Sémantique Mécanisée, Compilation Vérifiée et Compilation Certifiante pour Lustre

Séminaire SCALP

Lélio Brun[1]

20 mai 2021

[1]ISAE-SUPAERO – DISC – IpSC

Contexte

Systèmes embarqués

- systèmes informatiques au sein de systèmes physiques interagissant avec le monde réel, souvent sous des contraintes temps-réel
- logiciels habituellement développés avec des langages bas niveau : C, Ada, Assembleur

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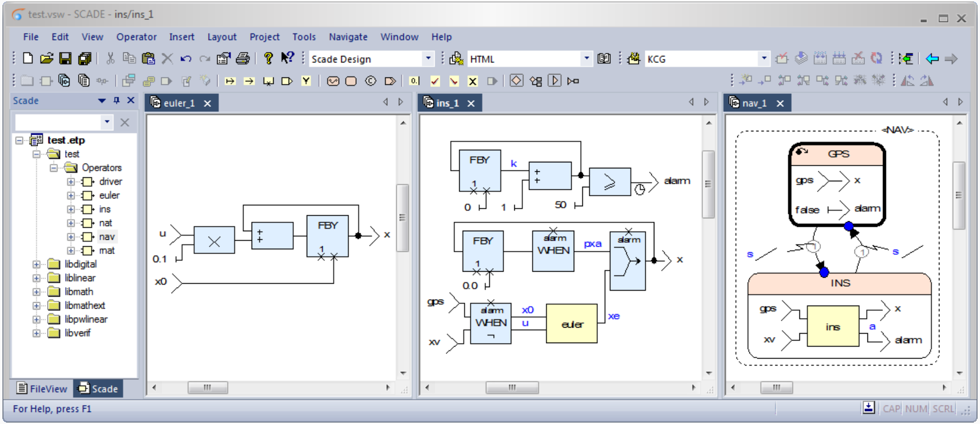
Model-Based Design

Spécifications abstraites de haut niveau exécutables

Model-Based Design dans SCADE Suite

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



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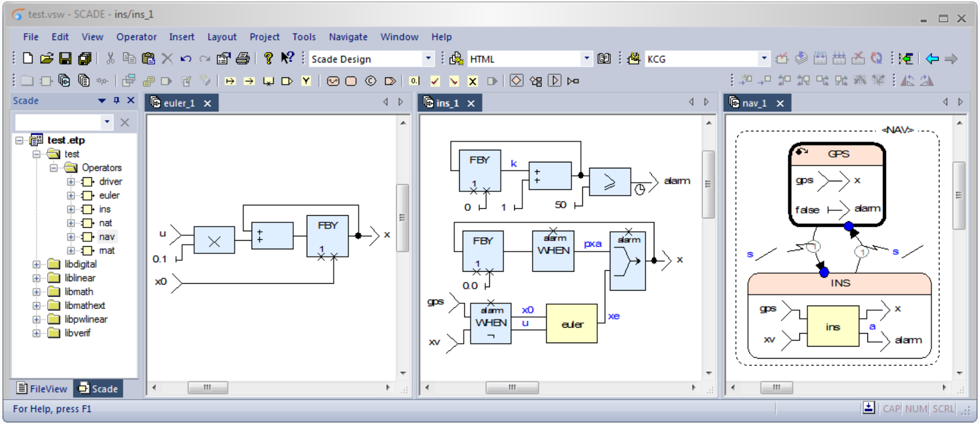

bloc / nœud = système

ligne = signal

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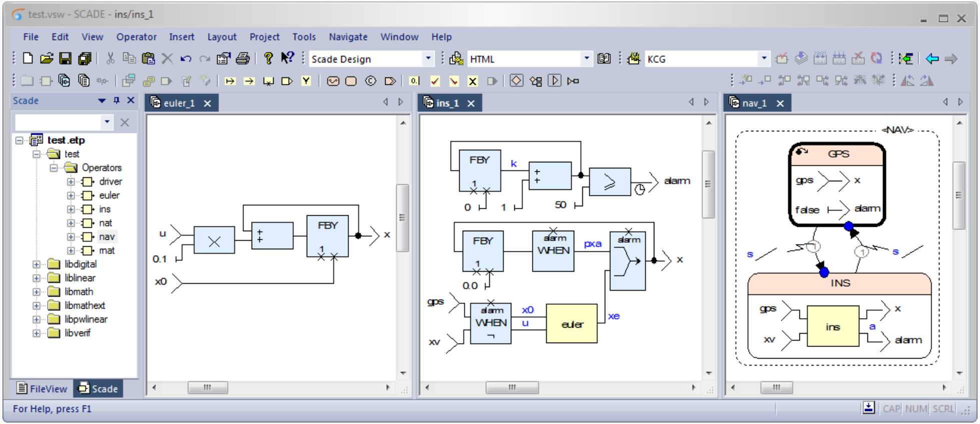

