From Lustre to C: a Proof-carrying Approach to Verified Compilation

AID Meeting – *Essaim de drones*

Lélio Brun[1]

October 12, 2021

[1]ISAE-SUPAERO – DISC – IpSC

Context

Embedded Systems Design

Embedded systems

- computer systems within physical systems that interact with the real world, often with real-time constraints
- software usually written in low-level languages: C, Ada, Assembly

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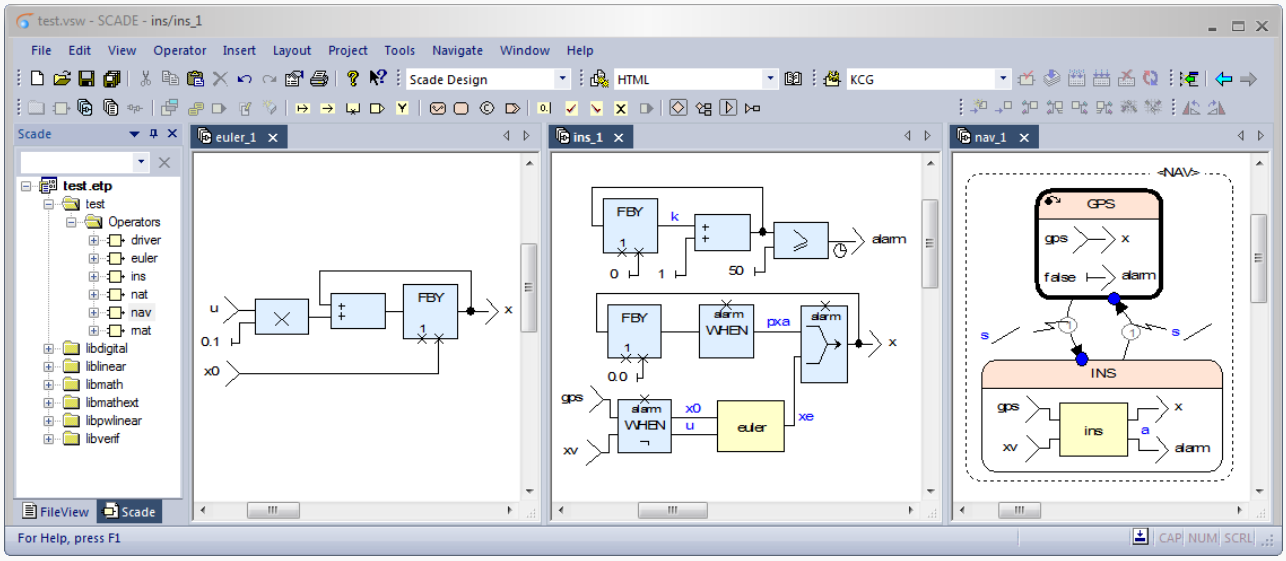
Model-Based Design

Executable high-level abstract specifications

Model-Based Design in SCADE Suite

www.ansys.com/products/embedded-software/ansys-scade-suite



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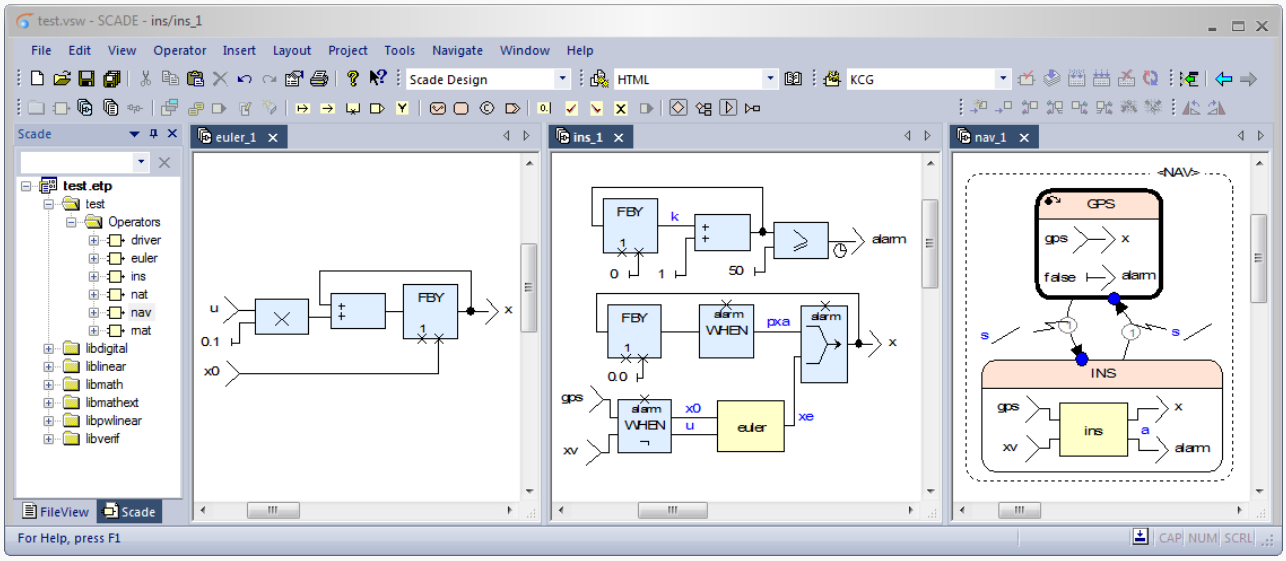

block / node = system

line = signal

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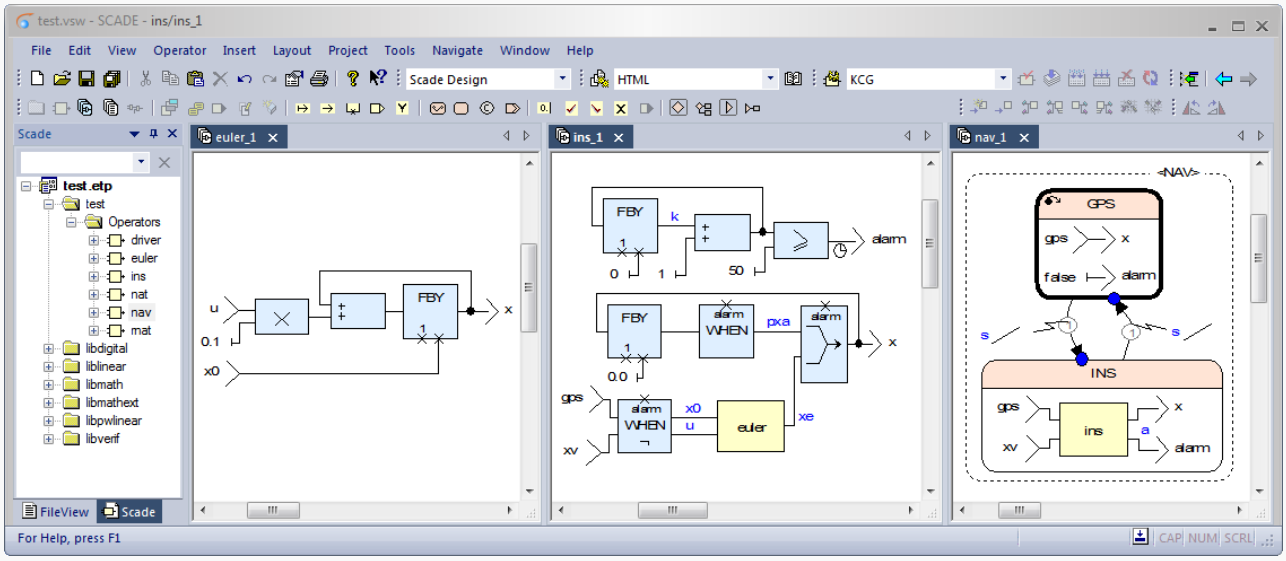

block / node = system = stream function

line = signal = stream of values

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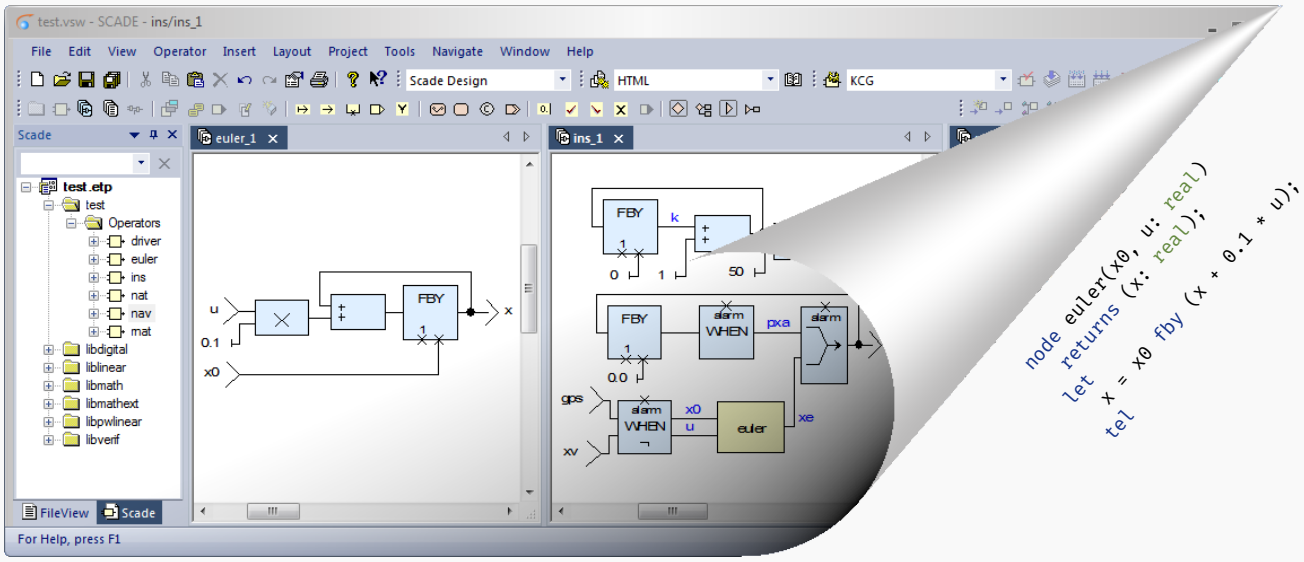

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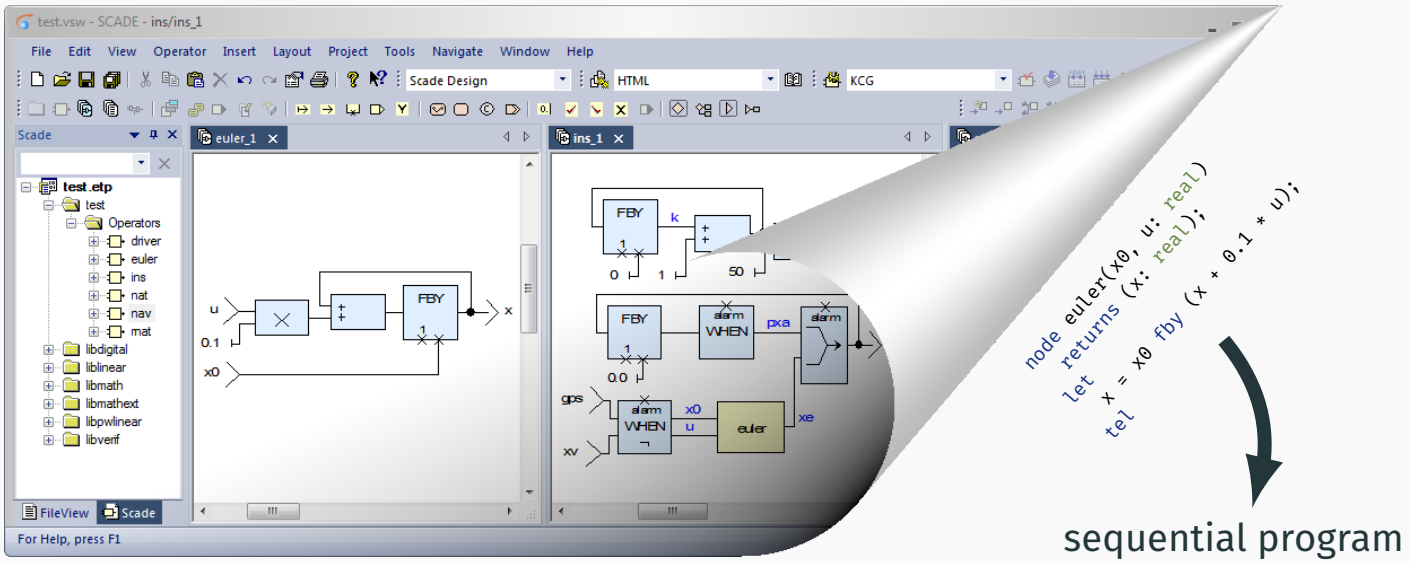

sequential program
(C, Ada, assembly)

block / node = system = stream function

line = signal = stream of values

Criticality

Systems that must not fail

- Flight control systems
- Automated train systems
- Power plant monitoring software

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State of the art: industrial certification of the development process, sometimes using *formal methods*, eg. SCADE

Scientific questions:

- Can we produce an end-to-end correctness proof?
- Can verification performed at high-level be transported and replayed at low-level?

Formal Verification

Leroy 2009
Appel 2011
Klein et al. 2009

Kumar, Myreen, Norrish, and Owens 2014
Bohrer, Tan, Mitsch, Myreen, and Platzer 2018

CompCert a verified C compiler in Coq

VST a C verification toolset based on CompCert

seL4 a verified micro-kernel in Isabelle

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Vélus a verified Lustre compiler in Coq, based on CompCert

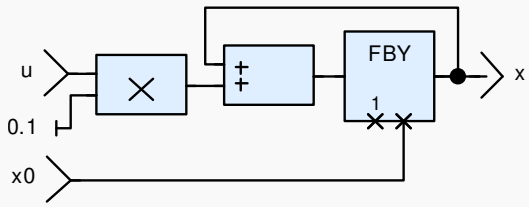
The LustreC Project

An academic Lustre compiler with several backends and verification abilities

- Generation of ACSL specification, along with the C code
- Encoding of the correctness result, to be proven by solvers
- Automatic contract translation

Software Analyzers

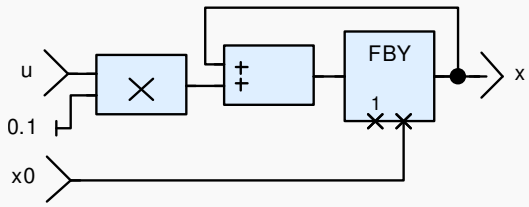
Example




```
node euler(x0, u: real)
  returns (x: real);
let
  x = x0 fby (x + 0.1 * u);
tel
```

x_0	0.00	1.55	3.62	5.46	$\cdots$
u	15.00	20.00	17.00	12.00	$\cdots$
$x + 0.1 \times u$	1.50	3.50	5.20	6.70	$\cdots$
x	0.00	1.50	3.50	5.20	$\cdots$

Example

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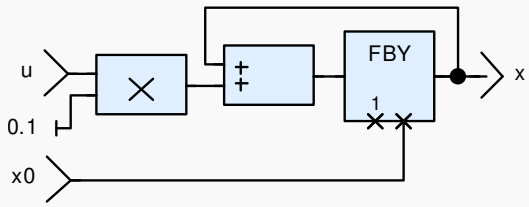


