From Lustre to C:
a Translation Validation Approach to Verified Compilation

AID Meeting

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[1]ISAE-SUPAERO – DISC – IpSC

Context

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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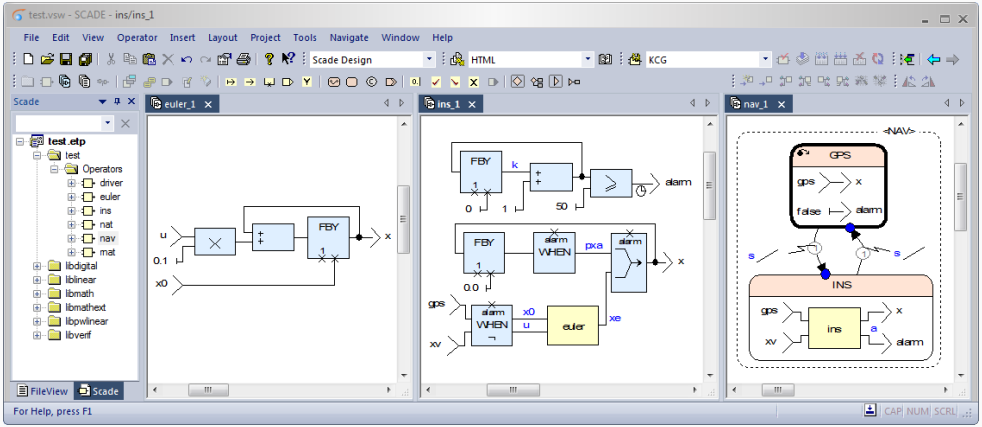
Model-Based Design

Executable high-level abstract specifications

Model-Based Design in SCADE Suite

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



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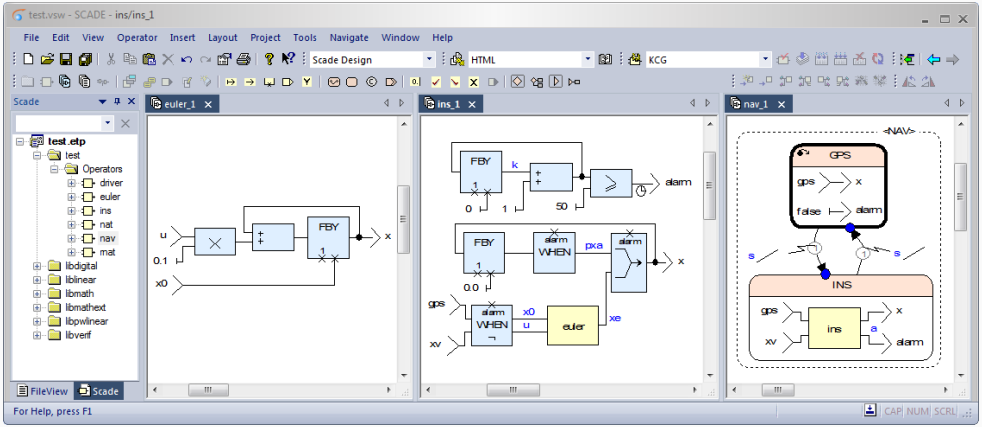

block / node = system

line = signal

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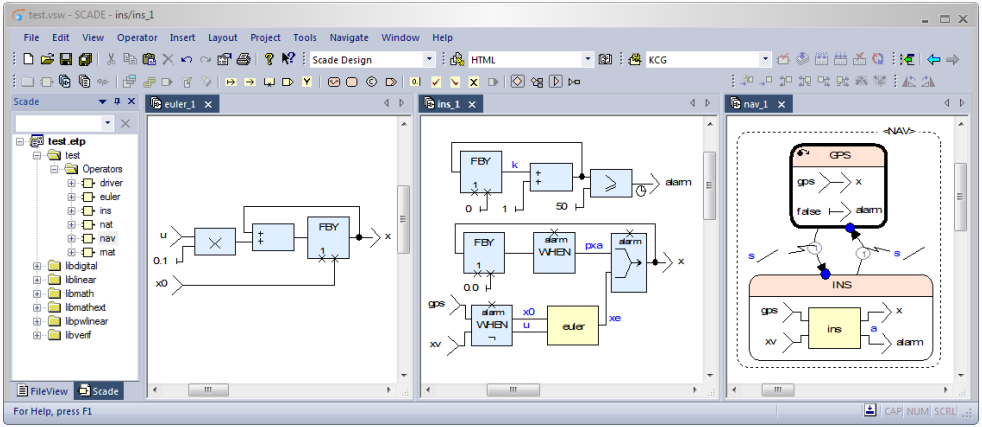

block / node = system = stream function

line = signal = stream of values

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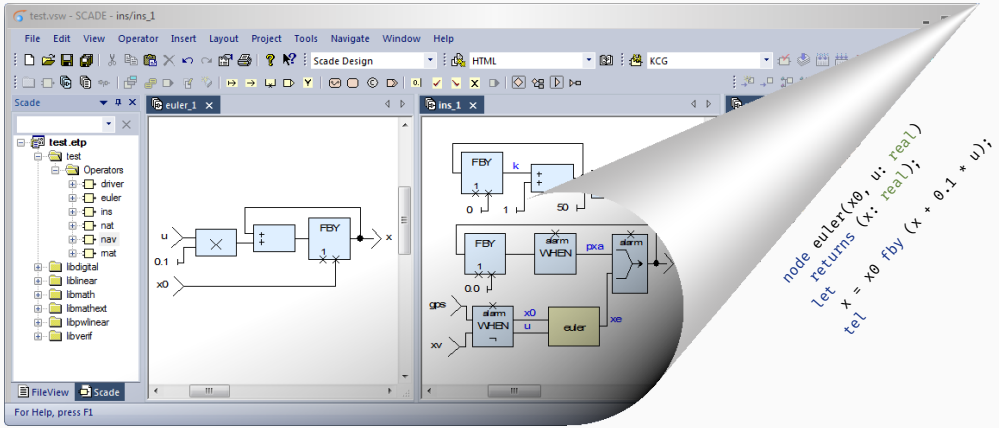