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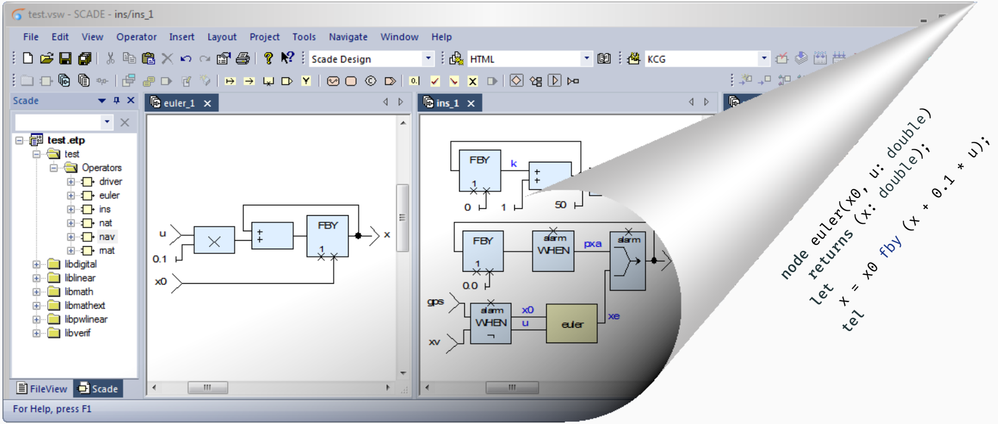

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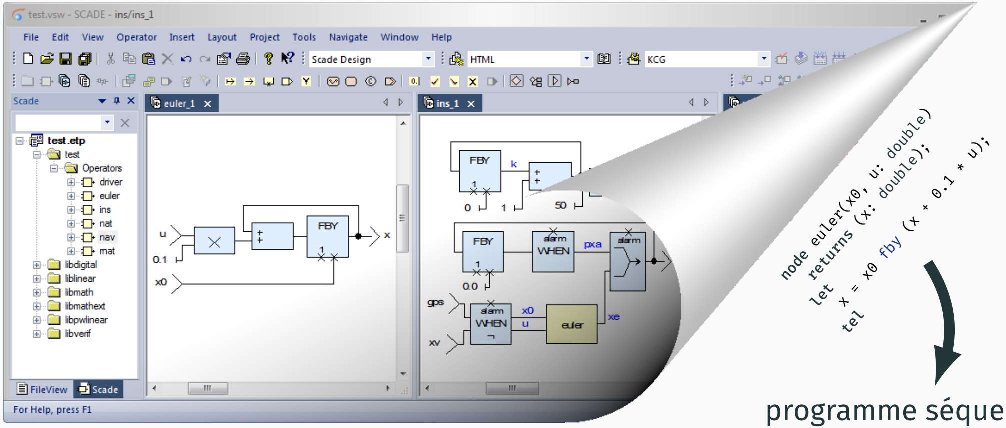


programme séquentiel
(C, Ada, Assembleur)

bloc / nœud = système = fonction de flots

ligne = signal = flot de valeurs

Systèmes qui ne doivent pas échouer

- Systèmes de contrôle de vol
- Systèmes ferroviaires automatiques
- Systèmes de contrôle de centrales

CRITICITÉ

Systèmes qui ne doivent pas échouer

- Systèmes de contrôle de vol
- Systèmes ferroviaires automatiques
- Systèmes de contrôle de centrales

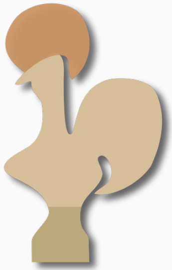
État de l'art : certification industrielle du processus de développement, parfois avec des *méthodes formelles*, ex. SCADE

Question scientifique : peut-on mécaniser les définitions formelles et produire une preuve de correction bout-à-bout ?

Formalisation Mécanisée

Assistant de Preuve

- Outils pour aider la formulation de théorèmes ainsi que le développement et la vérification de leurs preuves
- Mizar, Isabelle, HOL, Coq, ACL2, PVS, Agda, ...



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Formalisations mécanisées existantes

seL4 : un micro-noyau vérifié avec Isabelle

CakeML : un compilateur vérifié pour un langage fonctionnel avec HOL

CompCert : une étape clef

Formalisation mécanisée avec Coq du langage C et de la preuve de correction de sa compilation vers du code Assembleur.