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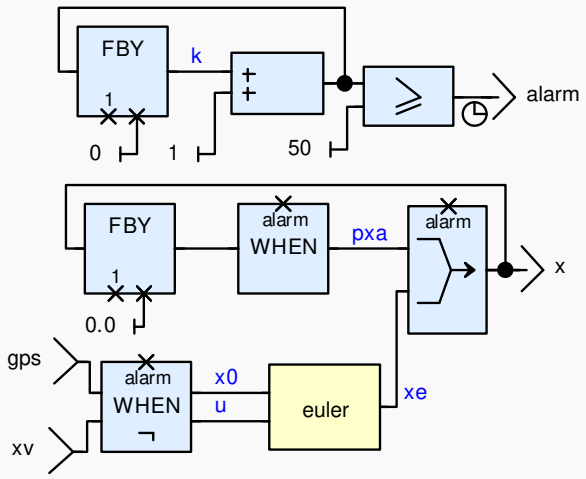


```
node ins(gps, xv: real)
  returns (x: real, alarm: bool)
  var pxa, xe: real; k: int;
let
  k = 0 fby (k + 1);
  alarm = (k >= 50);
  xe = euler((gps, xv) when not alarm);
  pxa = (0. fby x) when alarm;
  x = merge alarm pxa xe;
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gps	0.00	1.55	3.62	5.46	···	86.52	88.40	90.91	···
xv	15.00	20.00	17.00	12.00	···	18.00	23.00	20.00	···
k	0	1	2	3	···	49	50	51	···
alarm	F	F	F	F	···	F	T	T	···
xe	0.00	1.50	3.50	5.20	···	77.35			···
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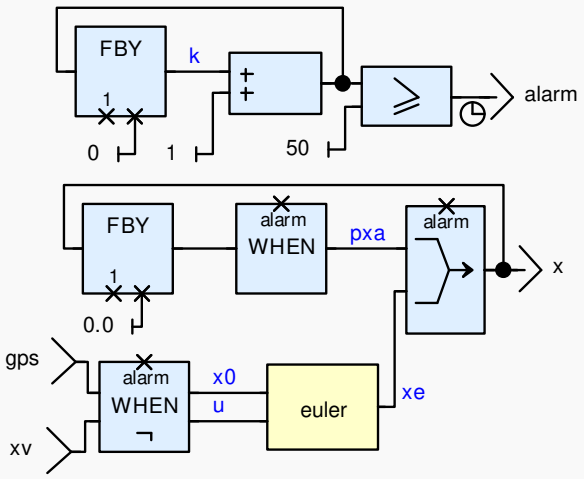


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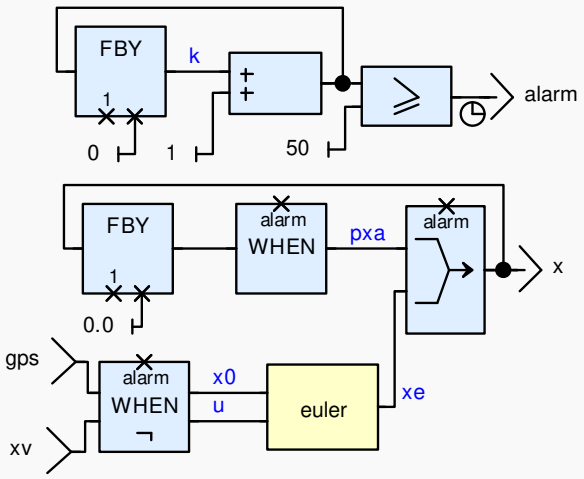


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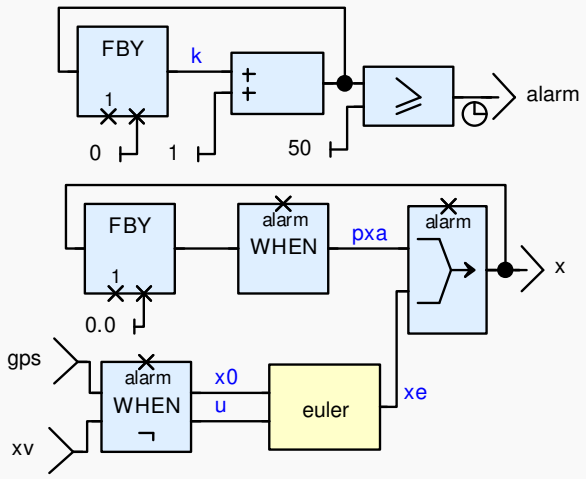


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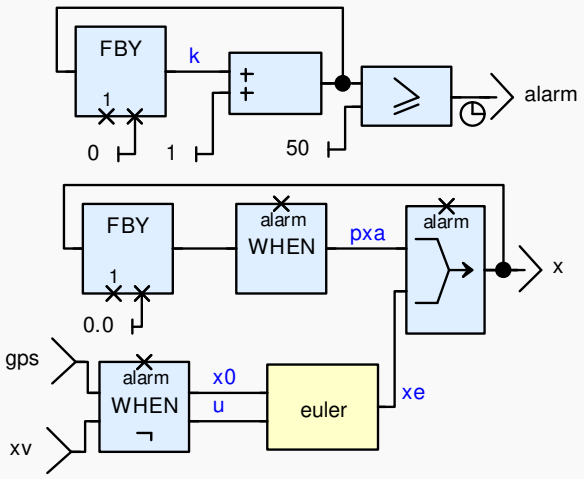


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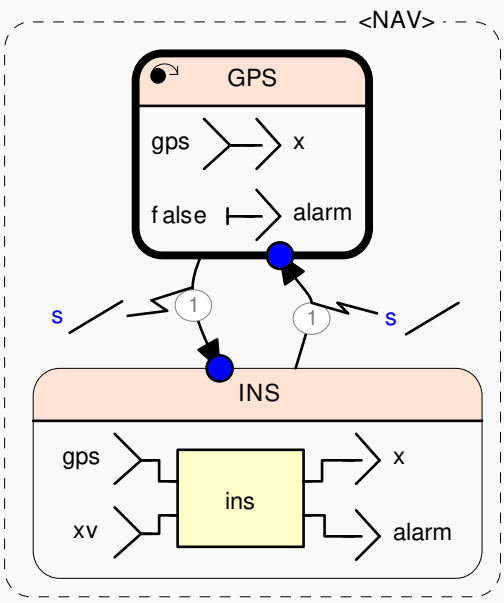
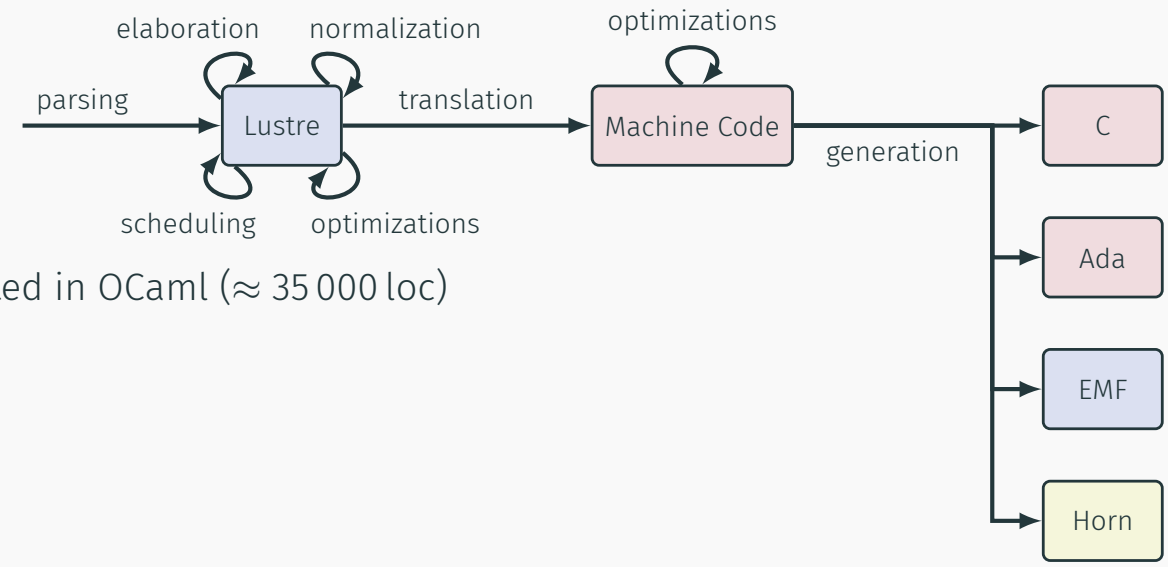
Example

Colaço, Pagano, and Pouzet 2005