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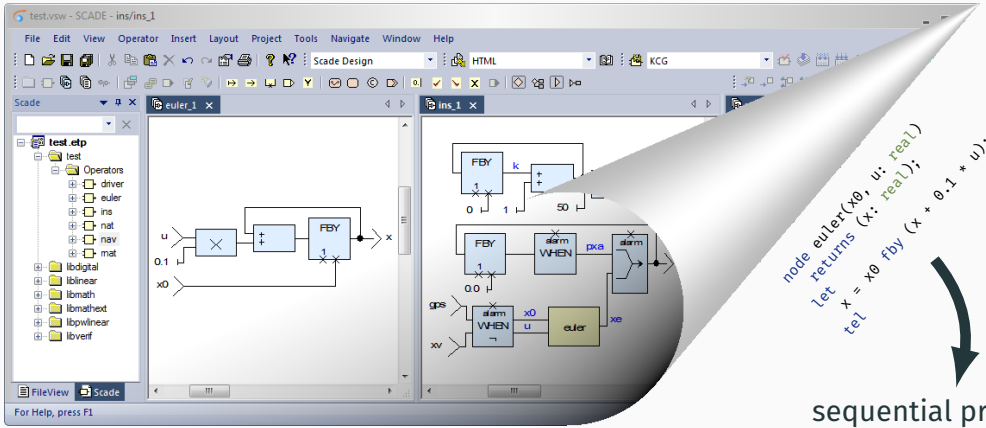

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Criticality

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?~~

Leroy 2009
Appel 2011
Klein et al. 2009
Kumar, Myreen, Norrish, and Owens 2014
Bohrer, Tan, Mitsch, Myreen, and Platzer 2018
Bourke, Brun, Dagand, Leroy, Pouzet, and Rieg 2017

CompCert a verified C compiler in Coq

VST a C verification toolset based on CompCert

seL4 a verified micro-kernel in Isabelle

CakeML a verified compiler for a functional language in HOL

VeriPhy a verified pipeline from CPS to controllers, using KeYmaera X, HOL4 and Isabelle

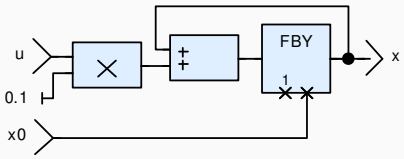
Vélus a verified Lustre compiler in Coq, based on CompCert

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~~

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	$\cdots$

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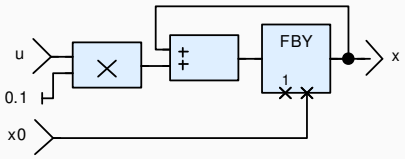


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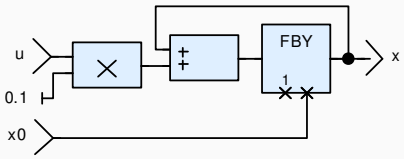


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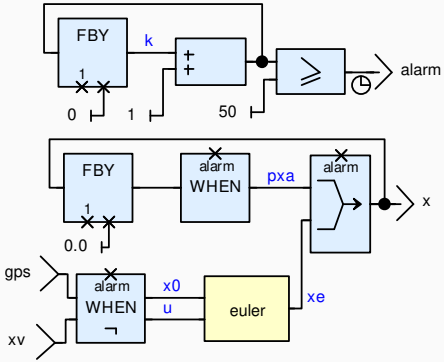


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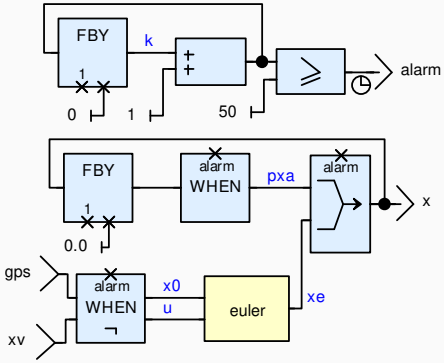


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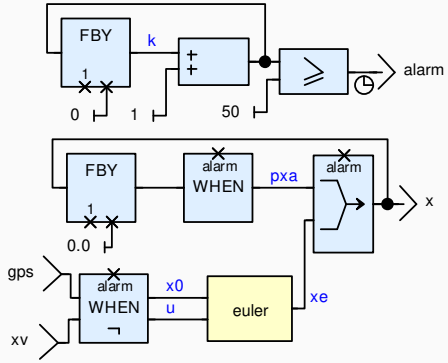


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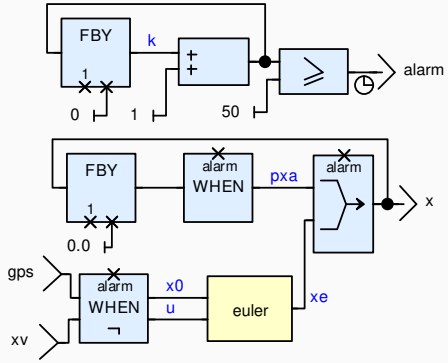


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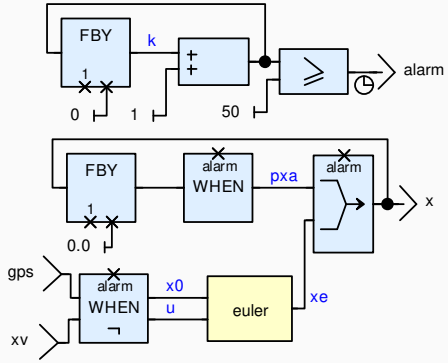