Langages pour le Model-Based Design
Scade 6, Lustre

+

Assistants de Preuve
Coq

Défis

1. Mécaniser les sémantiques
2. Prouver la correction des algorithmes de compilation

Langages pour le Model-Based Design
Scade 6, Lustre

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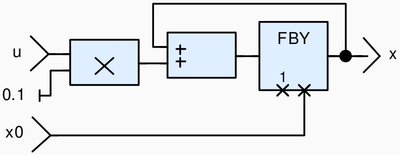
Assistants de Preuve
Coq

Défis

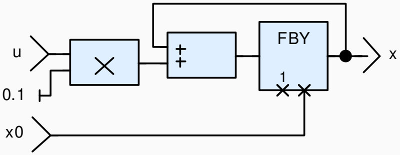
1. Mécaniser les sémantiques
2. Prouver la correction des algorithmes de compilation

Focus : réinitialisation modulaire (*modular reset*)




```
node euler(x0, u: double)
  returns (x: double);
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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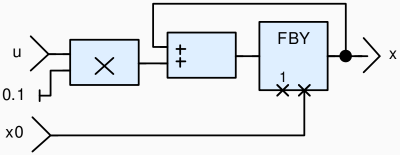
Exemple

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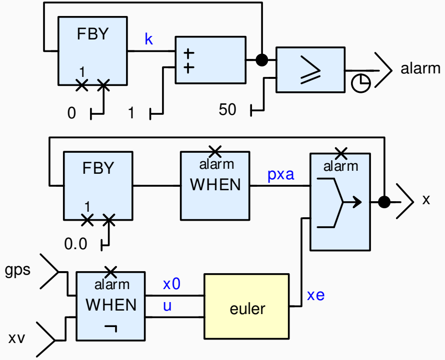


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k	0	1	2	3	...	49	50	51	...
alarm	F	F	F	F	...	F	T	T	...
xe	0.00	1.50	3.50	5.20	...	77.35			...
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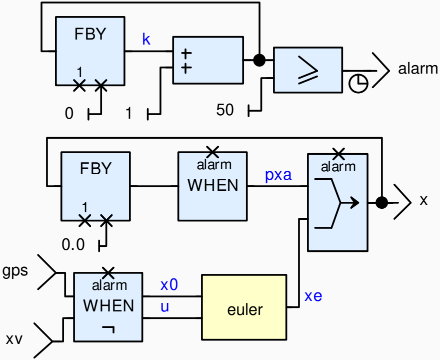


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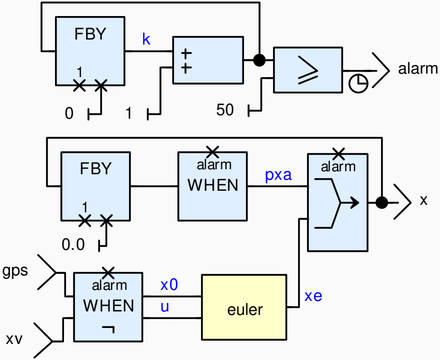


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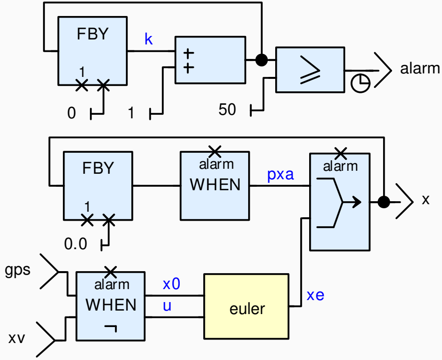


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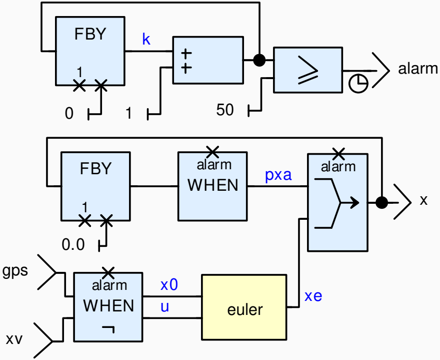