```
node nav(gps, xv: real, s: bool)
  returns (x: real, alarm: bool)
let
  automaton a
    state GPS:
      let
        x = gps;
        alarm = false;
      tel until s restart INS
    state INS:
      let
        (x, alarm) = ins(gps, xv);
      tel until s resume GPS
tel
```

LustreC: a Lustre Compiler



Implemented in OCaml (≈ 35 000 loc)

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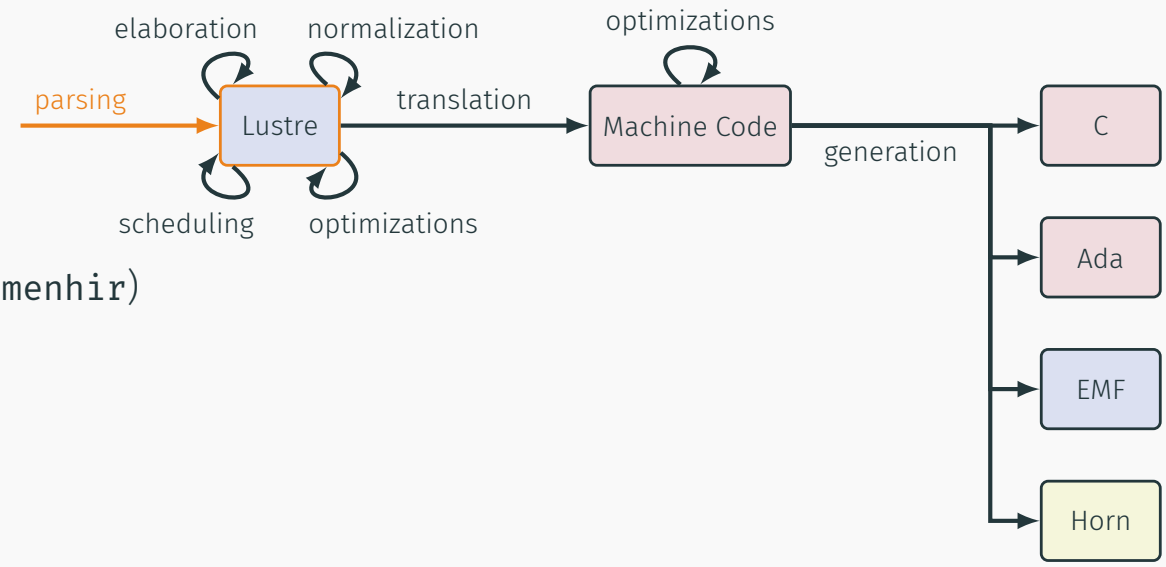

- parsing (`menhir`)

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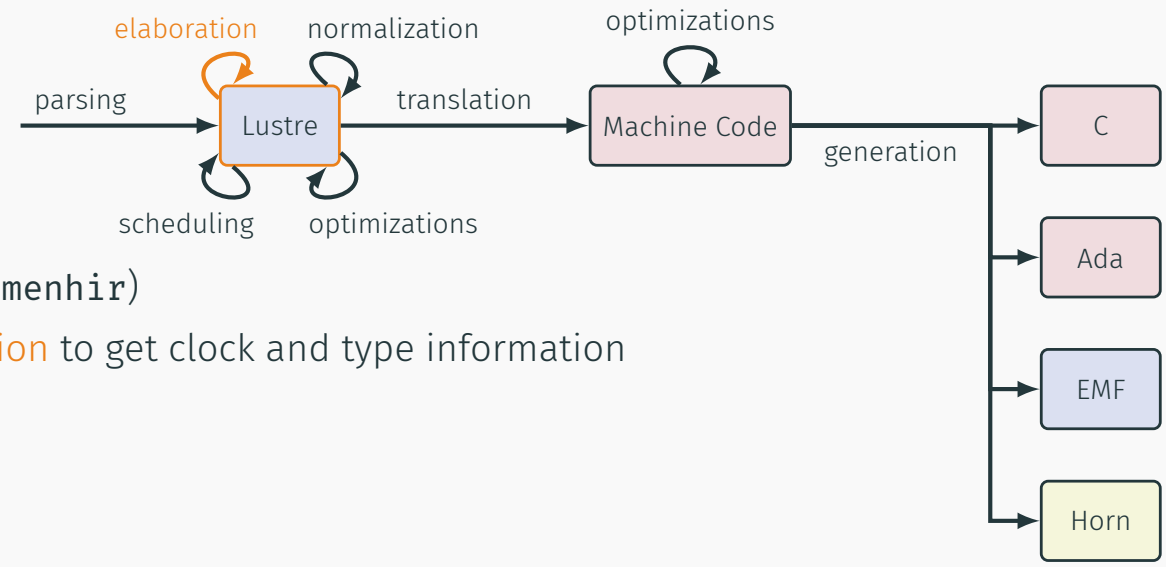

- parsing (`menhir`)
- elaboration to get clock and type information

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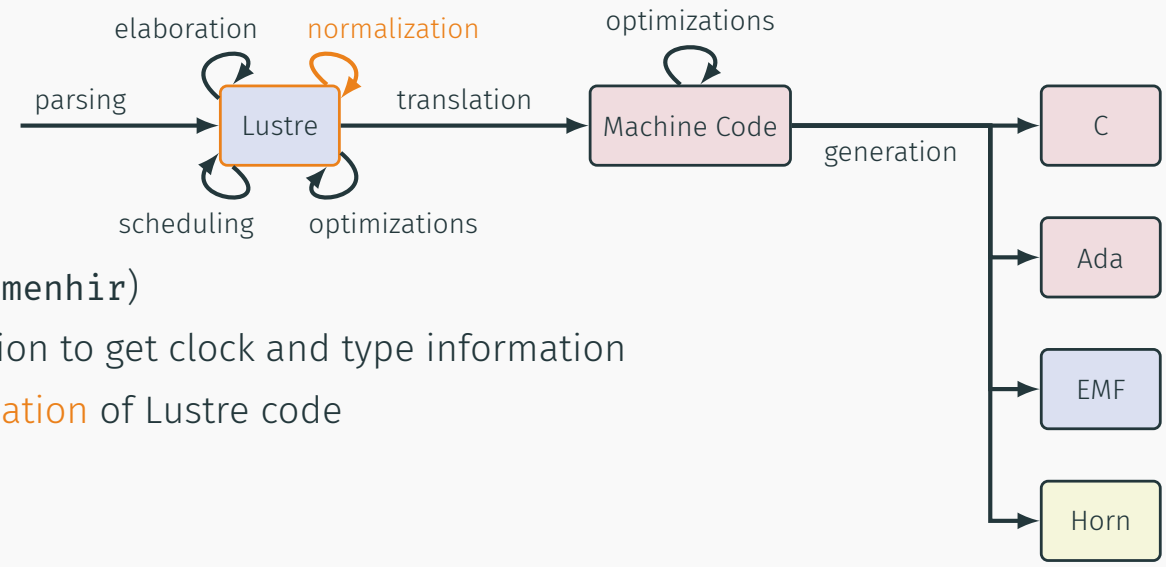

- parsing (`menhir`)
- elaboration to get clock and type information
- normalization of Lustre code

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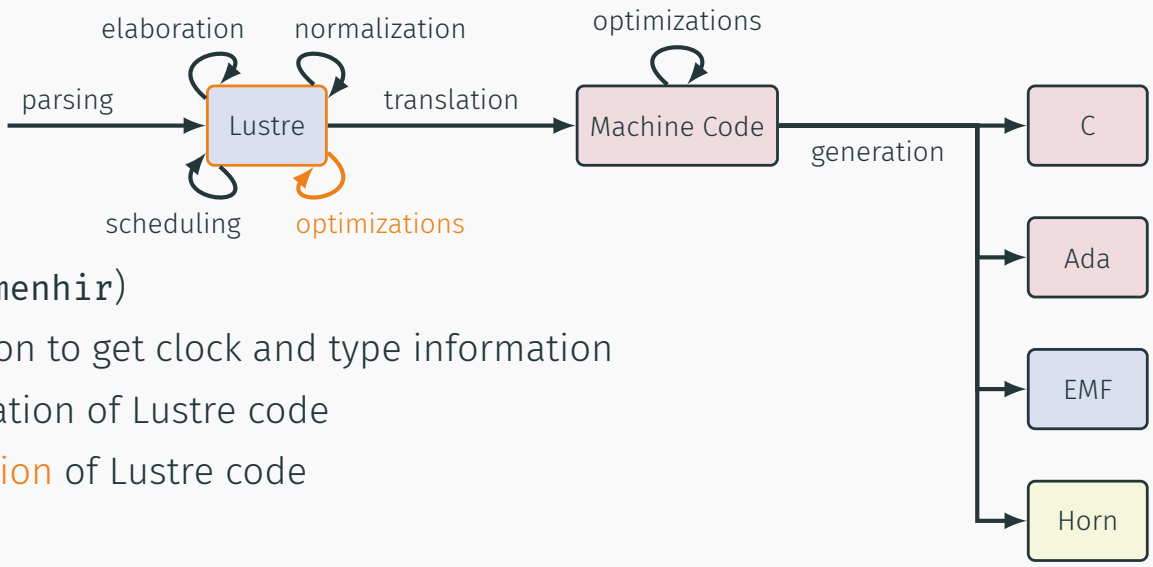

- parsing (`menhir`)
- elaboration to get clock and type information
- normalization of Lustre code
- optimization of Lustre code

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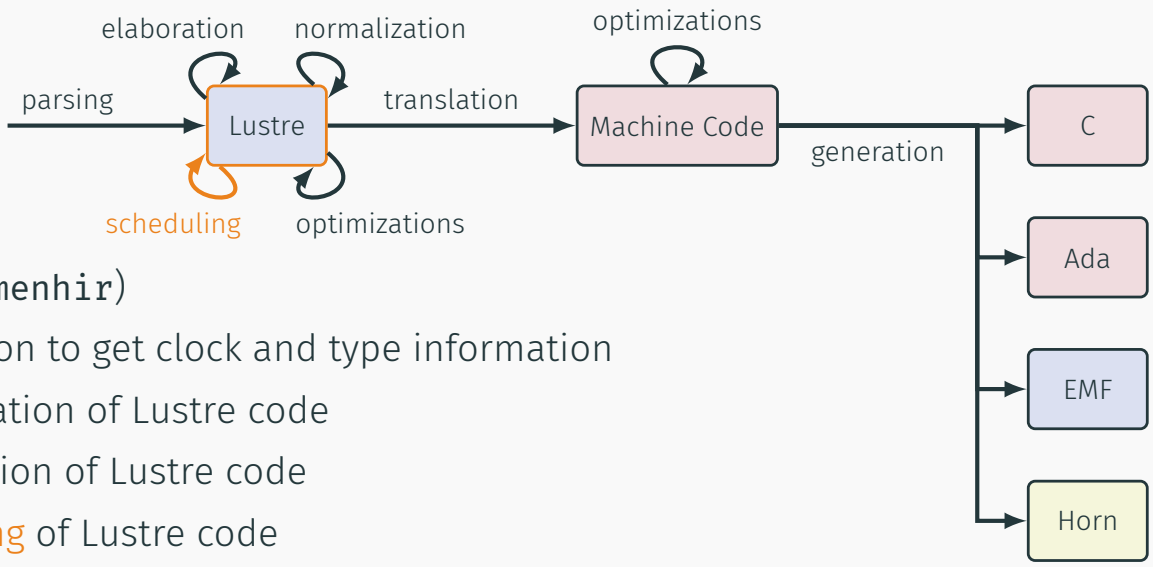

- parsing (`menhir`)
- elaboration to get clock and type information
- normalization of Lustre code
- optimization of Lustre code
- scheduling of Lustre code

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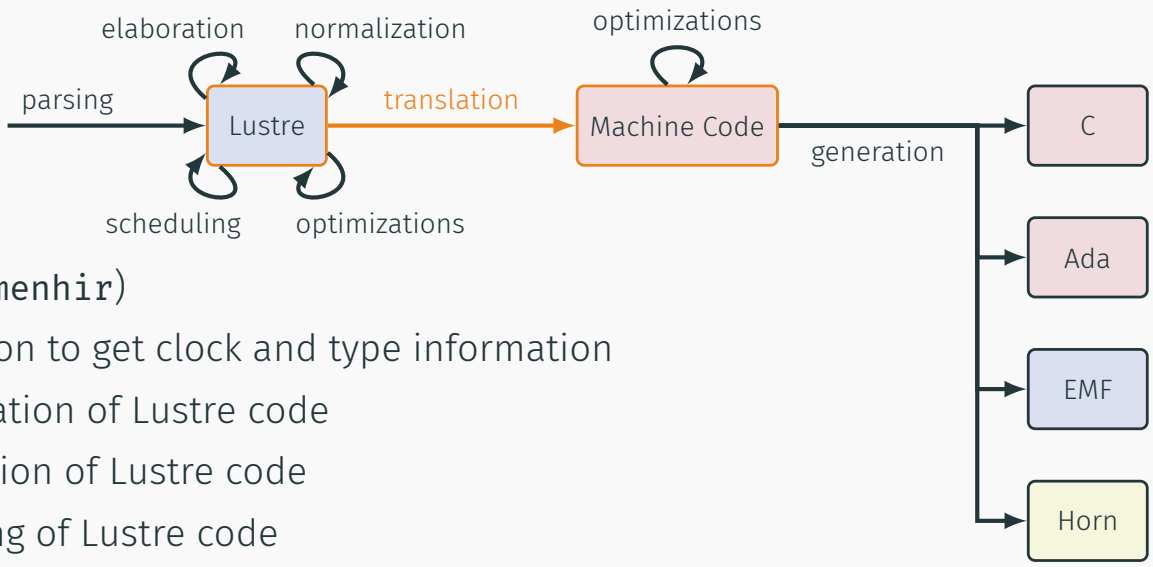

- parsing (`menhir`)
- elaboration to get clock and type information
- normalization of Lustre code
- optimization of Lustre code
- scheduling of Lustre code
- translation to Machine code

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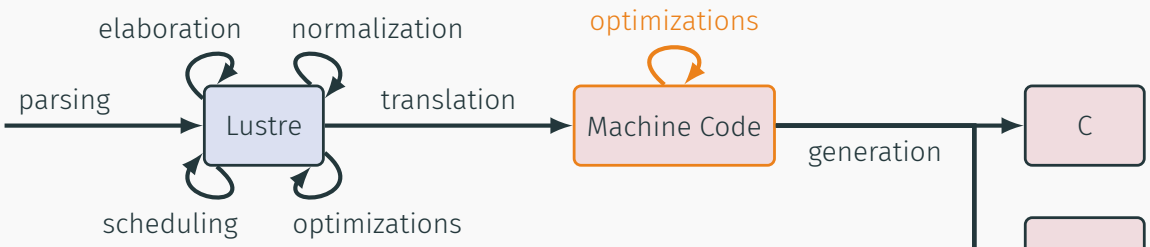

- parsing (`menhir`)
- elaboration to get clock and type information
- normalization of Lustre code
- optimization of Lustre code
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- translation to Machine code
- optimisation of Machine code

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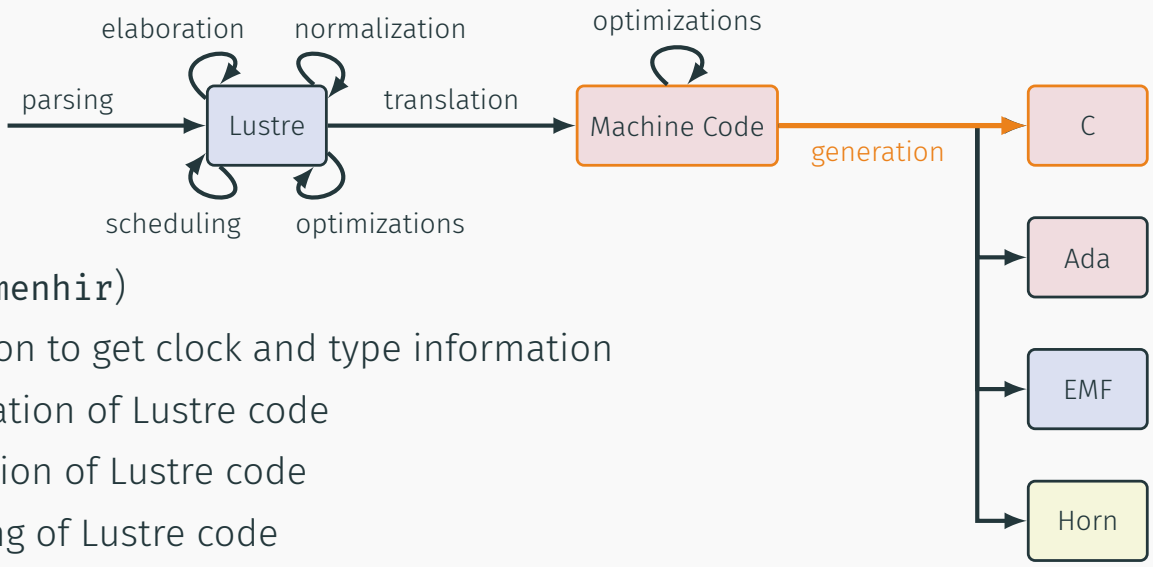

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- elaboration to get clock and type information
- normalization of Lustre code
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- scheduling of Lustre code
- translation to Machine code
- optimisation of Machine code
- generation of C code

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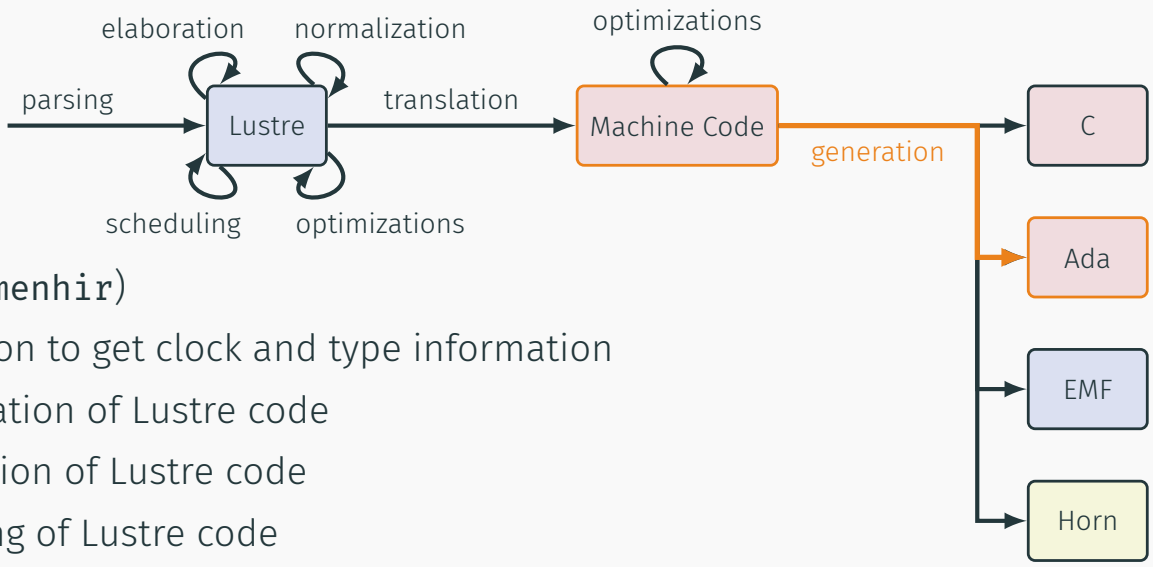

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- optimization of Lustre code
- scheduling of Lustre code
- translation to Machine code
- optimisation of Machine code
- generation of Ada code

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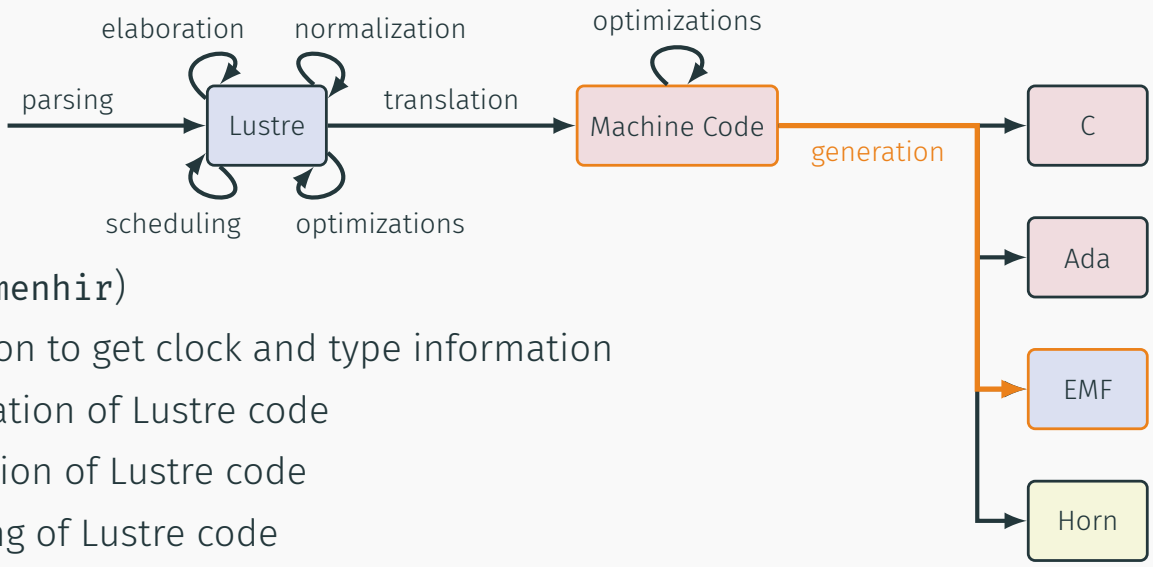

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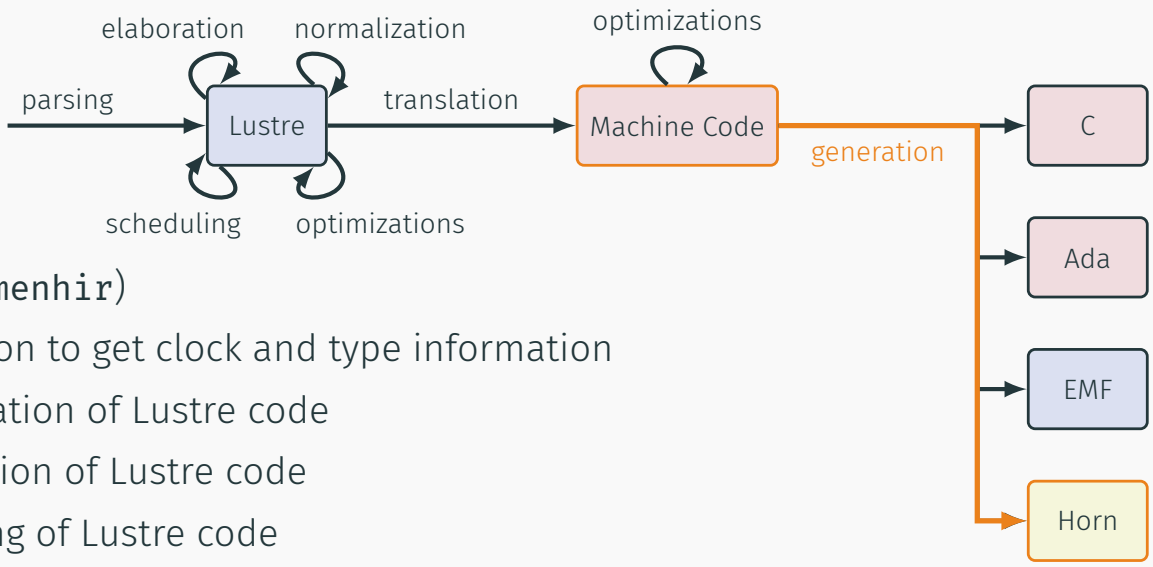
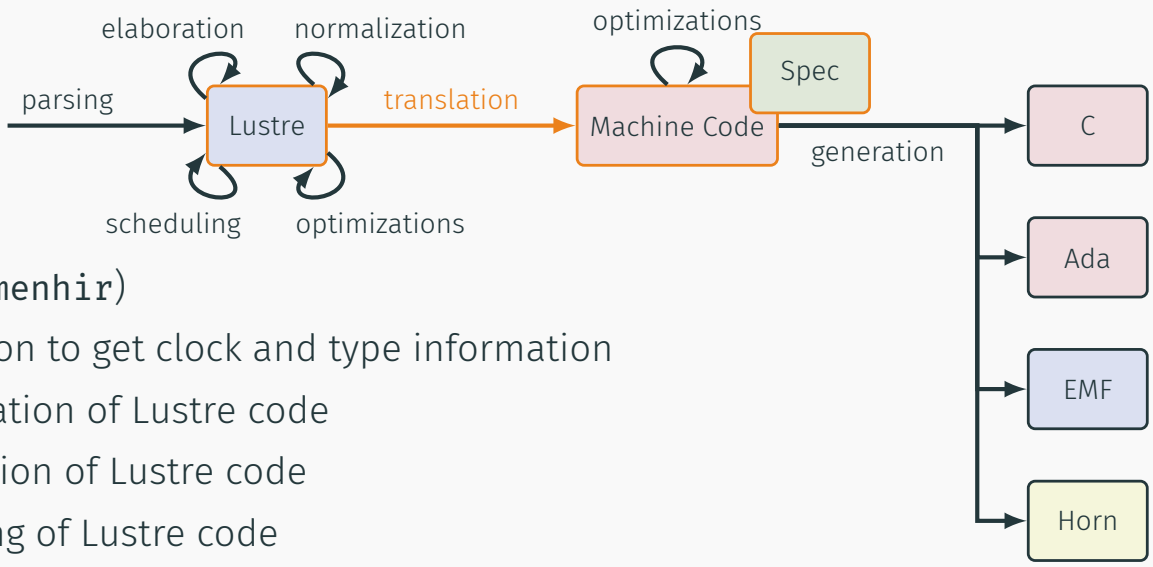
- scheduling of Lustre code
- translation to Machine code
- optimisation of Machine code
- generation of EMF code

LustreC: a Lustre Compiler



- parsing (`menhir`)
- elaboration to get clock and type information
- normalization of Lustre code
- optimization of Lustre code
- scheduling of Lustre code
- translation to Machine code
- optimisation of Machine code
- generation of Horn clauses

LustreC: a Certifying Lustre Compiler



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- scheduling of Lustre code
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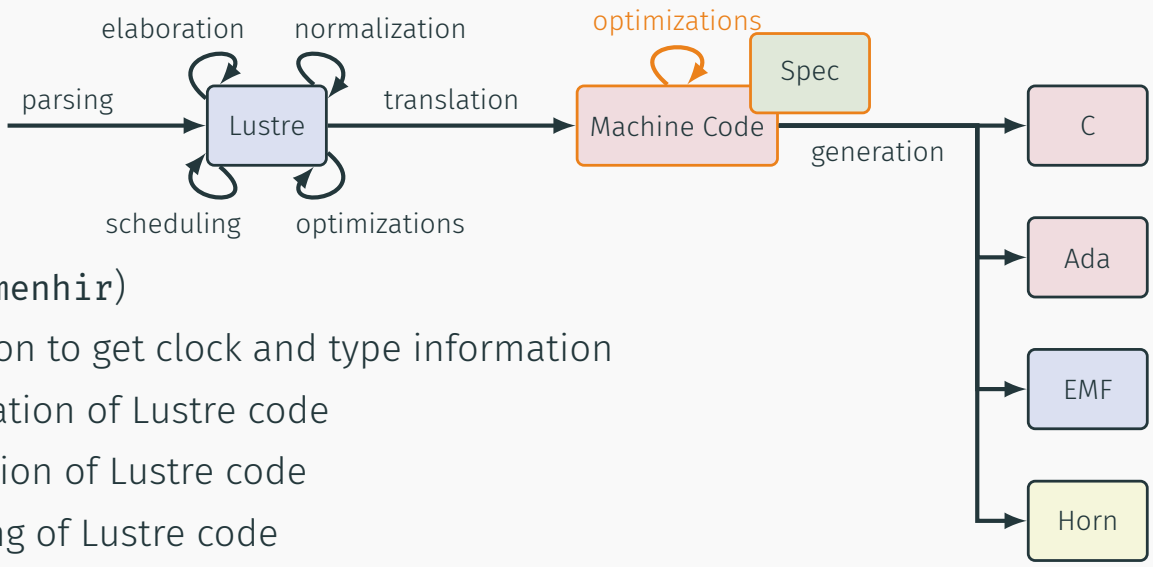

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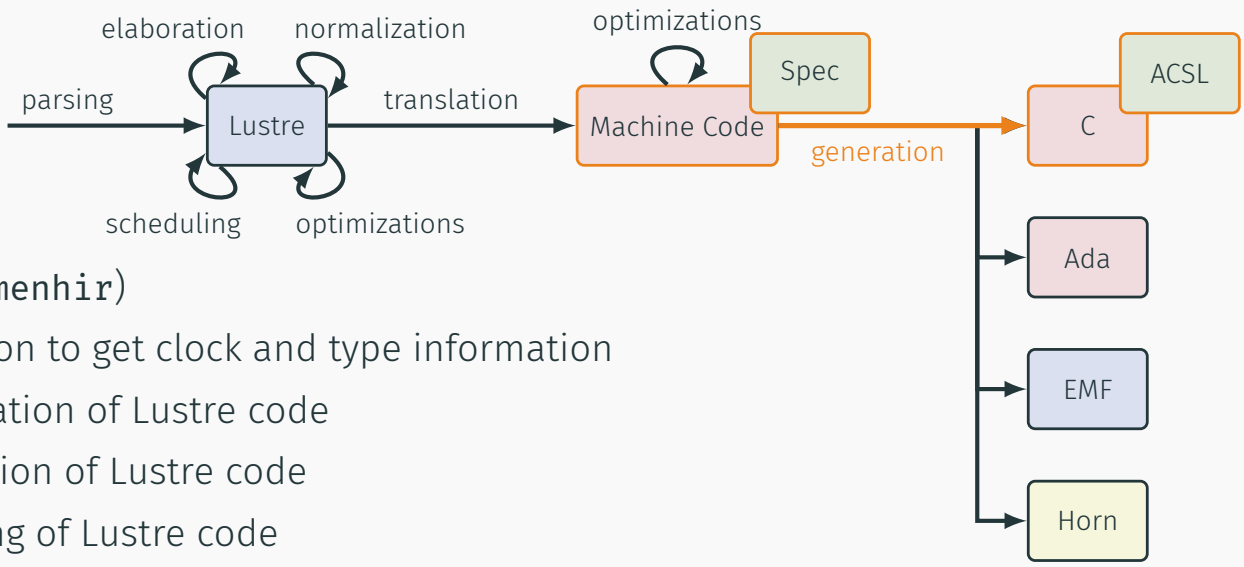

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- optimization of Lustre code
- scheduling of Lustre code
- translation to Machine code
- optimisation of Machine code
- generation of C code + ACSL specification

Lustre

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      tel until s restart INS
    state INS:
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      tel until s resume GPS
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Lustre

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  returns (x: real);
let
  x = x0 fby (x + 0.1 * u);
tel

node ins(gps, xv: real)
  returns (x: real, alarm: bool)
  var pxa, xe: real; k: int;
let
  k = 0 fby (k + 1);
  alarm = (k >= 50);
  xe = euler((gps, xv) when not alarm);
  pxa = (0. fby x) when alarm;
  x = merge alarm pxa xe;
tel

node nav(gps, xv: real, s: bool)
  returns (x: real, alarm: bool)
let
  automaton a
    state GPS:
      let
        x = gps;
        alarm = false;
      tel until s restart INS
    state INS:
      let
        (x, alarm) = ins(gps, xv);
      tel until s resume GPS
tel
```