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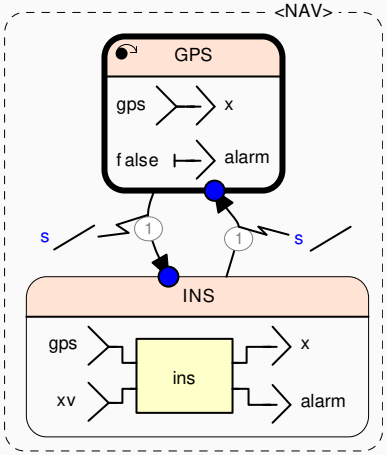


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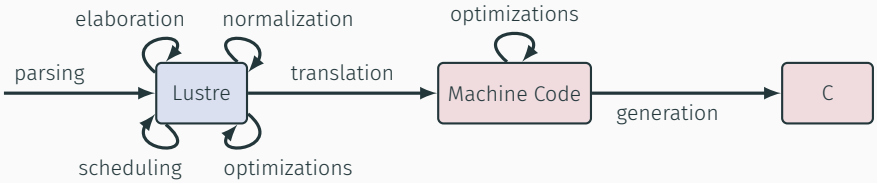
  automaton a
    state GPS:
      let
        x = gps;
        alarm = false;
      tel until s restart INS
    state INS:
      let
        (x, alarm) = ins(gps, xv);
      tel until s resume GPS
tel
```

LustreC: a Lustre Compiler



Implemented in OCaml ($\approx 35\,000$ loc)

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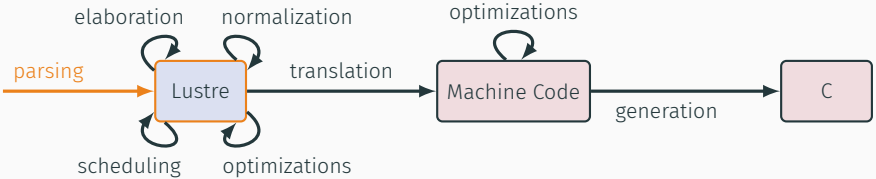

- parsing (`menhir`)

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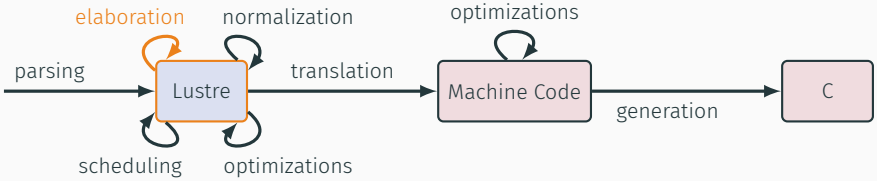

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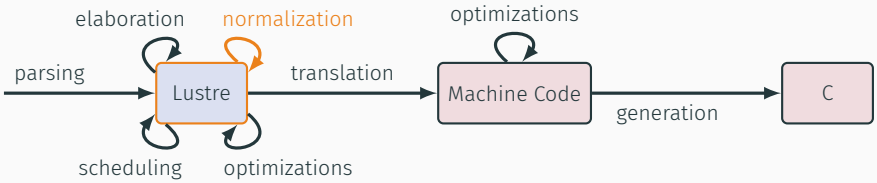

- parsing (`menhir`)
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- normalization of Lustre code

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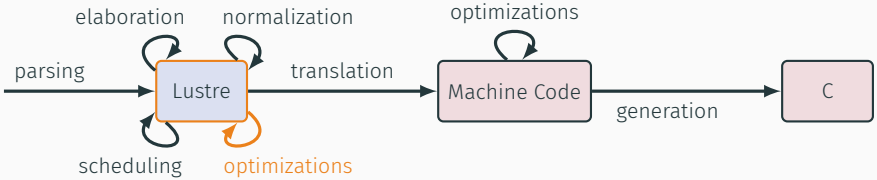

- parsing (`menhir`)
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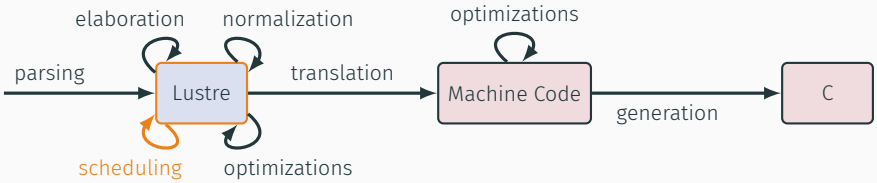

- parsing (`menhir`)
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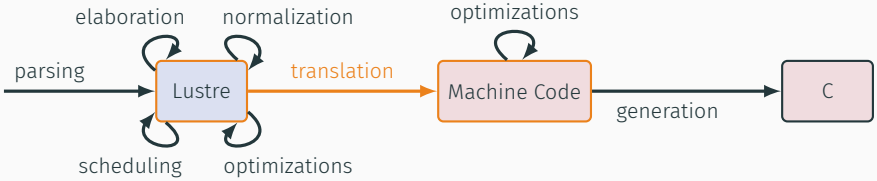

- parsing (`menhir`)
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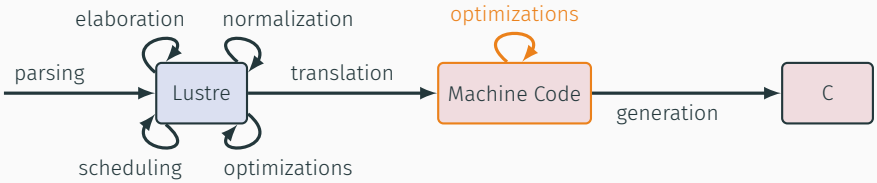

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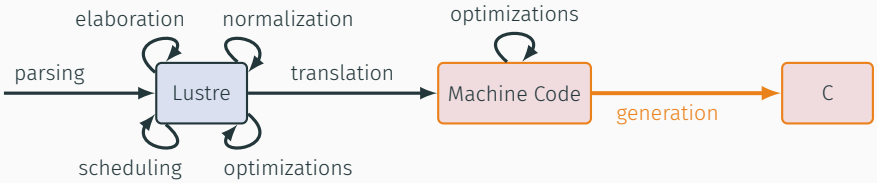

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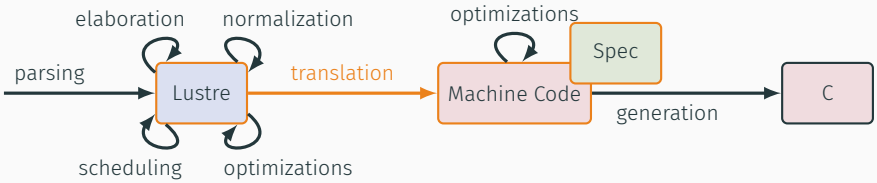

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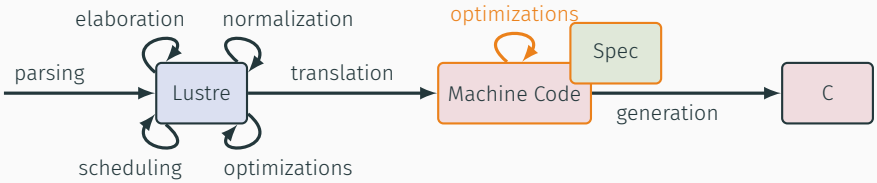

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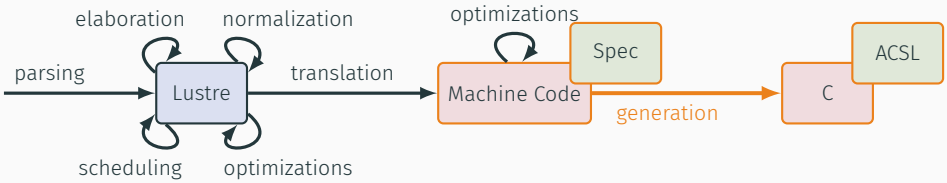

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- scheduling of Lustre code
- translation to Machine code
- optimisation of Machine code
- generation of C code + ACSL specification

Lustre

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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);
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C