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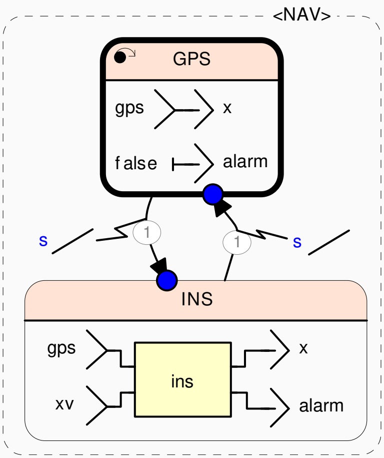


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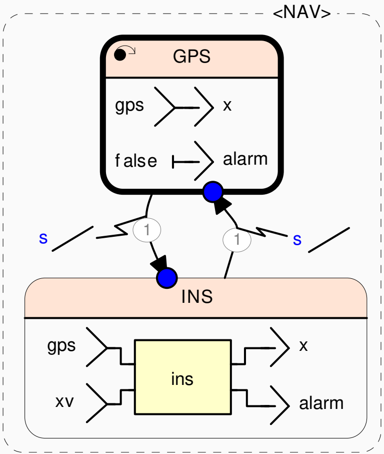


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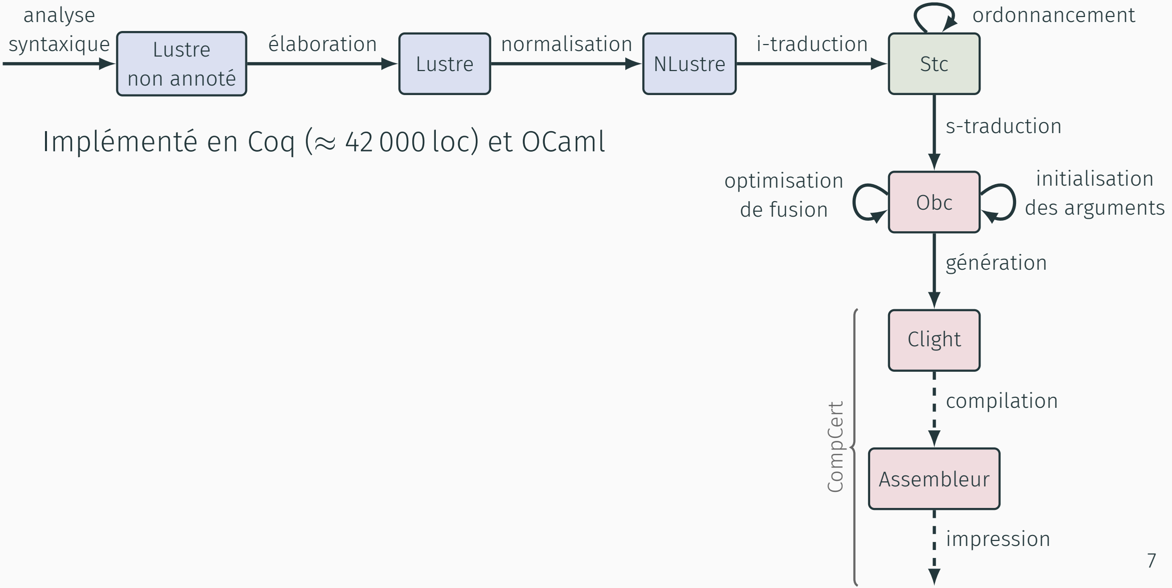
Il faut un moyen de réinitialiser l'état d'un nœud

Vélus : un Compilateur Lustre Vérifié

Biernacki, Colaço, Hamon et Pouzet 2008
Bourke, Brun, Dagand, Leroy, Pouzet et Rieg 2017
Bourke, Brun et Pouzet 2020



Implémenté en Coq ($\approx$ 42 000 loc) et OCaml

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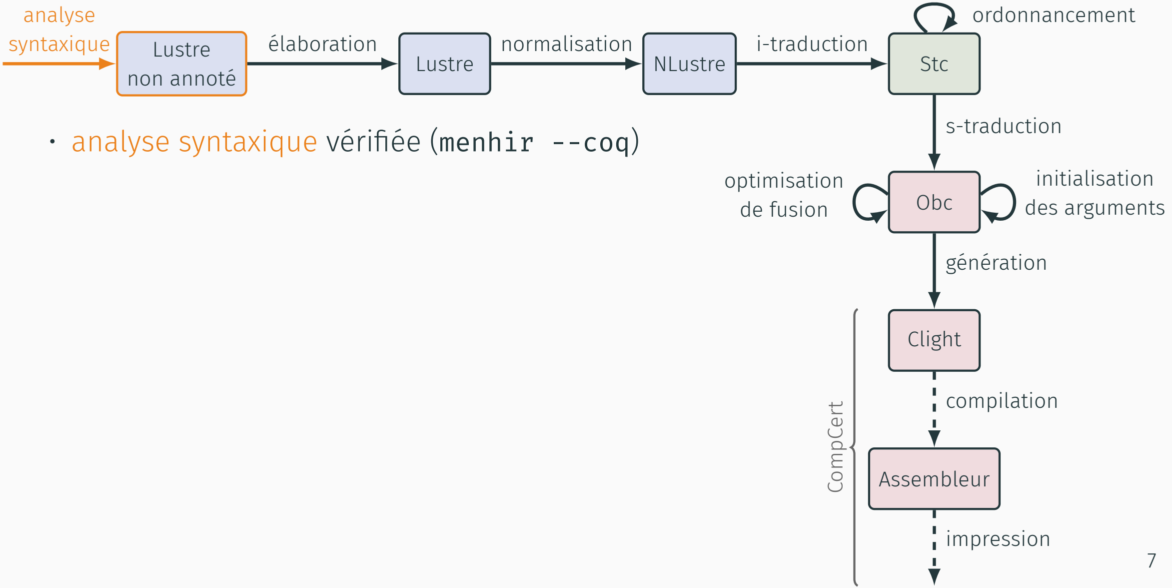

- analyse syntaxique vérifiée (`menhir --coq`)