C

Lustre

```
node euler(x0, u: real)
  returns (x: real);
let
  x = x0 fby (x + 0.1 * u);
tel

node ins(gps, xv: real)
  returns (x: real, alarm: bool)
  var pxa, xe: real; k: int;
let
  k = 0 fby (k + 1);
  alarm = (k >= 50);
  xe = euler((gps, xv) when not alarm);
  pxa = (0. fby x) when alarm;
  x = merge alarm pxa xe;
tel

node nav(gps, xv: real, s: bool)
  returns (x: real, alarm: bool)
let
  automaton a
    state GPS:
      let
        x = gps;
        alarm = false;
      tel until s restart INS
    state INS:
      let
        (x, alarm) = ins(gps, xv);
      tel until s resume GPS
tel
```

C

+ separated code for the main loop

Lustre

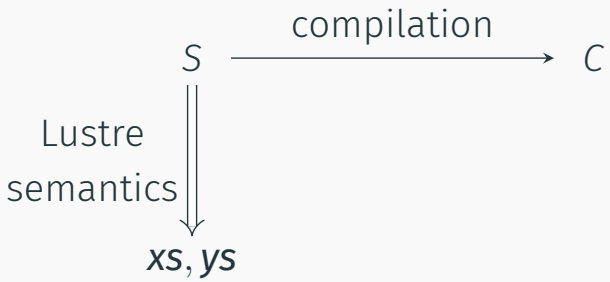
```
node euler(x0, u: real)
  returns (x: real);
let
  x = x0 fby (x + 0.1 * u);
tel

node ins(gps, xv: real)
  returns (x: real, alarm: bool)
  var pxa, xe: real; k: int;
let
  k = 0 fby (k + 1);
  alarm = (k >= 50);
  xe = euler((gps, xv) when not alarm);
  pxa = (0. fby x) when alarm;
  x = merge alarm pxa xe;
tel

node nav(gps, xv: real, s: bool)
  returns (x: real, alarm: bool)
let
  automaton a
    state GPS:
      let
        x = gps;
        alarm = false;
      tel until s restart INS
    state INS:
      let
        (x, alarm) = ins(gps, xv);
      tel until s resume GPS
tel
```

C + ACSL

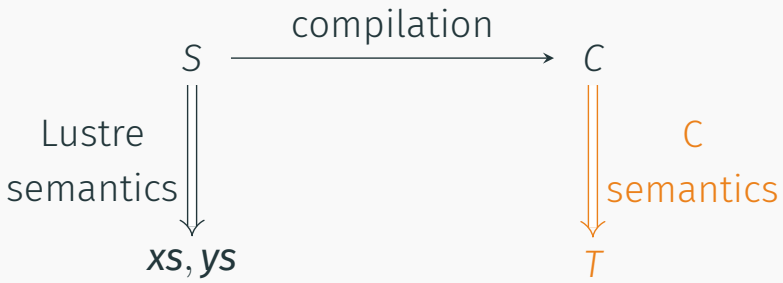
Correctness?

$$S \xrightarrow{\text{compilation}} C$$

Correctness?



Correctness?



Correctness?

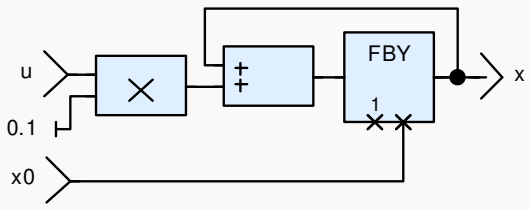
Correctness?

LustreC:

- no easy way to model streams in ACSL
- encoding of a state / transition semantics
- the simulation result is expressed as contracts

The Compilation Scheme

Example




```
node euler(x0, u: real)
  returns (x: real);
let
  x = x0 fby (x + 0.1 * u);
tel
```

Example: Normalization

```
node euler(x0, u: real)
  returns (x: real);
let
  x = x0 fby (x + 0.1 * u);
tel
```

```
node euler (x0: real; u: real)
  returns (x: real)
var euler_2: real; euler_1: bool;
let
  x = if euler_1 then x0 else euler_2;
  euler_2 = pre (x + 0.1 * u);
  euler_1 = true -> false;
tel
```

Example: Scheduling

```
node euler (x0: real; u: real)
  returns (x: real)
var euler_2: real; euler_1: bool;
let
  x = if euler_1 then x0 else euler_2;
  euler_2 = pre (x + 0.1 * u);
  euler_1 = true -> false;
tel
```

```
node euler (x0: real; u: real)
  returns (x: real)
var euler_2: real; euler_1: bool;
let
  euler_1 = true -> false;
  x = if euler_1 then x0 else euler_2;
  euler_2 = pre (x + 0.1 * u);
tel
```

Example: Machine code generation

```
node euler (x0: real; u: real)
  returns (x: real)
var euler_2: real; euler_1: bool;
let
  euler_1 = true -> false;
  x = if euler_1 then x0 else euler_2;
  euler_2 = pre (x + 0.1 * u);
tel
```

```
machine euler {
  mem euler_2: real;
  instance ni_0: arrow<>;

  step(x0, u: real) returns (x: double)
  var euler_1: bool;
  {
    euler_1 := ni_0(true, false);
    if euler_1 {
      x := x0
    } else {
      x := euler_2
    };
    euler_2 := x + 0.1 * u;
  }
}
```

Example: C code generation

```
machine euler {
  mem euler_2: real;
  instance ni_0: arrow<>;

  step(x0, u: real) returns (x: double)
  var euler_1: bool;
  {
    euler_1 := ni_0(true, false);
    if euler_1 {
      x := x0
    } else {
      x := euler_2
    };
    euler_2 := x + 0.1 * u;
  }
}
```

```
struct _arrow_mem {
  struct _arrow_reg {_Bool _first; } _reg;
};

#define _arrow_reset(self) \
  {(self)->_reg._first = 1;}

_Bool _arrow_step(struct _arrow_mem *self) {
  if (self->_reg._first) {
    self->_reg._first = 0;
    return 1;
  }
  return 0;
}
```

Example: C code generation

```
machine euler {
  mem euler_2: real;
  instance ni_0: arrow<>;

  step(x0, u: real) returns (x: double)
  var euler_1: bool;
  {
    euler_1 := ni_0(true, false);
    if euler_1 {
      x := x0
    } else {
      x := euler_2
    };
    euler_2 := x + 0.1 * u;
  }
}
```

```
struct euler_mem {
  _Bool _reset;
  struct euler_reg {double euler_2;} _reg;
  struct _arrow_mem *ni_0;
};
```

Example: C code generation

```
machine euler {
  mem euler_2: real;
  instance ni_0: arrow<>;

  step(x0, u: real) returns (x: double)
  var euler_1: bool;
  {
    euler_1 := ni_0(true, false);
    if euler_1 {
      x := x0
    } else {
      x := euler_2
    };
    euler_2 := x + 0.1 * u;
  }
}
```