```
#include <assert.h>
#include "acc_automaton.h"

// Struct definitions */
struct euler_mem {
  double x;
  struct euler_reg {double _euler_2;} _reg;
  struct _acrmp_mem ins_1;
};

struct ins_mem {
  _Bool _reset;
  struct ins_reg {double __ins_2;
                  int __ins_1;} _reg;
  struct _acrmp_mem ins_2;
  struct euler_mem ins_3;
};

struct a_INS_handler_until_mem {
  _Bool _reset;
  struct a_INS_handler_until_reg {int __a_INS_handler_until_1;} _reg;
  struct ins_mem ins_18;
  struct _acrmp_mem ins_4;
};

struct nav_mem {
  _Bool _reset;
  struct nav_reg { _Bool __nav_16;
                   double __ins_17;} _reg;
  struct _acrmp_mem ins_5;
  struct a_INS_handler_until_mem ins_19;
};

void euler_clear_reset (struct euler_mem *self) {
  if (self->_reset) {
    self->_reset = 0;
    _acrmp_reset(&self->ins_7);
  }
  return;
}

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

void euler_step (double u0, double u,
                 double *res,
                 struct euler_mem *self) {
  _Bool __euler_1;
  euler_set_reset(self);
  {
    _euler_2 = _acrmp_step(self->ins_7);
    if (self->_reset) {
      x = u0;
    } else {
      x = self->_reg._euler_2;
    }
    self->_reg._euler_2 = (*res = (0.1 * u));
  }
  return;
}

void ins_clear_reset (struct ins_mem *self) {
  if (self->_reset) {
    self->_reset = 0;
    _acrmp_reset(&self->ins_8);
    euler_set_reset(self->ins_9);
  }
  return;
}

void ins_set_reset (struct ins_mem *self) {
  self->_reset = 1;
  return;
}

void ins_step (double gps, double xv,
               double *res, _Bool *relarm_6),
               struct ins_mem *self) {
  int k;
  _Bool alarm;
  double __ins_2;
  _Bool __ins_1;
  double pxa;
  double xe;
  ins_clear_reset(self);
  {
    __ins_1 = _acrmp_step(self->ins_8);
    if (__ins_1) {
      k = 0;
    } else {
      k = self->_reg.__ins_2;
    }
    alarm = (k >= 50);
    if (!alarm) {
      euler_step(gps, xv, &xe, self->ins_9);
    }
    if (__ins_1) {
      __ins_2 = 0.0;
    } else {
      __ins_2 = self->_reg.__ins_2;
    }
    if (alarm) {
      pxa = __ins_2;
      *relarm_6 = 1;
    } else {
      pxa = 0.;
      *relarm_6 = 0;
    }
    self->_reg.__ins_2 = (k + 1);
    self->_reg.__ins_1 = 1;
    return;
  }
}

void a_GPS_handler_until_step (_Bool a_restart_ent, double gps, _Bool a,
                               _Bool (*a_restart_int),
                               a_type (*a_state_int), _Bool (*relarm_out),
                               int (*k_out), double (*xe_out)) {
  *a_out = gps;
  *k_out = 0;
  *xe_out = 0.;
  if (a) {
    *a_restart_int = 1;
    *a_state_int = GPS;
    *a_restart_int = 0;
  } else {
  }
  return;
}

void a_GPS_unless_step (_Bool a_restart_in,
                        _Bool (*a_restart_ent), a_type (*a_state_ent)) {
  *a_state_ent = GPS;
  *a_restart_ent = a_restart_in;
  return;
}

void a_INS_handler_until_clear_reset (struct a_INS_handler_until_mem *self) {
  if (self->_reset) {
    self->_reset = 0;
    ins_set_reset(self->ins_18);
    _acrmp_reset(&self->ins_19);
  }
  return;
}

void a_INS_handler_until_set_reset (struct a_INS_handler_until_mem *self) {
  self->_reset = 1;
  return;
}