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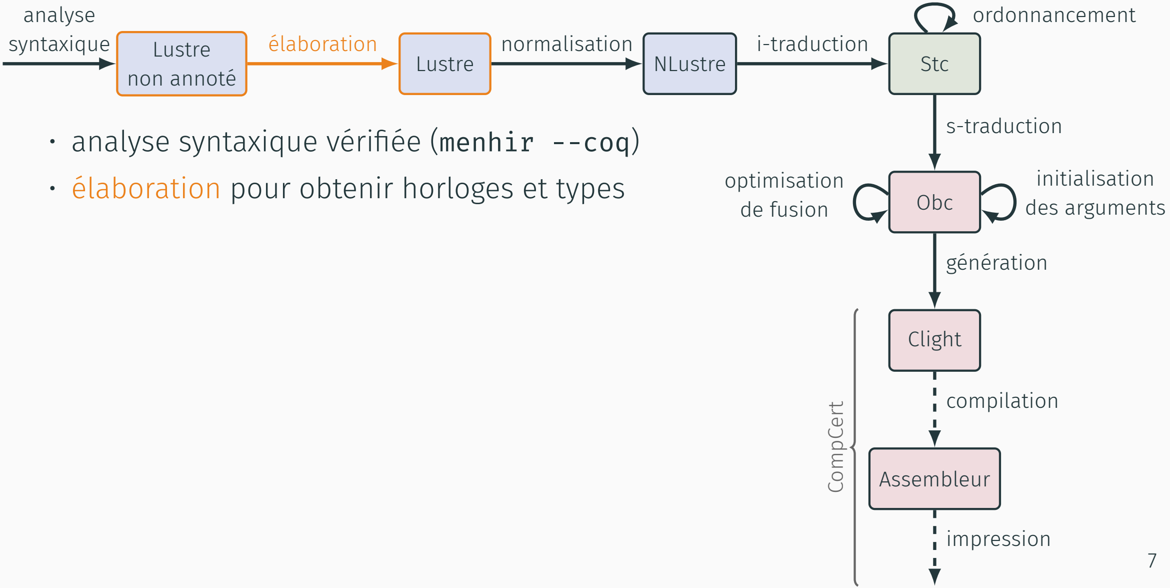

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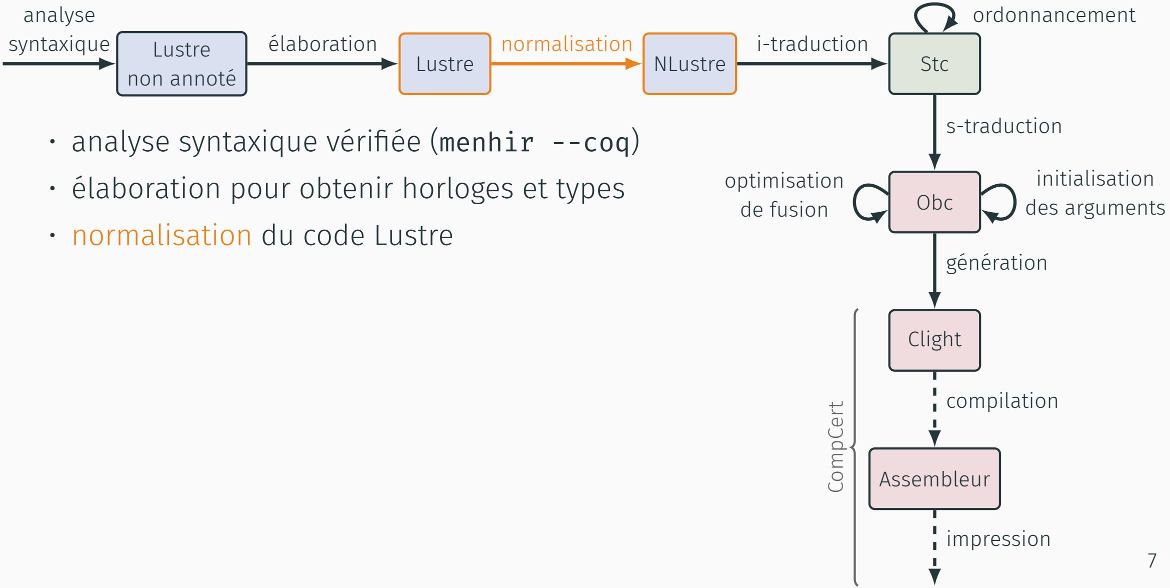

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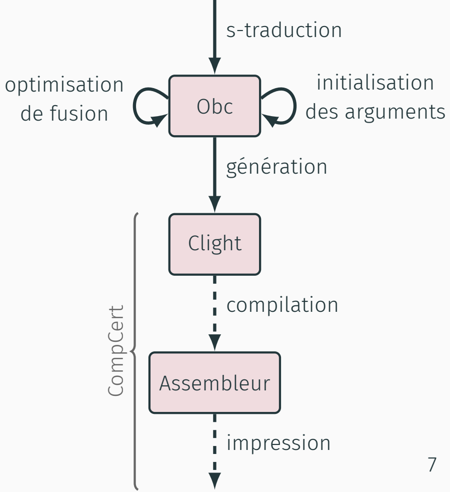

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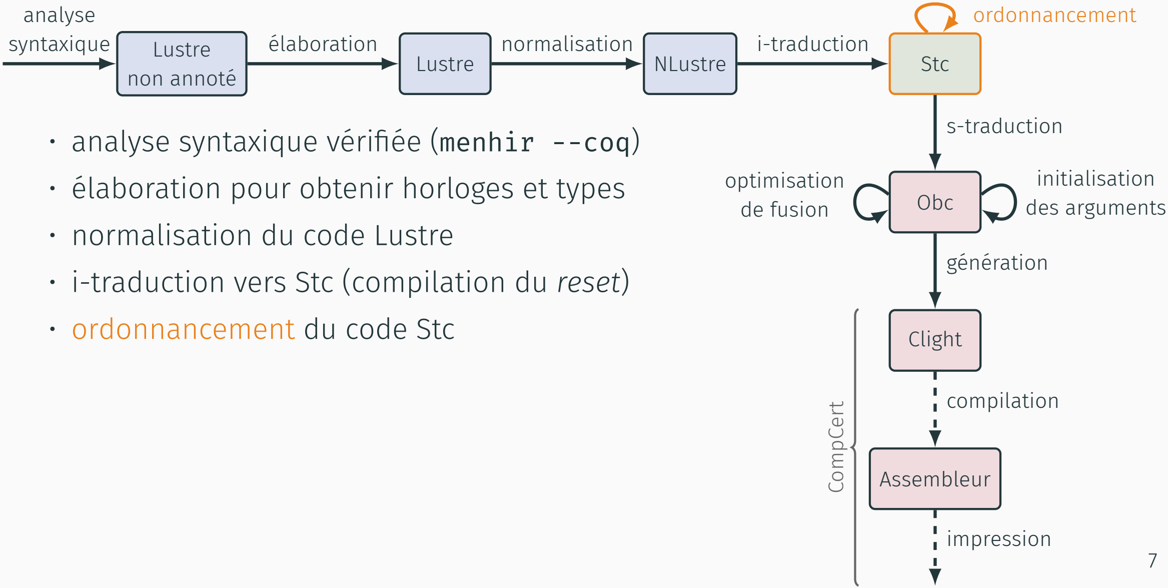

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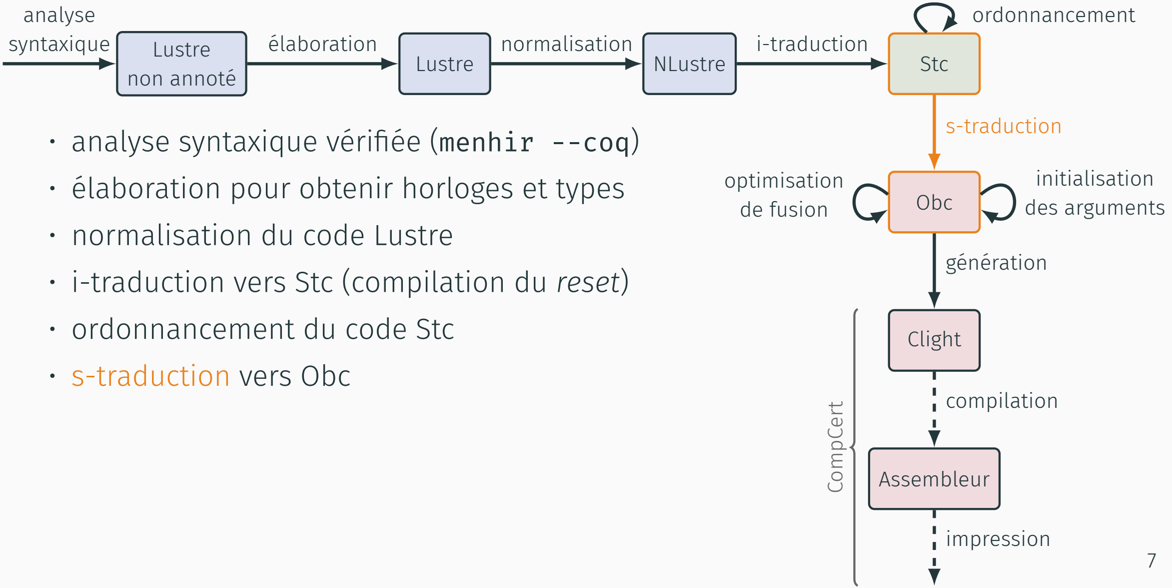

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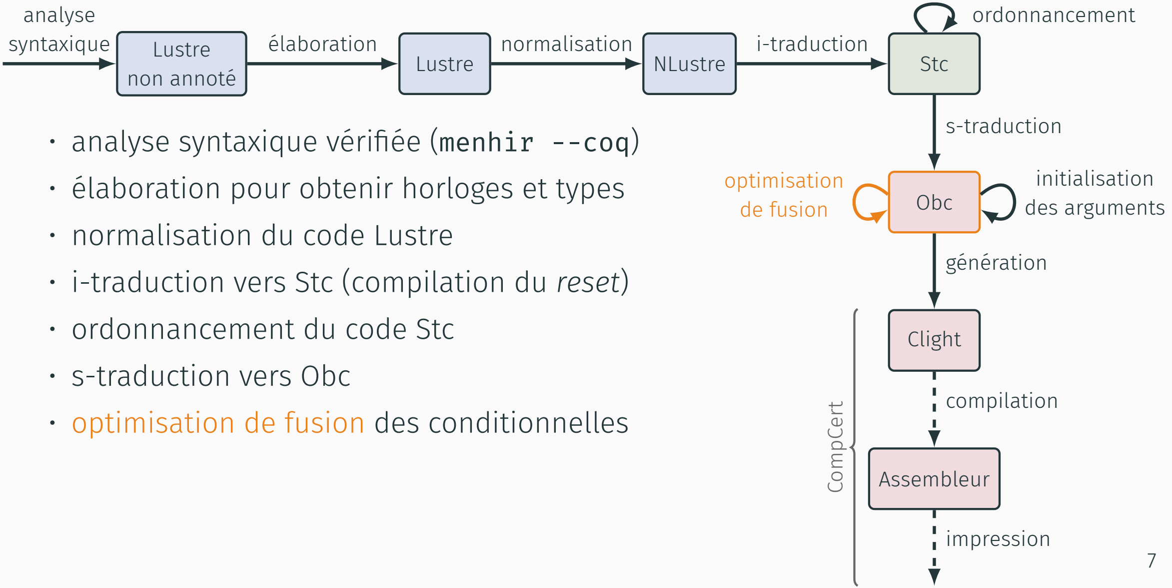
- s-traduction vers Obc



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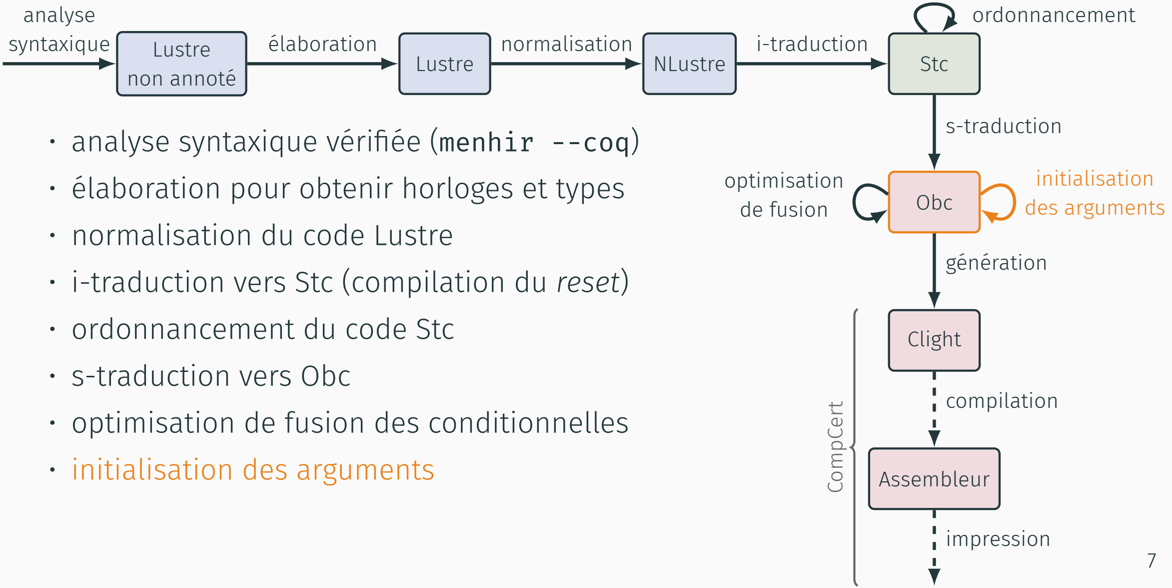