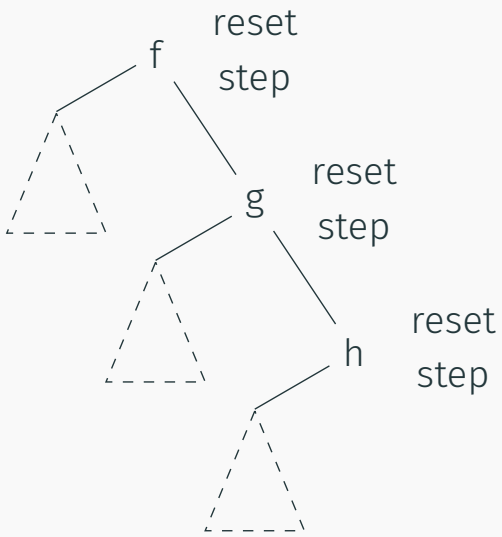
```
void euler_clear_reset
  (struct euler_mem *self)
{
  if (self->_reset) {
    self->_reset = 0;
    _arrow_reset(self->ni_0);
  }
  return;
}

void euler_set_reset
  (struct euler_mem *self)
{
  self->_reset = 1;
  return;
}
```

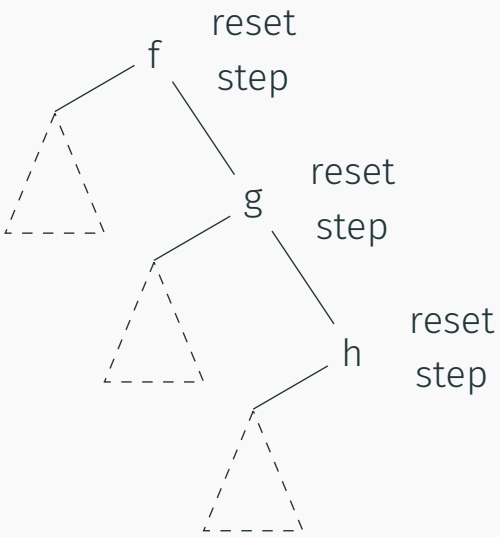
Example: C code generation

```
machine euler {
  mem euler_2: real;
  instance ni_0: arrow<>;

  step(x0, u: real) returns (x: double)
  var euler_1: bool;
  {
    euler_1 := ni_0(true, false);
    if euler_1 {
      x := x0
    } else {
      x := euler_2
    };
    euler_2 := x + 0.1 * u;
  }
}
```

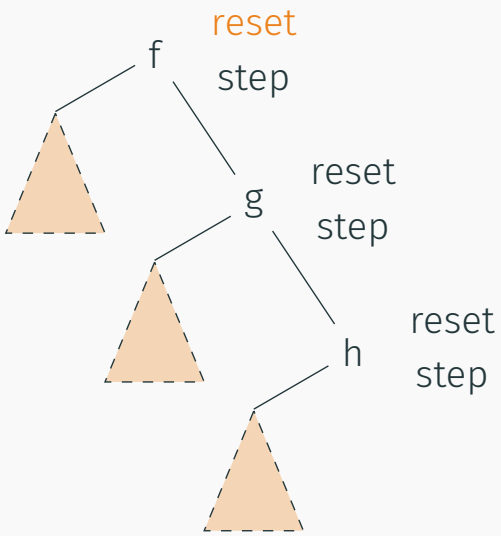
```
void euler_step(double x0, double u,
                double *x,
                struct euler_mem *self) {
  _Bool euler_1;
  euler_clear_reset(self);
  Reset:
  euler_1 = _arrow_step(self->ni_0);
  if (euler_1) {
    *x = x0;
  } else {
    *x = self->_reg.euler_2;
  }
  self->_reg.euler_2 = *x + 0.1 * u;
  return;
}
```