void a_INS_handler_until_step (_Bool a_restart_ent, double gps, double xv,
                               _Bool a,
                               _Bool (*a_restart_int),
                               a_type (*a_state_int), _Bool (*relarm_out),
                               int (*k_out), double (*xe_out),
                               struct a_INS_handler_until_mem *self) {

  double xe;
  int k;
  _Bool relarm;
  a_INS_handler_until_2();
  a_INS_handler_until_clear_reset(self);
  {
    ins_step(gps, xv, &xe, &relarm, self->ins_18);
    *k_out = k;
    if (a_INS_handler_until_1 = _acrmp_step(self->ins_19)) {
      if (_a_INS_handler_until_2) {
        k = 0;
      } else {
        k = self->_reg._a_INS_handler_until_1;
      }
    }
    *k_out = k;
    relarm_out = alarm;
    if (alarm) {
      *a_restart_int = 1;
      *a_state_int = GPS;
      *a_restart_int = 0;
    } else {
      *xe_out = xe;
    }
    self->_reg._a_INS_handler_until_2 = (k < 1);
    return;
  }
}

void a_INS_unless_step (_Bool a_restart_in,
                        _Bool (*a_restart_ent), a_type (*a_state_ent)) {
  *a_state_ent = INS;
  *a_restart_ent = a_restart_in;
  return;
}

void nav_clear_reset (struct nav_mem *self) {
  if (self->_reset) {
    self->_reset = 0;
    _acrmp_reset(&self->ins_12);
    a_INS_handler_until_set_reset(&self->ins_13);
  }
  return;
}

void nav_set_reset (struct nav_mem *self) {
  self->_reset = 1;
  return;
}

void nav_step (double gps, double xv, _Bool s,
               double (*x), int (*ok), _Bool (*relarm),
               struct nav_mem *self) {
  _Bool a_next_restart_in;
  _Bool a_restart_ent;
  _Bool a_restart_int;
  a_type a_next_state_in;
  a_type a_state_ent;
  a_type a_state_int;
  _Bool __nav_15;
  double __nav_9;
  int __nav_10;
  _Bool __nav_11;
  double __nav_12;
  _Bool __nav_13;
  _Bool __nav_14;
  a_type __nav_7;
  a_type __nav_8;
  nav_clear_reset(self);
  {
    __nav_10 = _acrmp_step(self->ins_12);
    if (self->_reset) {
      __nav_9 = 0.0;
      __nav_11 = 1;
      __nav_12 = 0.;
      __nav_13 = 1;
      __nav_14 = 0;
      __nav_7 = INS;
      __nav_8 = INS;
    } else {
      __nav_9 = self->_reg.__nav_12;
      __nav_11 = self->_reg.__nav_13;
      __nav_12 = self->_reg.__nav_14;
      __nav_13 = self->_reg.__nav_15;
      __nav_14 = self->_reg.__nav_16;
      __nav_7 = self->_reg.__nav_17;
      __nav_8 = self->_reg.__nav_18;
    }
    switch(a_state_int) {
      case GPS:
        a_GPS_unless_step(s, a_restart_in, &__nav_11, &__nav_13);
        a_state_ent = __nav_7;
        a_restart_ent = __nav_11;
        break;
      default: // INS
        a_INS_unless_step(s, a_restart_in, &__nav_11, &__nav_13);
        a_state_ent = __nav_8;
        a_restart_ent = __nav_11;
    }
    switch(a_state_int) {
      case GPS:
        a_GPS_handler_until_step(a_restart_ent, gps, x, &__nav_10, &__nav_12,
                                 &__nav_13, &__nav_14,
                                 &__nav_15);
        *x = __nav_9;
        *ok = __nav_10;
        *relarm = __nav_12;
        a_next_restart_in = __nav_13;
        a_next_restart_int = __nav_14;
        break;
      default: // INS
        if (a_restart_ent) {
          a_INS_handler_until_set_reset(self->ins_13);
        }
        a_INS_handler_until_step(a_restart_ent, gps, xv, x, &__nav_9,
                                 &__nav_10,
                                 &__nav_11,
                                 &__nav_12,
                                 &__nav_13,
                                 &__nav_14,
                                 &__nav_15,
                                 &__nav_16,
                                 &__nav_17,
                                 &__nav_18);
        *x = __nav_9;
        *ok = __nav_10;
        *relarm = __nav_12;
        a_next_state_in = __nav_8;
        a_next_restart_in = __nav_13;
        a_next_restart_int = __nav_14;
    }
    self->_reg.__nav_12 = a_next_state_in;
    self->_reg.__nav_13 = a_next_restart_in;
    self->_reg.__nav_14 = a_next_restart_int;
    return;
  }
}
```

+ separated code for the main loop

Lustre

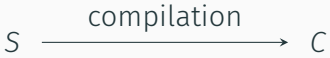
```
node euler(x0, u: real)
  returns (x: real);
let
  x = x0 fby (x + 0.1 * u);
tel

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

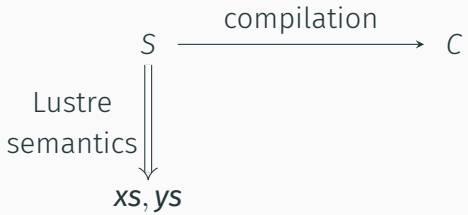
node nav(gps, xv: real, s: bool)
  returns (x: real, alarm: bool)
let
  automaton a
    state GPS:
      let
        x = gps;
        alarm = false;
      tel until s restart INS
    state INS:
      let
        (x, alarm) = ins(gps, xv);
      tel until s resume GPS
tel
```

C + ACSL

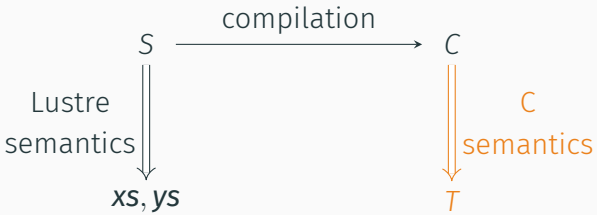
Correctness?



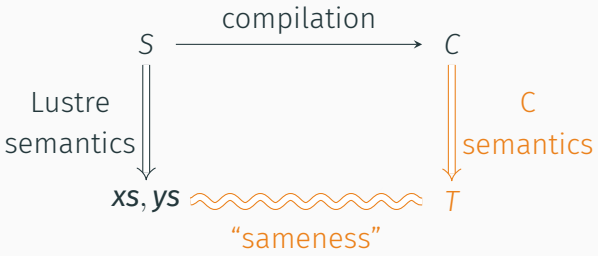
Correctness?



Correctness?



Correctness?



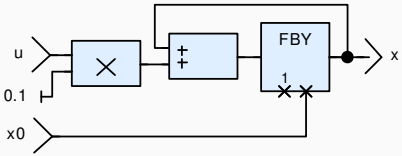
Correctness?

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 y: real; c: bool;
let
  x = if c then x0 else y;
  y = pre (x + 0.1 * u);
  c = true -> false;
tel
```

```
a fby b ≡ a -> pre (b)
        ≡ if (true -> false) then a else pre (b)
```

