  - Based on Java (jAADD) and Z3

Outlook: Agile development of AMS systems with AGILA



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Many Thanks!

SAVE THE DATE // FAC 2017
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Complementary Slides

Instrumentation of Selection and Iteration Statements

In EBNF from C++14 grammar:

```
1:  if (condition)
2:    statement
3:  [ else
4:    statement ]
```

instrumented →

```
1:  ifS (condition)
2:    statement
3:  [ elseS
4:    statement ] endS
```

```
1:  while (condition)
2:    statement
```

instrumented →

```
1:  whileS (condition)
2:    statement endS
```

- **ifS, elseS, whileS, endS** are macros that introduce more complex C++ code.
- Instrumentations can be done manually or by simple preprocessor.
- *statement* can be any C++ statement including *selection* and *iteration statements*.

Definition: Path condition & block condition

Path condition

- Conjunction of all conditions from start of program to current state
- Represented in BDD-like part of symbolic variables of type BDD/AADD

Block condition

- Conjunction of elementary predicates whose control flow is not yet joined

  (*"nested blocks"* of selection and iteration statements in C++)

```
1:  a = 0;
2:  ifS (c2)
3:    a = 1;
4:  elseS
5:    a = 2; endS;
6:
```

Block condition is c2.

Block condition is $\overline{c2}$

$a = 1|_{c2}$ *or* $2|_{\overline{c2}}$.
Block condition is true.

Algorithm: Block condition tracking

Global stack of conditions stores all conditions (maybe negated) of the block condition as a BDD (boolean part) w/ symbolic predicates on ε_i (comparisons):

- For all **conditional branches** (no matter by which statement: ifS, whileS, ...)
  - Push condition on stack of block conditions
- For all **merges in control flow**
  - Pop condition from stack of block conditions

Overloaded assignment operators (=, -=, +=, ... on AADD or BDD):

```
1:  METHOD assign(rval, lval: AADD or BDD)
2:    bc := AND(all conditions on stack);
3:    lval := ITE(bc, lval, rval);
4:    return lval;
```

Symbolic Simulation of SystemC (AMS, TDF)

- Concrete and (value-)symbolic signals are sequences of samples $s_i = (s, t)$
  Concrete signal: $s_T := \langle s_0, s_1, s_2, \dots \rangle$
  Symbolic signal: $\hat{s}_T := \langle \hat{s}_0, \hat{s}_1, \hat{s}_2, \dots \rangle$; values can be AADD but not time-tags.

- Concrete and symbolic process activation

```
sc_in<bool>    clk; // concrete signal
sc_in<doubleS> th;  // symbolic signals
sc_out<intS>   cnt;

void count() {
  if (th > 2) cnt += 1;
}
SC_METHOD(count) sensitive << clk;
```

- *Concrete process activation if clk is concrete.*
- *Symbolic activation if clk is symbolic.*

- **TDF & DE MoC** with concrete clk require no further precautions;
  otherwise: overloaded update() of sc_prim_channel needed