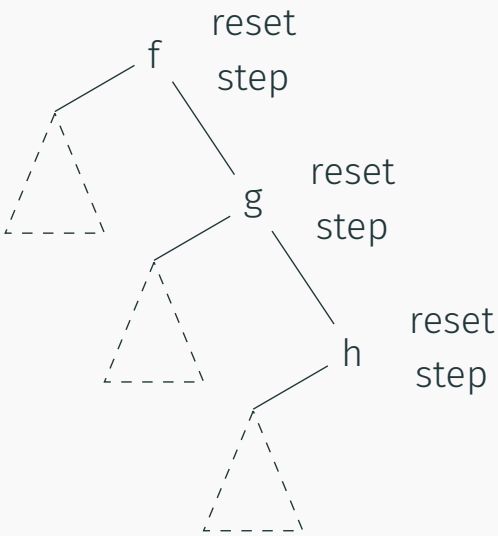
SCADE-like reset compilation scheme



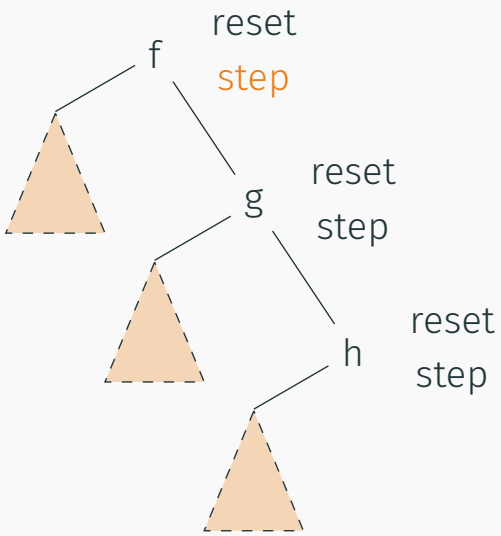


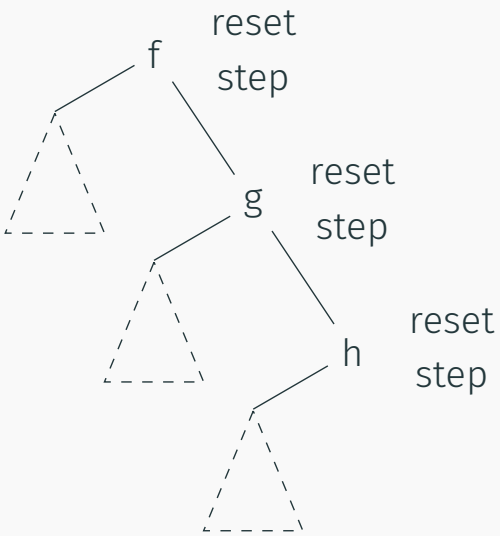
SCADE-like reset compilation scheme



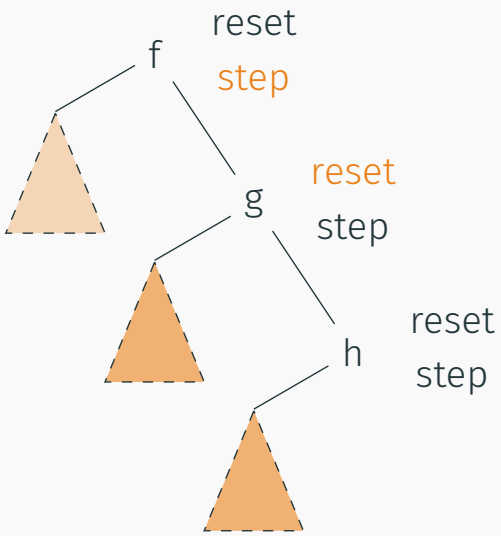


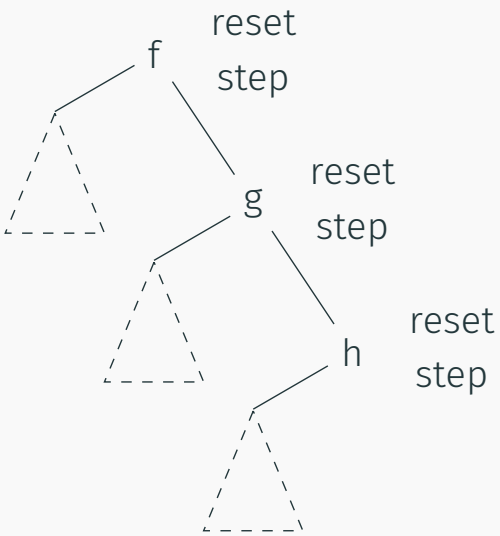
SCADE-like reset compilation scheme



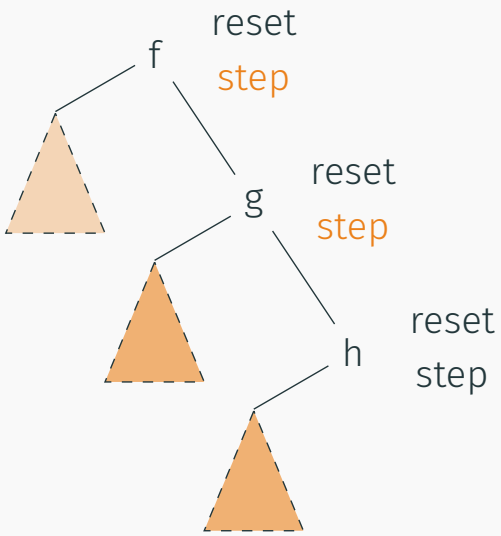


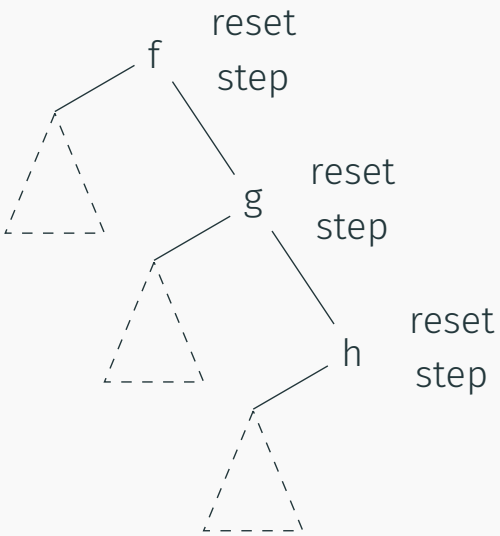
SCADE-like reset compilation scheme



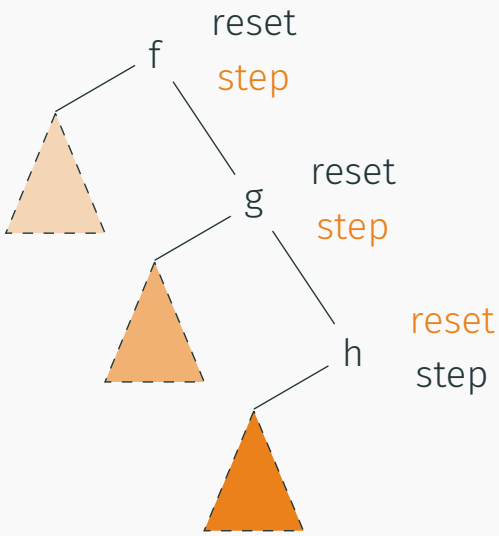


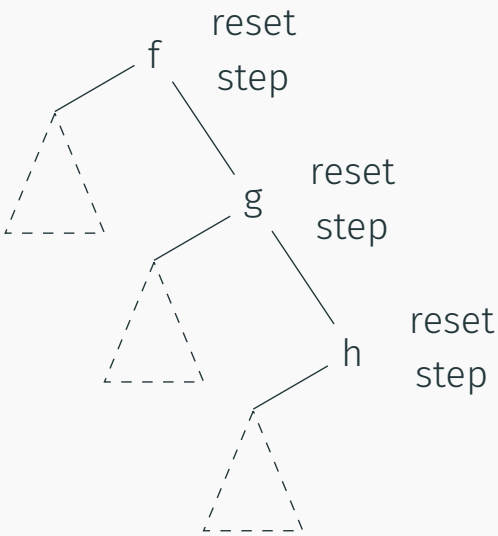
SCADE-like reset compilation scheme



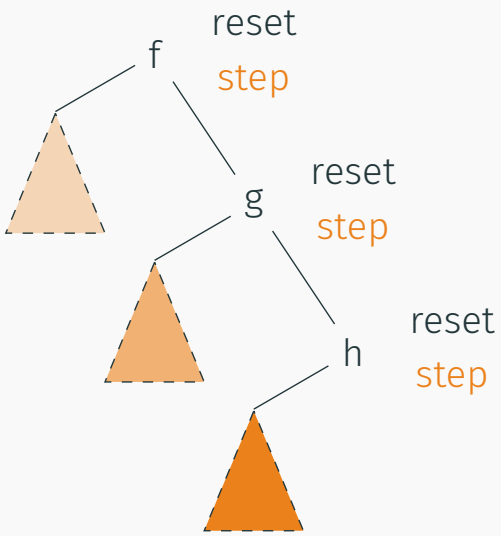


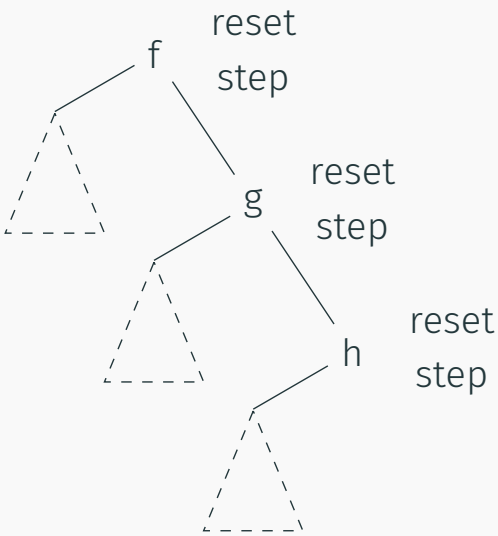
SCADE-like reset compilation scheme



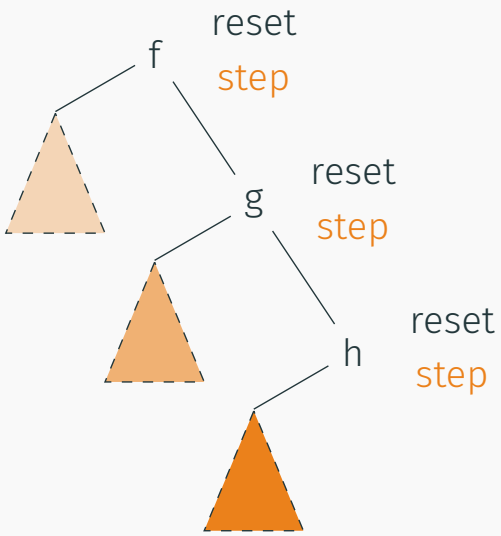


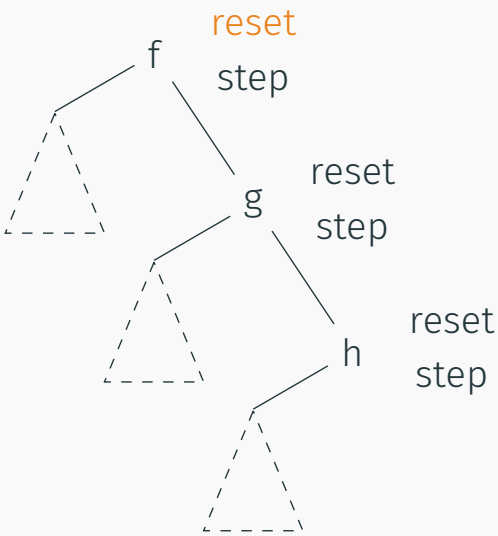
SCADE-like reset compilation scheme



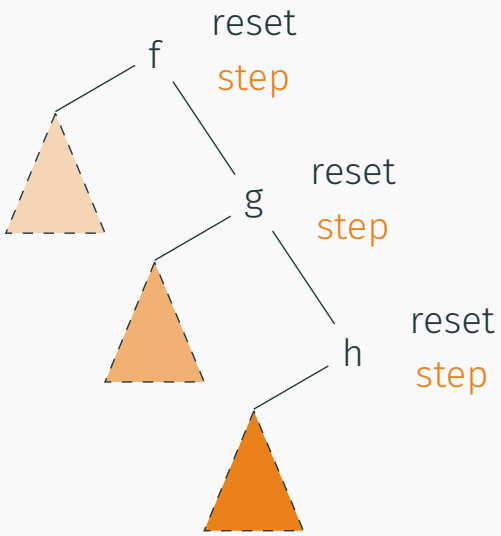


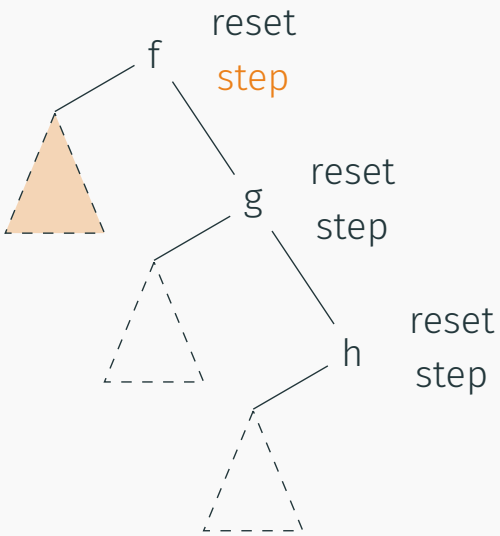
SCADE-like reset compilation scheme



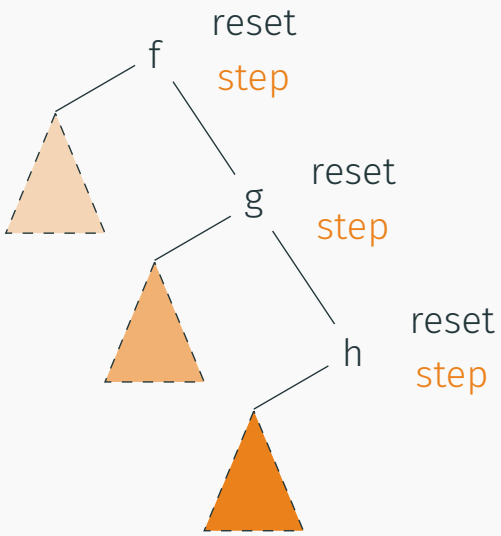


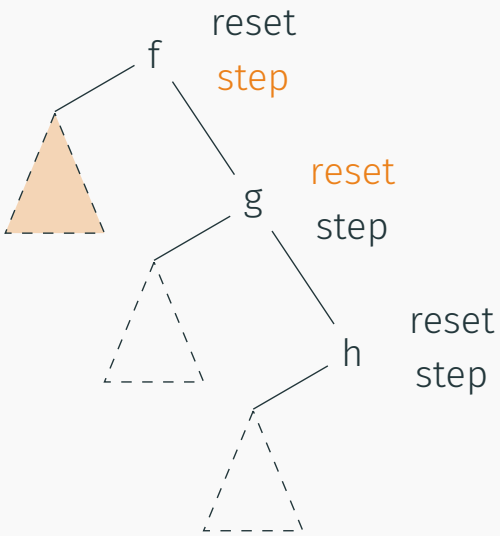
SCADE-like reset compilation scheme



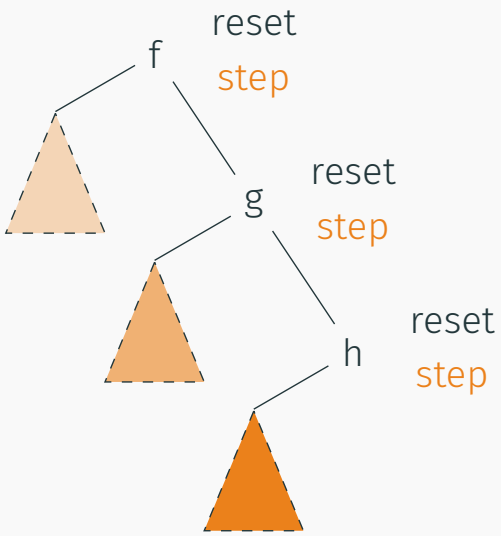


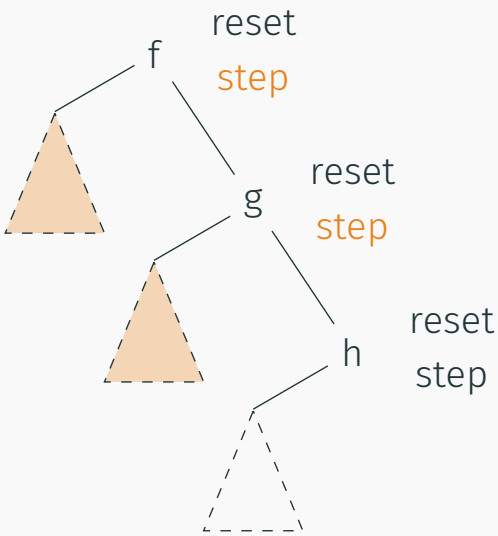
SCADE-like reset compilation scheme



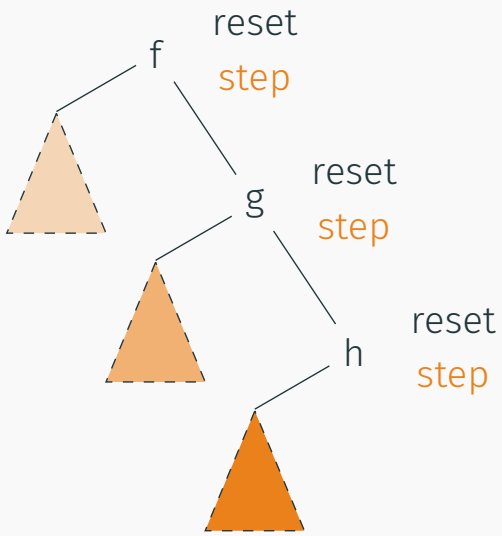


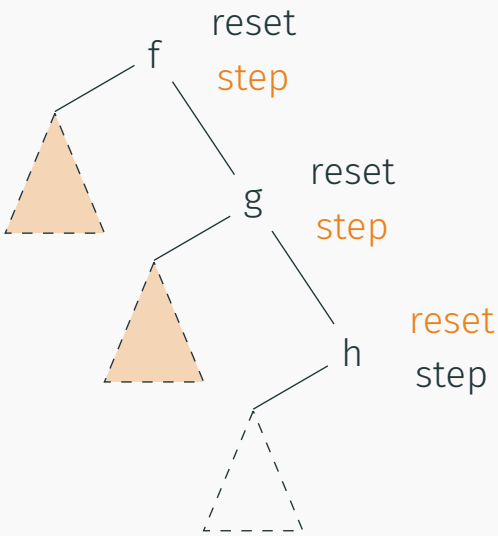
SCADE-like reset compilation scheme



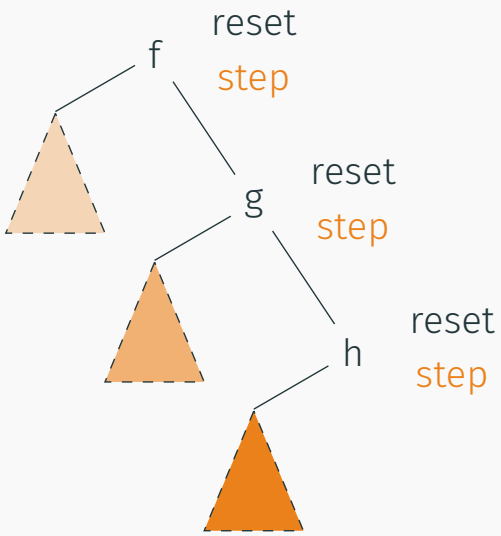


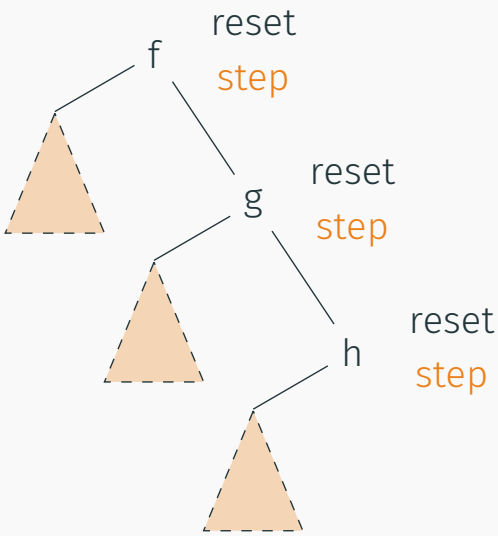
SCADE-like reset compilation scheme





SCADE-like reset compilation scheme





Encoding of the Semantics

State / Transition Semantics

```
node euler (x0: real; u: real)
  returns (x: real)
var euler_2: real; euler_1: bool;
let
  euler_1 = true -> false;
  x = if euler_1 then x0 else euler_2;
  euler_2 = pre (x + 0.1 * u);
tel
```

$$euler\_init(S) = arrow\_init(S[ni_0])$$

$$euler\_reset(S, S') = S(\_reset) \rightarrow S'(\_reset) = false \wedge euler\_init(S') \wedge \neg S(\_reset) \rightarrow S' = S$$

State / Transition Semantics

```
node euler (x0: real; u: real)
  returns (x: real)
var euler_2: real; euler_1: bool;
let
  euler_1 = true -> false;
  x = if euler_1 then x0 else euler_2;
  euler_2 = pre (x + 0.1 * u);
tel
```

$$
\begin{aligned}
&euler\_tr\left(S, x_0, u, x, S'\right) = \\
&\quad \exists S_r, \\
&\qquad euler\_reset\left(S, S_r\right) \\
&\qquad \wedge S'(\_reset) = S_r(\_reset) \\
&\qquad \wedge \exists euler_1, \\
&\qquad\qquad arrow\_tr\left(S_r[ni_0], euler_1, S'[ni_0]\right) \\
&\qquad\qquad \wedge euler_1 \rightarrow x = x_0 \\
&\qquad\qquad \wedge \neg euler_1 \rightarrow x = S_r(euler_2) \\
&\qquad\qquad \wedge S'(euler_2) = x + 0.1 \times u
\end{aligned}
$$

Machine code specification generation

- Internal AST for an ad-hoc first order logic
- Generation from each Lustre equation
- Optimizations

ACSL GENERATION: MEMORY CORRESPONDENCE

Notion of state in ACSL: same C structures, *flattened*

```
struct _arrow_mem {
  struct _arrow_reg {_Bool _first; } _reg;
};

struct euler_mem {
  _Bool _reset;
  struct euler_reg {double euler_2;} _reg;
  struct _arrow_mem *ni_0;
};
```

```
/*@ ghost struct _arrow_mem_ghost {
              struct _arrow_reg _reg;
    };
*/

/*@ ghost struct euler_mem_ghost {
              _Bool _reset;
              struct euler_reg _reg;
              struct _arrow_mem_ghost ni_0;
    };
*/
```

ACSL generation: memory correspondence

```
/*@ predicate euler_pack0(struct euler_mem_ghost mem, struct euler_mem *self) =
      mem._reset == self->_reset
      && mem._reset == 0;
*/
/*@ predicate euler_pack1(struct euler_mem_ghost mem, struct euler_mem *self) =
      euler_pack0(mem, self)
      && _arrow_pack(mem.ni_0, self->ni_0);
*/
/*@ predicate euler_pack2(struct euler_mem_ghost mem, struct euler_mem *self) =
      euler_pack1(mem, self);
*/
/*@ predicate euler_pack3(struct euler_mem_ghost mem, struct euler_mem *self) =
      euler_pack2(mem, self)
      && !_arrow_initialization(mem.ni_0) ==> mem._reg.euler_2 == self->_reg.euler_2;
*/
/*@ predicate euler_pack(struct euler_mem_ghost mem, struct euler_mem *self) =
      (mem._reset ? mem._reset == self->_reset : euler_pack3(mem, self));
*/
```

ACSL generation: transition relation

$$euler\_init\,(S) =$$
$$\quad arrow\_init\,(S[ni_0])$$

$$euler\_reset\,(S, S') =$$
$$\quad S(\_reset) \rightarrow S'(\_reset) = false$$
$$\qquad\qquad \wedge\, euler\_init(S')$$
$$\quad \wedge\, \neg S(\_reset) \rightarrow S' = S$$

```
/*@ predicate euler_init(struct euler_mem_ghost mem_in) =
      _arrow_init(mem_in.ni_0);
*/

/*@ predicate euler_reset(struct euler_mem_ghost mem_in,
                          struct euler_mem_ghost mem_out) =
      mem_in._reset ? mem_out._reset == 0
                      && euler_init(mem_out)
                    : mem_out == mem_in;
*/
```

ACSL generation: transition relation

$$
\begin{aligned}
&\mathit{euler\_tr}\,(S, x_0, u, x, S') = \\
&\quad \exists S_r, \\
&\qquad \mathit{euler\_reset}\,(S, S_r) \\
&\qquad \wedge\, S'(\_reset) = S_r(\_reset) \\
&\qquad \wedge\, \exists \mathit{euler}_1, \\
&\qquad\quad \wedge\, \mathit{arrow\_tr}\,(S_r[ni_0], \mathit{euler}_1, S'[ni_0]) \\
&\qquad\quad \wedge\, \mathit{euler}_1 \rightarrow x = x_0 \\
&\qquad\quad \wedge\, \neg \mathit{euler}_1 \rightarrow x = S_r(\mathit{euler}_2) \\
&\qquad\quad \wedge\, S'(\mathit{euler}_2) = x + 0.1 \times u
\end{aligned}
$$

```
/*@ predicate euler_tr(struct euler_mem_ghost mem_in,
                       double x0, double u, double x,
                       struct euler_mem_ghost mem_out) =
      \exists struct euler_mem_ghost mem_reset;
        euler_reset(mem_in, mem_reset)
        && euler_tr3(mem_reset, x0, u, x, mem_out);
*/
```

ACSL generation: transition relation

$$
\begin{aligned}
&\mathit{euler\_tr}\left(S, x_0, u, x, S'\right) = \\
&\quad \exists S_r, \\
&\qquad \mathit{euler\_reset}\left(S, S_r\right) \\
&\qquad \wedge\, S'(\mathit{\_reset}) = S_r(\mathit{\_reset}) \\
&\qquad \wedge\, \exists \mathit{euler}_1, \\
&\qquad\quad \wedge\, \mathit{arrow\_tr}\left(S_r[ni_0], \mathit{euler}_1, S'[ni_0]\right) \\
&\qquad\quad \wedge\, \mathit{euler}_1 \rightarrow x = x_0 \\
&\qquad\quad \wedge\, \neg \mathit{euler}_1 \rightarrow x = S_r(\mathit{euler}_2) \\
&\qquad\quad \wedge\, S'(\mathit{euler}_2) = x + 0.1 \times u
\end{aligned}
$$

```
/*@ predicate euler_tr3(struct euler_mem_ghost mem_in,
                        double x0, double u, double x,
                        struct euler_mem_ghost mem_out) =
      euler_tr2(mem_in, x0, u, x, mem_out)
      && mem_out._reg.euler_2 == x + 0.1 * u;
*/
```

ACSL generation: transition relation

$$
\begin{aligned}
&\mathit{euler\_tr}\left(S, x_0, u, x, S'\right) = \\
&\quad \exists S_r, \\
&\qquad \mathit{euler\_reset}\left(S, S_r\right) \\
&\qquad \wedge S'(\mathit{\_reset}) = S_r(\mathit{\_reset}) \\
&\qquad \wedge \exists \mathit{euler}_1, \\
&\qquad\quad \wedge \mathit{arrow\_tr}\left(S_r[\mathit{ni}_0], \mathit{euler}_1, S'[\mathit{ni}_0]\right) \\
&\qquad\quad \wedge \mathit{euler}_1 \rightarrow x = x_0 \\
&\qquad\quad \wedge \neg \mathit{euler}_1 \rightarrow x = S_r(\mathit{euler}_2) \\
&\qquad\quad \wedge S'(\mathit{euler}_2) = x + 0.1 \times u
\end{aligned}
$$

```
/*@ predicate euler_tr2(struct euler_mem_ghost mem_in,
                        double x0, double u, double x,
                        struct euler_mem_ghost mem_out) =
    \exists _Bool euler_1;
        euler_tr1(mem_in, x0, u, euler_1, mem_out)
        && euler_1 ? x == x0
                   : !_arrow_init(mem_in.ni_0) ==>
                     x == mem_in._reg.euler_2;
*/
```