Example: Scheduling

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

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

Example: Machine code generation

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

```
machine euler {
  mem y: real;
  instance a: arrow<>;

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

Example: Machine code generation

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

```
machine euler {
  mem y: real;
  instance a: arrow<>;

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

Example: Machine code generation

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

```
machine euler {
  mem y: real;
  instance a: arrow<>;

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

Example: C code generation

```
machine euler {
  mem y: real;
  instance a: arrow<>;

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

```
struct _arrow_mem {
  _Bool _first;
};

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

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

Example: C code generation

```
machine euler {
  mem y: real;
  instance a: arrow<>;

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

```
struct euler_mem {
  _Bool _reset;
  double y;
  struct _arrow_mem *a;
};
```

Example: C code generation

```
machine euler {
  mem y: real;
  instance a: arrow<>;

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

```
struct euler_mem {
  _Bool _reset;
  double y;
  struct _arrow_mem *a;
};
```

Example: C code generation

```
machine euler {
  mem y: real;
  instance a: arrow<>;

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

```
struct euler_mem {
  _Bool _reset;
  double y;
  struct _arrow_mem *a;
};
```

Example: C code generation

```
machine euler {
  mem y: real;
  instance a: arrow<>;

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

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

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

Example: C code generation

```
machine euler {
  mem y: real;
  instance a: arrow<>;

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

```
void euler_step(double x0, double u,
                double *x,
                struct euler_mem *self) {
  _Bool c;
  euler_clear_reset(self);
  c = _arrow_step(self->a);
  if (c) {
    *x = x0;
  } else {
    *x = self->y;
  }
  self->y = *x + 0.1 * u;
  return;
}
```

Encoding of the Semantics

State / Transition Semantics

$S[i]$ sub-instance

$S(x)$ state variabe

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

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

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

State / Transition Semantics

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

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

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 {
  _Bool _first;
};

struct euler_mem {
  _Bool _reset;
  double y;
  struct _arrow_mem *a;
};
```

```
/*@ ghost struct _arrow_mem_ghost {
            _Bool _first;
    };
*/

/*@ ghost struct euler_mem_ghost {
            _Bool _reset;
            double y;
            struct _arrow_mem_ghost a;
    };
*/
```

ACSL generation: memory correspondence

```
/*@ predicate euler_pack_base(struct euler_mem_ghost mem, struct euler_mem *self) =
      mem._reset == self->_reset && mem._reset == 0
      && _arrow_pack(mem.a, self->a);

    predicate euler_pack0(struct euler_mem_ghost mem_reset,
                          struct euler_mem_ghost mem, struct euler_mem *self) =
      euler_pack_base(mem, self)
      && !_arrow_initialization(mem.a) ==> mem.y == self->y;

    predicate euler_pack1(struct euler_mem_ghost mem_reset,
                          struct euler_mem_ghost mem, struct euler_mem *self) =
      euler_pack_base(mem, self)
      && !_arrow_initialization(mem_reset.a) ==> mem.y == self->y;

    predicate euler_pack(struct euler_mem_ghost mem, struct euler_mem *self) =
      mem._reset ? mem._reset == self->_reset : euler_pack0(mem, mem, self);
*/
```

ACSL generation: transition relation

$$
\begin{aligned}
&\mathit{euler\_init}\,(S) = \\
&\quad \mathit{arrow\_init}\,(S[a])
\end{aligned}
$$

$$
\begin{aligned}
&\mathit{euler\_reset}\,(S, S') = \\
&\quad S(\_reset) \rightarrow S'(\_reset) = \mathit{false} \\
&\qquad\qquad \wedge\, \mathit{euler\_init}(S') \\
&\quad \wedge\, \neg S(\_reset) \rightarrow S' = S
\end{aligned}
$$

```
/*@ predicate euler_init(struct euler_mem_ghost mem) =
      _arrow_init(mem.a);
*/

/*@ 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

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

```
/*@ 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

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

```
/*@ 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.y == x + 0.1 * u;
*/
```

ACSL generation: transition relation

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

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

ACSL generation: transition relation

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

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

ACSL generation: transition relation

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

```
/*@ 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->a);
    requires euler_pack(*mem, self);
    ensures euler_pack0(*mem, *mem, self);
    ensures euler_reset(\old(*mem), *mem);
    assigns self->_reset, self->a->_first, mem->_reset, mem->a._first;
*/
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->a);
    //@ ghost _arrow_reset_ghost(mem->a);
  }
  return;
}
```

ACSL generation: contracts and assertions

```
/*@ requires euler_valid(self);
    requires \separated(self, mem, self->a);
    requires euler_pack(*mem, self);
    ensures euler_pack0(*mem, *mem, self);
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    //@ ghost mem->_reset = 0;
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    //@ ghost _arrow_reset_ghost(mem->a);
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ACSL generation: contracts and assertions