ACSL generation: transition relation

$$
\begin{aligned}
&euler\_tr\,(S, x_0, u, x, S') = \\
&\quad \exists S_r, \\
&\qquad euler\_reset\,(S, S_r) \\
&\qquad \wedge\, S'(\_reset) = S_r(\_reset) \\
&\qquad \wedge\, \exists euler_1, \\
&\qquad\quad \wedge\, arrow\_tr\,(S_r[ni_0], euler_1, S'[ni_0]) \\
&\qquad\quad \wedge\, euler_1 \rightarrow x = x_0 \\
&\qquad\quad \wedge\, \neg euler_1 \rightarrow x = S_r(euler_2) \\
&\qquad\quad \wedge\, S'(euler_2) = x + 0.1 \times u
\end{aligned}
$$

```
/*@ predicate euler_tr1(struct euler_mem_ghost mem_in,
                         double x0, double u, _Bool euler_1,
                         struct euler_mem_ghost mem_out) =
      euler_tr0(mem_in, x0, u, mem_out)
      && _arrow_tr(mem_in.ni_0, euler_1, mem_out.ni_0);
*/
```

ACSL GENERATION: TRANSITION RELATION

$$
\begin{aligned}
&\mathit{euler\_tr}\,(S, x_0, u, x, S') = \\
&\quad \exists S_r, \\
&\qquad \mathit{euler\_reset}\,(S, S_r) \\
&\qquad \wedge\, S'(\mathit{\_reset}) = S_r(\mathit{\_reset}) \\
&\qquad \wedge\, \exists \mathit{euler}_1, \\
&\qquad\quad \wedge\, \mathit{arrow\_tr}\,(S_r[ni_0], \mathit{euler}_1, S'[ni_0]) \\
&\qquad\quad \wedge\, \mathit{euler}_1 \rightarrow x = x_0 \\
&\qquad\quad \wedge\, \neg \mathit{euler}_1 \rightarrow x = S_r(\mathit{euler}_2) \\
&\qquad\quad \wedge\, S'(\mathit{euler}_2) = x + 0.1 \times u
\end{aligned}
$$

```
/*@ predicate euler_tr0(struct euler_mem_ghost mem_in,
                         double x0, double u,
                         struct euler_mem_ghost mem_out) =
      mem_out._reset == mem_in._reset; */
```

ACSL generation: contracts and assertions

```
/*@ requires euler_valid(self);
    requires \separated(self, mem,
                        self->ni_0);
    requires euler_pack(*mem, self);
    ensures euler_pack3(*mem, self);
    assigns self->_reset, self->ni_0->_reg,
      mem->_reset, mem->ni_0._reg;
    behavior reset:
      assumes mem->_reset == 1;
      ensures euler_init(*mem);
    behavior no_reset:
      assumes mem->_reset == 0;
      ensures *mem == \old(*mem);
    complete behaviors;
    disjoint behaviors;
*/
```

```
void euler_clear_reset
  (struct euler_mem *self)
/*@ ghost
  (struct euler_mem_ghost \ghost *mem) */
{
  if (self->_reset) {
    self->_reset = 0;
    //@ ghost mem->_reset = 0;
    _arrow_reset(self->ni_0);
    //@ ghost _arrow_reset_ghost(mem->ni_0);
  }
  return;
}
```

ACSL generation: contracts and assertions

```
/*@ ensures euler_pack(*mem, self);
    ensures mem->_reset == 1;
    assigns self->_reset, mem->_reset;
*/
void euler_set_reset(struct euler_mem *self)
/*@ ghost (struct euler_mem_ghost \ghost *mem) */ {
  self->_reset = 1;
  //@ ghost mem->_reset = 1;
  return;
}
```

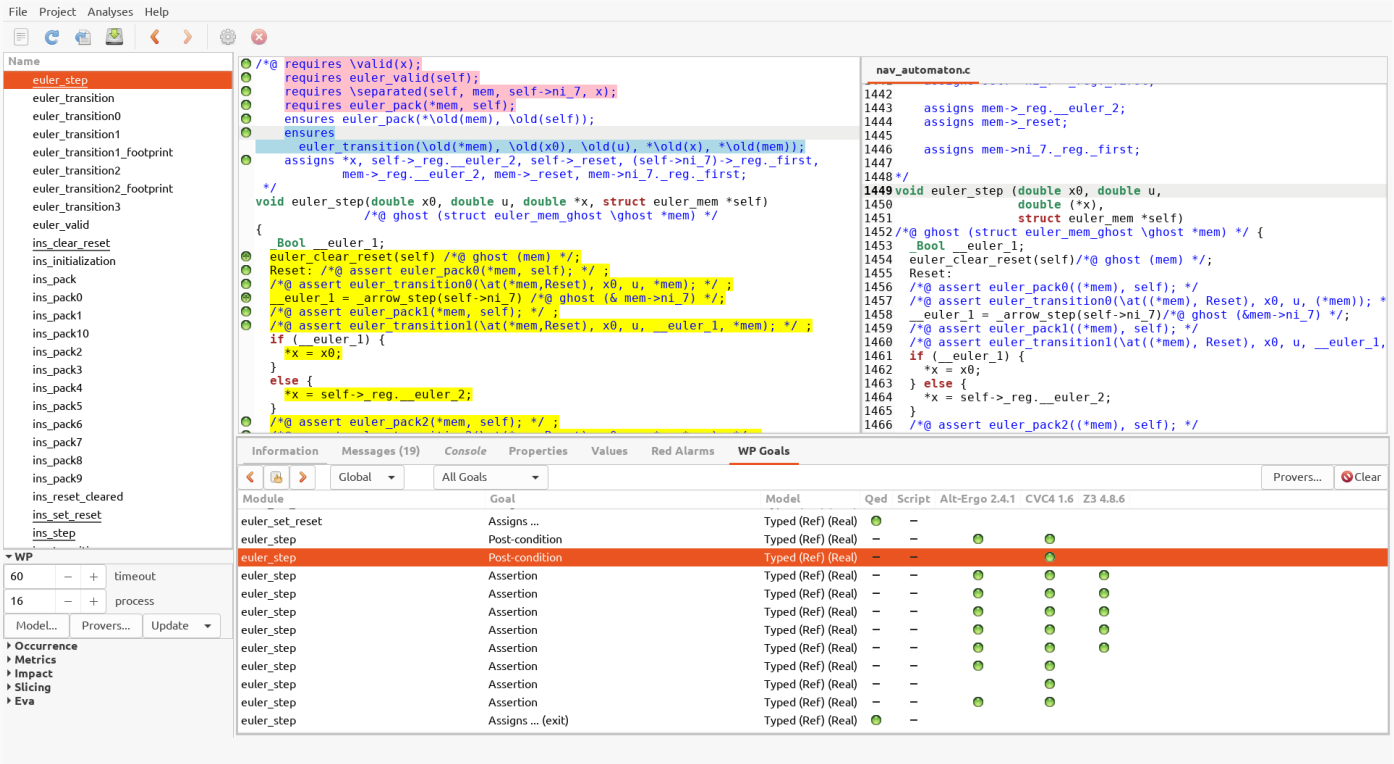
ACSL generation: contracts and assertions

```
/*@ requires \valid(x);
    requires euler_valid(self);
    requires \separated(self, mem, self->ni_0, x);
    requires euler_pack(*mem, self);
    ensures euler_pack(*mem, self);
    ensures euler_tr(\old(*mem), x0, u, *x, *mem);
    assigns *x, self->_reg, self->_reset, self->ni_0->_reg,
      mem->_reg, mem->_reset, mem->ni_0._reg;
*/
```

ACSL GENERATION: CONTRACTS AND ASSERTIONS

```
void euler_step(double x0, double u,
                double *x,
                struct euler_mem *self)
/*@ ghost
  (struct euler_mem_ghost \ghost *mem) */
{
  _Bool euler_1;
  euler_clear_reset(self)/*@ ghost (mem) */;
  Reset:
  //@ assert euler_pack0(*mem, self);
  /*@ assert euler_tr0
        (\at(*mem, Reset), x0, u, *mem); */
  euler_1 = _arrow_step(self->ni_0)
             /*@ ghost (&mem->ni_0) */;
  //@ assert euler_pack1(*mem, self);
  /*@ assert euler_tr1
        (\at(*mem, Reset),
         x0, u, euler_1, *mem); */
  if (euler_1) {
    *x = x0;
  } else {
    *x = self->_reg.euler_2;
  }
  //@ assert euler_pack2((*mem), self);
  /*@ assert euler_tr2
        (\at(*mem, Reset), x0, u, *x, *mem); */
  self->_reg.euler_2 = *x + 0.1 * u;
  //@ ghost mem->_reg.euler_2 = *x + 0.1 * u;
  //@ assert euler_pack3(*mem, self);
  /*@ assert euler_tr3
        (\at(*mem, Reset), x0, u, *x, *mem); */
  return;
}
```

FRAMA-C


File Project Analyses Help
Name
euler_step
euler_transition
euler_transition0
euler_transition1
euler_transition1_footprint
euler_transition2
euler_transition2_footprint
euler_transition3
euler_valid
ins_clear_reset
ins_initialization
ins_pack
ins_pack0
ins_pack1
ins_pack10
ins_pack2
ins_pack3
ins_pack4
ins_pack5
ins_pack6
ins_pack7
ins_pack8
ins_pack9
ins_reset_cleared
ins_set_reset
ins_step
WP
60 timeout
16 process
Model... Provers... Update
Occurrence
Metrics
Impact
Slicing
Eva
/*@ requires \valid(x);
requires euler_valid(self);
requires \separated(self, mem, self->ni_7, x);
requires euler_pack(*mem, self);
ensures euler_pack(*\old(mem), \old(self));
ensures
euler_transition(\old(*mem), \old(x0), \old(u), *\old(x), *\old(mem));
assigns *x, self->_reg.__euler_2, self->_reset, (self->ni_7)->_reg._first,
mem->_reg.__euler_2, mem->_reset, mem->ni_7._reg._first;
*/
void euler_step(double x0, double u, double *x, struct euler_mem *self)
/*@ ghost (struct euler_mem_ghost \ghost *mem) */
{
_Bool __euler_1;
euler_clear_reset(self) /*@ ghost (mem) */;
Reset: /*@ assert euler_pack0(*mem, self); */ ;
/*@ assert euler_transition0(\at(*mem,Reset), x0, u, *mem); */ ;
__euler_1 = _arrow_step(self->ni_7) /*@ ghost (& mem->ni_7) */;
/*@ assert euler_pack1(*mem, self); */ ;
/*@ assert euler_transition1(\at(*mem,Reset), x0, u, __euler_1, *mem); */ ;
if (__euler_1) {
*x = x0;
}
else {
*x = self->_reg.__euler_2;
}
/*@ assert euler_pack2(*mem, self); */ ;
nav_automaton.c
1442
1443 assigns mem->_reg.__euler_2;
1444 assigns mem->_reset;
1445
1446 assigns mem->ni_7._reg._first;
1447
1448 */
1449 void euler_step (double x0, double u,
1450 double (*x),
1451 struct euler_mem *self)
1452 /*@ ghost (struct euler_mem_ghost \ghost *mem) */ {
1453 _Bool __euler_1;
1454 euler_clear_reset(self)/*@ ghost (mem) */;
1455 Reset:
1456 /*@ assert euler_pack0((*mem), self); */
1457 /*@ assert euler_transition0(\at((*mem), Reset), x0, u, (*mem)); *
1458 __euler_1 = _arrow_step(self->ni_7)/*@ ghost (&mem->ni_7) */;
1459 /*@ assert euler_pack1((*mem), self); */
1460 /*@ assert euler_transition1(\at((*mem), Reset), x0, u, __euler_1,
1461 if (__euler_1) {
1462 *x = x0;
1463 } else {
1464 *x = self->_reg.__euler_2;
1465 }
1466 /*@ assert euler_pack2((*mem), self); */
Information Messages (19) Console Properties Values Red Alarms WP Goals
Global All Goals Provers... Clear
Module Goal Model Qed Script Alt-Ergo 2.4.1 CVC4 1.6 Z3 4.8.6
euler_set_reset Assigns ... Typed (Ref) (Real) – –
euler_step Post-condition Typed (Ref) (Real) – –
euler_step Post-condition Typed (Ref) (Real) – –
euler_step Assertion Typed (Ref) (Real) – –
euler_step Assertion Typed (Ref) (Real) – –
euler_step Assertion Typed (Ref) (Real) – –
euler_step Assertion Typed (Ref) (Real) – –
euler_step Assertion Typed (Ref) (Real) – –
euler_step Assertion Typed (Ref) (Real) – –
euler_step Assertion Typed (Ref) (Real) – –
euler_step Assertion Typed (Ref) (Real) – –
euler_step Assertion Typed (Ref) (Real) – –
euler_step Assigns ... (exit) Typed (Ref) (Real) – –

Contract Translation

Principles

High-level specification

- contracts expressed at dataflow level
- verified by model checking techniques (eg. Kind2)

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High-level specification

- contracts expressed at dataflow level
- verified by model checking techniques (eg. Kind2)

Logical meaning

- synchronous observers
- $\square\left(\mathcal{H}\left(Pre(S,x)\right) \wedge tr(S,x,y,S') \rightarrow Post(S,x,y,S')\right)$

Principles

High-level specification

- contracts expressed at dataflow level
- verified by model checking techniques (eg. Kind2)

Logical meaning

- synchronous observers
- $\square\left(\mathcal{H}\left(Pre(S,x)\right) \wedge tr(S,x,y,S') \rightarrow Post(S,x,y,S')\right)$

Code-level specification

- encoding as specific transition predicates and contracts in ACSL
- focus: k-induction

Example

```
node greycounter (x:bool) returns (out:bool);
var a,b:bool;
let
  a = false -> not pre(b);
  b = false -> pre(a);
  out = a and b;
tel

node intloopcounter (x:bool) returns (out:bool);
var time: int;
let
  time = 0 -> if pre(time) = 3 then 0
              else pre time + 1;
  out = (time = 2);
tel

node top (x:bool) returns (OK:bool);
--@ guarantee OK;
var b,d:bool;
let
  b = greycounter(x);
  d = intloopcounter(x);
  OK = b = d;
  --%PROPERTY OK;
tel
```

a	*F*	*T*	*T*	*F*	*F*	···
b	*F*	*F*	*T*	*T*	*F*	···
out	*F*	*F*	*T*	*F*	*F*	···
time	0	1	2	3	0	···
out	*F*	*F*	*T*	*F*	*F*	···
OK	*T*	*T*	*T*	*T*	*T*	···

Example: Model-checking

```
node greycounter (x:bool) returns (out:bool);
var a,b:bool;
let
  a = false -> not pre(b);
  b = false -> pre(a);
  out = a and b;
tel

node intloopcounter (x:bool) returns (out:bool);
var time: int;
let
  time = 0 -> if pre(time) = 3 then 0
              else pre time + 1;
  out = (time = 2);
tel

node top (x:bool) returns (OK:bool);
--@ guarantee OK;
var b,d:bool;
let
  b = greycounter(x);
  d = intloopcounter(x);
  OK = b = d;
  --%PROPERTY OK;
tel
```

```
> kind2 --enable BMC --enable IND two_counters.lus
 kind2 v1.5.0

==========================================================================
Analyzing top
  with First top: 'top'
              subsystems
                | concrete: intloopcounter, greycounter

<Success> Property OK is valid by inductive step after 0.062s.

--------------------------------------------------------------------------
Summary of properties:
--------------------------------------------------------------------------
OK: valid (at 5)
==========================================================================
```

Example: k-induction annotation

```
node top (x:bool) returns (OK:bool);
--@ guarantee OK by 5-induction;
var b,d:bool;
let
  b = greycounter(x);
  d = intloopcounter(x);
  OK = b = d;
tel
```

Example: ACSL generation

Contract node compiled as a transition predicate

```
/*@ predicate top_contract_tr0(_Bool x, _Bool OK) =
      \true;
*/
/*@ predicate top_contract_tr1(_Bool x, _Bool OK, _Bool spec36) =
      top_contract_tr0(x, OK)
      && spec36 == OK;
*/
/*@ predicate top_contract_tr(_Bool x, _Bool OK, _Bool spec36) =
      top_contract_tr1(x, OK, spec36);
*/
```

Example: ACSL generation

Requirements as contracts

```
//@ ghost _Bool spec36;
/*@ ...
    requires top_pack(*mem, self);
    ensures top_pack(*mem, self);
    ensures top_tr(\old(*mem), x, *OK, *mem);
    ensures top_contract_tr(x, *OK, spec36) ==>
            spec36;
    ...
*/
void top_step(_Bool x, _Bool *OK, struct top_mem *self)
/*@ ghost (struct top_mem_ghost \ghost *mem) */ {
```

Example: ACSL generation

k-induction base cases predicates

```
predicate top_full_init(struct top_mem_ghost mem) =
   top_init(mem) && mem._reset;

 predicate top_base_1(struct top_mem_ghost mem_0,
                      _Bool x_1, _Bool OK_1,
                      struct top_mem_ghost mem_1) =
   \forall _Bool spec36_1;
     top_full_init(mem_0)
     && top_tr(mem_0, x_1, OK_1, mem_1)
     && top_contract_tr(x_1, OK_1, spec36_1) ==>
     spec36_1;
```

Example: ACSL generation

k-induction base cases predicates

```
predicate top_base_2(struct top_mem_ghost mem_1,
                     _Bool x_2, _Bool OK_2,
                     struct top_mem_ghost mem_2) =
  \forall _Bool spec36_2;
    \forall struct top_mem_ghost mem_0, _Bool x_1, _Bool OK_1;
      top_full_init(mem_0)
      && top_tr(mem_0, x_1, OK_1, mem_1)
      && top_contract_tr(x_1, OK_1, (_Bool) 1)
      && top_tr(mem_1, x_2, OK_2, mem_2)
      && top_contract_tr(x_2, OK_2, spec36_2) ==>
      spec36_2;
```

Example: ACSL generation

k-induction base cases predicates

```
predicate top_base_3(struct top_mem_ghost mem_2,
                     _Bool x_3, _Bool OK_3,
                     struct top_mem_ghost mem_3) =
  \forall _Bool spec36_3;
    \forall struct top_mem_ghost mem_0, mem_1,
             _Bool x_1, _Bool OK_1, _Bool x_2, _Bool OK_2;
      top_full_init(mem_0)
      && top_tr(mem_0, x_1, OK_1, mem_1)
      && top_contract_tr(x_1, OK_1, (_Bool) 1)
      && top_tr(mem_1, x_2, OK_2, mem_2)
      && top_contract_tr(x_2, OK_2, (_Bool) 1)
      && top_tr(mem_2, x_3, OK_3, mem_3)
      && top_contract_tr(x_3, OK_3, spec36_3) ==>
      spec36_3;
```

Example: ACSL generation

k-induction base cases predicates

```
predicate top_base_4(struct top_mem_ghost mem_3,
                     _Bool x_4, _Bool OK_4,
                     struct top_mem_ghost mem_4) =
  \forall _Bool spec36_4;
    \forall struct top_mem_ghost mem_0, mem_1, mem_2,
            _Bool x_1, _Bool OK_1, _Bool x_2, _Bool OK_2, _Bool x_3,
            _Bool OK_3;
      top_full_init(mem_0)
      && top_tr(mem_0, x_1, OK_1, mem_1)
      && top_contract_tr(x_1, OK_1, (_Bool) 1)
      && top_tr(mem_1, x_2, OK_2, mem_2)
      && top_contract_tr(x_2, OK_2, (_Bool) 1)
      && top_tr(mem_2, x_3, OK_3, mem_3)
      && top_contract_tr(x_3, OK_3, (_Bool) 1)
      && top_tr(mem_3, x_4, OK_4, mem_4)
      && top_contract_tr(x_4, OK_4, spec36_4) ==>
      spec36_4;
```

Example: ACSL generation

k-induction inductive case predicate

```
predicate top_inductive_5(struct top_mem_ghost mem_4,
                          _Bool x_5, _Bool OK_5,
                          struct top_mem_ghost mem_5) =
  \forall _Bool spec36_5;
    \forall struct top_mem_ghost mem_0, mem_1, mem_2, mem_3,
            _Bool x_1, _Bool OK_1, _Bool x_2, _Bool OK_2, _Bool x_3,
            _Bool OK_3, _Bool x_4, _Bool OK_4;
      top_tr(mem_0, x_1, OK_1, mem_1)
      && top_contract_tr(x_1, OK_1, (_Bool) 1)
      && top_tr(mem_1, x_2, OK_2, mem_2)
      && top_contract_tr(x_2, OK_2, (_Bool) 1)
      && top_tr(mem_2, x_3, OK_3, mem_3)
      && top_contract_tr(x_3, OK_3, (_Bool) 1)
      && top_tr(mem_3, x_4, OK_4, mem_4)
      && top_contract_tr(x_4, OK_4, (_Bool) 1)
      && top_tr(mem_4, x_5, OK_5, mem_5)
      && top_contract_tr(x_5, OK_5, spec36_5) ==>
      spec36_5;
```

Example: ACSL generation

k-induction corresponding lemmas

```
lemma top_k_induction_1:
  \forall struct top_mem_ghost mem_in, mem_out, _Bool x, _Bool OK;
    top_base_1(mem_in, x, OK, mem_out);

lemma top_k_induction_2:
  \forall struct top_mem_ghost mem_in, mem_out, _Bool x, _Bool OK;
    top_base_2(mem_in, x, OK, mem_out);

lemma top_k_induction_3:
  \forall struct top_mem_ghost mem_in, mem_out, _Bool x, _Bool OK;
    top_base_3(mem_in, x, OK, mem_out);

lemma top_k_induction_4:
  \forall struct top_mem_ghost mem_in, mem_out, _Bool x, _Bool OK;
    top_base_4(mem_in, x, OK, mem_out);

lemma top_k_induction_5:
  \forall struct top_mem_ghost mem_in, mem_out, _Bool x, _Bool OK;
    top_inductive_5(mem_in, x, OK, mem_out);
```

Example: ACSL generation

k-induction principle as an axiom

```
axiomatic top_k_Induction {
  axiom top_k_induction:
    \forall struct top_mem_ghost mem_in, mem_out, _Bool x, _Bool OK;
      top_base_1(mem_in, x, OK, mem_out)
      && top_base_2(mem_in, x, OK, mem_out)
      && top_base_3(mem_in, x, OK, mem_out)
      && top_base_4(mem_in, x, OK, mem_out)
      && top_inductive_5(mem_in, x, OK, mem_out) ==>
      \forall _Bool spec36;
        top_tr(mem_in, x, OK, mem_out)
        && top_contract_tr(x, OK, spec36) ==>
        spec36;
}
```

Stateful contract example

```
node fibo(x: bool) returns(a: int);
--@ guarantee a = (0 -> pre a) + (0 -> pre (1 -> pre a));
var b: int;
let
  a = 0 -> pre b;
  b = 1 -> pre (a + b);
  --%PROPERTY a = (0 -> pre a) + (0 -> pre (1 -> pre a));
tel
```

Stateful contract example

```
node fibo(x: bool) returns(a: int);
--@ guarantee a = (0 -> pre a) + (0 -> pre (1 -> pre a));
var b: int;
let
  a = 0 -> pre b;
  b = 1 -> pre (a + b);
  --%PROPERTY a = (0 -> pre a) + (0 -> pre (1 -> pre a));
tel
```

```
> kind2 --enable BMC --enable IND fibo.lus
 kind2 v1.5.0

==========================================================================================================================
Analyzing fibo
  with First top: 'fibo' (no subsystems)

<Success> Property (a = ((0 -> (pre a)) + (0 -> (pre (1 -> (pre a)))))) is valid by inductive step after 0.05

--------------------------------------------------------------------------------------------------------------------------
Summary of properties:
--------------------------------------------------------------------------------------------------------------------------
(a = ((0 -> (pre a)) + (0 -> (pre (1 -> (pre a)))))): valid (at 3)
==========================================================================================================================
```

Stateful contract example

```
node fibo(x: bool) returns(a: int);
--@ guarantee a = (0 -> pre a) + (0 -> pre (1 -> pre a)) by 3-induction;
var b: int;
let
  a = 0 -> pre b;
  b = 1 -> pre (a + b);
tel
```

Stateful contract example

Much more complex contract transition predicate

```
/*@ predicate fibo_contract_tr0(struct fibo_contract_mem_ghost mem_in,
                                 _Bool x, integer a,
                                 struct fibo_contract_mem_ghost mem_out) =
      mem_out._reset == mem_in._reset;
*/
/*@ predicate fibo_contract_tr1(struct fibo_contract_mem_ghost mem_in,
                                 _Bool x, integer a,
                                 _Bool __fibo_contract_7,
                                 struct fibo_contract_mem_ghost mem_out) =
      fibo_contract_tr0(mem_in, x, a, mem_out)
      && _arrow_transition(mem_in.ni_4, __fibo_contract_7, mem_out.ni_4);
*/
/*@ predicate fibo_contract_tr2(struct fibo_contract_mem_ghost mem_in,
                                 _Bool x, integer a,
                                 integer __fibo_contract_9,
                                 struct fibo_contract_mem_ghost mem_out) =
      \exists _Bool __fibo_contract_7;
        fibo_contract_tr1(mem_in, x, a, __fibo_contract_7, mem_out)
        && (__fibo_contract_7 ? __fibo_contract_9 == 0
                              : (!_arrow_initialization(mem_in.ni_4) ==>
                                 __fibo_contract_9 == mem_in._reg.__fibo_contract_8
                                 ));
*/
```

Stateful contract example

Much more complex contract transition predicate

```
/*@ predicate fibo_contract_tr3(struct fibo_contract_mem_ghost mem_in,
                                 _Bool x, integer a,
                                 integer __fibo_contract_9,
                                 _Bool __fibo_contract_1,
                                 struct fibo_contract_mem_ghost mem_out) =
      fibo_contract_tr2(mem_in, x, a, __fibo_contract_9, mem_out)
      && _arrow_transition(mem_in.ni_5, __fibo_contract_1, mem_out.ni_5);
*/
/*@ predicate fibo_contract_tr4(struct fibo_contract_mem_ghost mem_in,
                                 _Bool x, integer a,
                                 integer __fibo_contract_9,
                                 integer __fibo_contract_6,
                                 struct fibo_contract_mem_ghost mem_out) =
      \exists _Bool __fibo_contract_1;
        fibo_contract_tr3(mem_in,
                          x, a, __fibo_contract_9, __fibo_contract_1,
                          mem_out)
        && (__fibo_contract_1 ? __fibo_contract_6 == 0
                        : (!_arrow_initialization(mem_in.ni_4) ==>
                           __fibo_contract_6 == mem_in._reg.__fibo_contract_5
                           ));
*/
```

Stateful contract example

Much more complex contract transition predicate

```
/*@ predicate fibo_contract_tr5(struct fibo_contract_mem_ghost mem_in,
                                 _Bool x, integer a, _Bool spec19,
                                 struct fibo_contract_mem_ghost mem_out) =
      \exists integer __fibo_contract_9, integer __fibo_contract_6;
        fibo_contract_tr4(mem_in,
                          x, a, __fibo_contract_9, __fibo_contract_6,
                          mem_out)
        && spec19 == (a == (__fibo_contract_9 + __fibo_contract_6));
*/
/*@ predicate fibo_contract_tr6(struct fibo_contract_mem_ghost mem_in,
                                 _Bool x, integer a, _Bool spec19,
                                 struct fibo_contract_mem_ghost mem_out) =
      fibo_contract_tr5(mem_in, x, a, spec19, mem_out)
      && mem_out._reg.__fibo_contract_8 == a;
*/
/*@ predicate fibo_contract_tr7(struct fibo_contract_mem_ghost mem_in,
                                 _Bool x, integer a,
                                 _Bool __fibo_contract_2, _Bool spec19,
                                 struct fibo_contract_mem_ghost mem_out) =
      fibo_contract_tr6(mem_in, x, a, spec19, mem_out)
      && _arrow_transition(mem_in.ni_6, __fibo_contract_2, mem_out.ni_6);
*/
```

Stateful contract example

Much more complex contract transition predicate

```
/*@ predicate fibo_contract_tr8(struct fibo_contract_mem_ghost mem_in,
                                 _Bool x, integer a,
                                 integer __fibo_contract_4,
                                 _Bool spec19,
                                 struct fibo_contract_mem_ghost mem_out) =
      \exists _Bool __fibo_contract_2;
        fibo_contract_tr7(mem_in, x, a, __fibo_contract_2, spec19,
                          mem_out)
        && (__fibo_contract_2 ? __fibo_contract_4 == 1
                        : (!_arrow_initialization(mem_in.ni_4) ==>
                           __fibo_contract_4 == mem_in._reg.__fibo_contract_3
                           ));
*/
/*@ predicate fibo_contract_tr9(struct fibo_contract_mem_ghost mem_in,
                                 _Bool x, integer a, _Bool spec19,
                                 struct fibo_contract_mem_ghost mem_out) =
      \exists integer __fibo_contract_4;
        fibo_contract_tr8(mem_in, x, a, __fibo_contract_4, spec19,
                          mem_out)
        && mem_out._reg.__fibo_contract_5 == __fibo_contract_4;
*/
```

Stateful contract example

Much more complex contract transition predicate

```
/*@ predicate fibo_contract_tr10(struct fibo_contract_mem_ghost mem_in,
                                  _Bool x, integer a, _Bool spec19,
                                  struct fibo_contract_mem_ghost mem_out) =
      fibo_contract_tr9(mem_in, x, a, spec19, mem_out)
      && mem_out._reg.__fibo_contract_3 == a;
*/
/*@ predicate fibo_contract_tr(struct fibo_contract_mem_ghost mem_in,
                               _Bool x, integer a, _Bool spec19,
                               struct fibo_contract_mem_ghost mem_out) =
      \exists struct fibo_contract_mem_ghost mem_reset;
        fibo_contract_reset_cleared(mem_in, mem_reset)
        && fibo_contract_tr10(mem_reset, x, a, spec19, mem_out);
*/
```

Stateful contract example

Same k-induction principles, with state

```
/*@ ghost
      _Bool spec19;
      struct fibo_contract_mem_ghost mem_in_c, mem_out_c;
*/
/*@ ...
    requires fibo_pack(*mem, self);
    ensures fibo_pack(*mem, self);
    ensures fibo_transition(\old(*mem), x, *a, *mem);
    ensures fibo_contract_tr(mem_in_c, x, *a, spec19, mem_out_c) ==>
            spec19;
    ...
*/
void fibo_step(_Bool x, int *a, struct fibo_mem *self)
/*@ ghost (struct fibo_mem_ghost \ghost *mem) */ {
```

Conclusion

Summary

- A certifying compiler from Lustre to C / ACSL
- Certificate of correctness wrt a state / transition semantics
- Automatic translation of high-level contracts

Future

- Prototype
- Other alternative for compiling the *reset*
- Optimizations
- Invariant generation
- Encoding a synchronous dataflow semantics?
- SPARK / Ada

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