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    ensures euler_pack0(*mem, *mem, self);
    ensures euler_reset(\old(*mem), *mem);
    assigns self->_reset, self->a->_first, mem->_reset, mem->a._first;
*/
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->a);
    //@ ghost _arrow_reset_ghost(mem->a);
  }
  return;
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```

ACSL generation: contracts and assertions

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    ensures euler_pack0(*mem, *mem, self);
    ensures euler_reset(\old(*mem), *mem);
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           /*@ ghost (struct euler_mem_ghost \ghost *mem) */ {
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    //@ ghost mem->_reset = 0;
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    //@ ghost _arrow_reset_ghost(mem->a);
  }
  return;
}
```

ACSL generation: contracts and assertions

```
/*@ requires euler_valid(self);
    requires \separated(self, mem, self->a);
    requires euler_pack(*mem, self);
    ensures euler_pack0(*mem, *mem, self);
    ensures euler_reset(\old(*mem), *mem);
    assigns self->_reset, self->a->_first, mem->_reset, mem->a._first;
*/
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->a);
    //@ ghost _arrow_reset_ghost(mem->a);
  }
  return;
}
```

ACSL generation: contracts and assertions

```
/*@ requires euler_valid(self);
    requires \separated(self, mem, self->a);
    requires euler_pack(*mem, self);
    ensures euler_pack0(*mem, *mem, self);
    ensures euler_reset(\old(*mem), *mem);
    assigns self->_reset, self->a->_first, mem->_reset, mem->a._first;
*/
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->a);
    //@ ghost _arrow_reset_ghost(mem->a);
  }
  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->a, x);
    requires euler_pack(*mem, self);
    ensures euler_pack(*mem, self);
    ensures euler_tr(\old(*mem), x0, u, *x, *mem);
    assigns *x, self->y, self->_reset, self->a->_first,
            mem->y, mem->_reset, mem->a._first;
*/
void euler_step(double x0,
                double u, double *x,
                struct euler_mem *self)
     /*@ ghost (struct euler_mem_ghost \ghost *mem) */ {
```

ACSL generation: contracts and assertions

```
/*@ requires \valid(x);
    requires euler_valid(self);
    requires \separated(self, mem, self->a, x);
    requires euler_pack(*mem, self);
    ensures euler_pack(*mem, self);
    ensures euler_tr(\old(*mem), x0, u, *x, *mem);
    assigns *x, self->y, self->_reset, self->a->_first,
            mem->y, mem->_reset, mem->a._first;
*/
void euler_step(double x0,
                double u, double *x,
                struct euler_mem *self)
 /*@ ghost (struct euler_mem_ghost \ghost *mem) */ {
```

ACSL generation: contracts and assertions

```
/*@ requires \valid(x);
    requires euler_valid(self);
    requires \separated(self, mem, self->a, x);
    requires euler_pack(*mem, self);
    ensures euler_pack(*mem, self);
    ensures euler_tr(\old(*mem), x0, u, *x, *mem);
    assigns *x, self->y, self->_reset, self->a->_first,
            mem->y, mem->_reset, mem->a._first;
*/
void euler_step(double x0,
                double u, double *x,
                struct euler_mem *self)
 /*@ ghost (struct euler_mem_ghost \ghost *mem) */ {
```

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 c;
  euler_clear_reset(self)/*@ ghost (mem) */;
  /*@ ghost struct euler_mem_ghost mem_reset = *mem; */
  /*@ assert euler_pack0(mem_reset, *mem, self); */
  /*@ assert euler_tr0(mem_reset, x0, u, *mem); */
  c = _arrow_step(self->a)/*@ ghost (&mem->a) */;
  /*@ assert euler_pack1(mem_reset, *mem, self); */
  /*@ assert euler_tr1(mem_reset, x0, u, c, *mem); */
  if (c) { *x = x0; } else { *x = self->y; }
  /*@ assert euler_tr2(mem_reset, x0, u, *x, *mem); */
  self->y = *x + 0.1 * u;
  //@ ghost mem->y = *x + 0.1 * u;
  /*@ assert euler_pack0(mem_reset, *mem, self); */
  /*@ assert euler_tr3(mem_reset, x0, u, *x, *mem); */
  return;
}
```

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 c;
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  /*@ ghost struct euler_mem_ghost mem_reset = *mem; */
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  /*@ assert euler_tr0(mem_reset, x0, u, *mem); */
  c = _arrow_step(self->a)/*@ ghost (&mem->a) */;
  /*@ assert euler_pack1(mem_reset, *mem, self); */
  /*@ assert euler_tr1(mem_reset, x0, u, c, *mem); */
  if (c) { *x = x0; } else { *x = self->y; }
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ACSL generation: contracts and assertions

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  /*@ ghost struct euler_mem_ghost mem_reset = *mem; */
  /*@ assert euler_pack0(mem_reset, *mem, self); */
  /*@ assert euler_tr0(mem_reset, x0, u, *mem); */
  c = _arrow_step(self->a)/*@ ghost (&mem->a) */;
  /*@ assert euler_pack1(mem_reset, *mem, self); */
  /*@ assert euler_tr1(mem_reset, x0, u, c, *mem); */
  if (c) { *x = x0; } else { *x = self->y; }
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ACSL generation: contracts and assertions

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  /*@ assert euler_tr0(mem_reset, x0, u, *mem); */
  c = _arrow_step(self->a)/*@ ghost (&mem->a) */;
  /*@ assert euler_pack1(mem_reset, *mem, self); */
  /*@ assert euler_tr1(mem_reset, x0, u, c, *mem); */
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ACSL generation: contracts and assertions

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  /*@ assert euler_pack0(mem_reset, *mem, self); */
  /*@ assert euler_tr0(mem_reset, x0, u, *mem); */
  c = _arrow_step(self->a)/*@ ghost (&mem->a) */;
  /*@ assert euler_pack1(mem_reset, *mem, self); */
  /*@ assert euler_tr1(mem_reset, x0, u, c, *mem); */
  if (c) { *x = x0; } else { *x = self->y; }
  /*@ assert euler_tr2(mem_reset, x0, u, *x, *mem); */
  self->y = *x + 0.1 * u;
  //@ ghost mem->y = *x + 0.1 * u;
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ACSL generation: contracts and assertions

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  euler_clear_reset(self)/*@ ghost (mem) */;
  /*@ ghost struct euler_mem_ghost mem_reset = *mem; */
  /*@ assert euler_pack0(mem_reset, *mem, self); */
  /*@ assert euler_tr0(mem_reset, x0, u, *mem); */
  c = _arrow_step(self->a)/*@ ghost (&mem->a) */;
  /*@ assert euler_pack1(mem_reset, *mem, self); */
  /*@ assert euler_tr1(mem_reset, x0, u, c, *mem); */
  if (c) { *x = x0; } else { *x = self->y; }
  /*@ assert euler_tr2(mem_reset, x0, u, *x, *mem); */
  self->y = *x + 0.1 * u;
  //@ ghost mem->y = *x + 0.1 * u;
  /*@ assert euler_pack0(mem_reset, *mem, self); */
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ACSL generation: contracts and assertions

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                double u, double *x,
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    /*@ ghost (struct euler_mem_ghost \ghost *mem) */ {
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  /*@ ghost struct euler_mem_ghost mem_reset = *mem; */
  /*@ assert euler_pack0(mem_reset, *mem, self); */
  /*@ assert euler_tr0(mem_reset, x0, u, *mem); */
  c = _arrow_step(self->a)/*@ ghost (&mem->a) */;
  /*@ assert euler_pack1(mem_reset, *mem, self); */
  /*@ assert euler_tr1(mem_reset, x0, u, c, *mem); */
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  /*@ assert euler_pack0(mem_reset, *mem, self); */
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ACSL generation: contracts and assertions

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  /*@ assert euler_tr1(mem_reset, x0, u, c, *mem); */
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ACSL generation: contracts and assertions

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  //@ ghost mem->y = *x + 0.1 * u;
  /*@ assert euler_pack0(mem_reset, *mem, self); */
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}
```
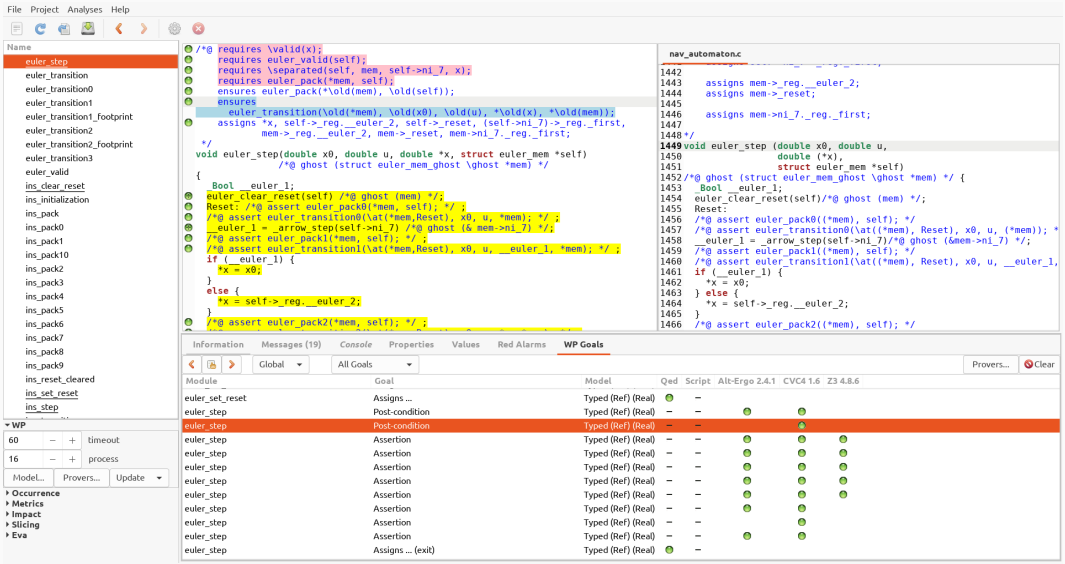

ACSL generation: contracts and assertions

```
void euler_step(double x0,
                double u, double *x,
                struct euler_mem *self)
    /*@ ghost (struct euler_mem_ghost \ghost *mem) */ {
  _Bool c;
  euler_clear_reset(self)/*@ ghost (mem) */;
  /*@ ghost struct euler_mem_ghost mem_reset = *mem; */
  /*@ assert euler_pack0(mem_reset, *mem, self); */
  /*@ assert euler_tr0(mem_reset, x0, u, *mem); */
  c = _arrow_step(self->a)/*@ ghost (&mem->a) */;
  /*@ assert euler_pack1(mem_reset, *mem, self); */
  /*@ assert euler_tr1(mem_reset, x0, u, c, *mem); */
  if (c) { *x = x0; } else { *x = self->y; }
  /*@ assert euler_tr2(mem_reset, x0, u, *x, *mem); */
  self->y = *x + 0.1 * u;
  //@ ghost mem->y = *x + 0.1 * u;
  /*@ assert euler_pack0(mem_reset, *mem, self); */
  /*@ assert euler_tr3(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->n1_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->n1_7)->_reg._first,
mem->_reg.__euler_2, mem->_reset, mem->n1_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 assigns mem->_reg.__euler_2;
1443 assigns mem->_reset;
1444
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)
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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)

Preliminary results

Test bench: $\sim$ 500 Lustre files

- $\sim$ 70% success (per file)
- $\sim$ 99% success (per proof obligation)

Test bench: $\sim$ 500 Lustre files

- $\sim$ 70% success (per file)
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Custom proof tactics as an OCaml plugin

Conclusion

Summary

- A certifying compiler from Lustre to C / ACSL
- Certificate of correctness wrt a state / transition semantics

Currently

- Promising results
- Automatic translation of high-level contracts

Future

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

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