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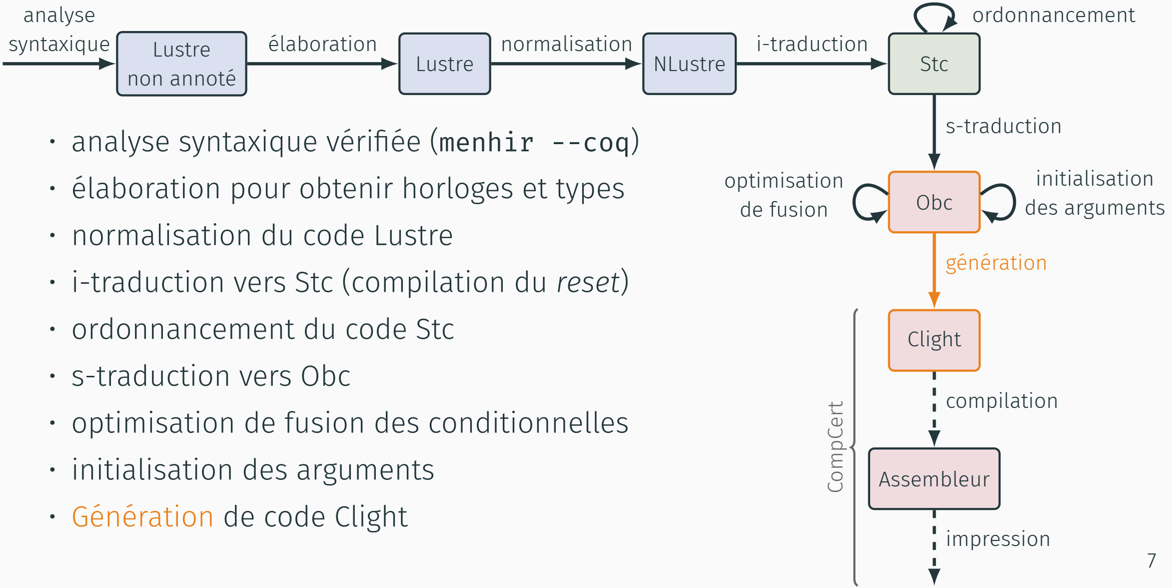

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- Génération de code Clight

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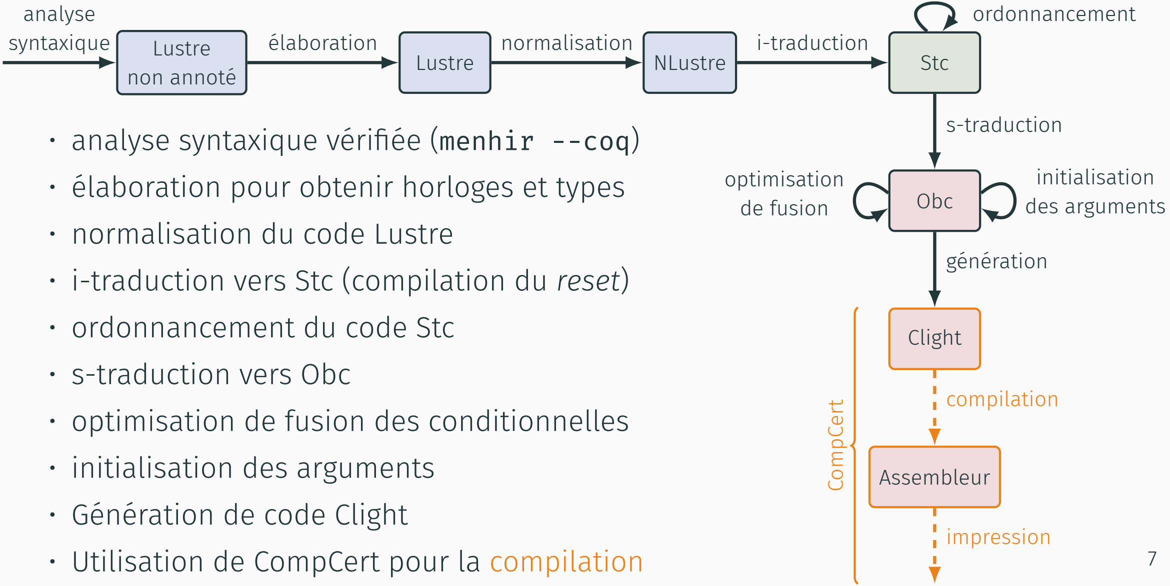

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- Utilisation de CompCert pour la compilation

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Lustre

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C

```
struct euler {
  bool i;
  double px;
};
struct ins {
  int k;
  double px;
  struct euler xe;
};
struct fun$ins$step {
  double x;
  bool alarm;
};
struct nav {
  bool c;
  bool r;
  struct ins insr;
};
struct fun$nav$step {
  double x;
  bool alarm;
};

double fun$euler$step(struct euler *self,
                      double x0, double u) {
  register double x;
  if (self->i) {
    x = x0;
  } else {
    x = self->px;
  }
  self->i = false;
  self->px = x + 0.100000000000000006 * u;
  return x;
}

void fun$euler$reset(struct euler *self) {
  self->i = true;
  self->px = 0;
  return;
}

void fun$ins$step(struct ins *self,
                  struct fun$ins$step *out,
                  double gps, double xv) {
  register double step$x;
  register double xe;
  out->alarm = self->k >= 50;
  self->k = self->k + 1;
  if (out->alarm) { out->x = self->px; }
  else {
    step$x = fun$euler$step(&(self->xe), gps, xv);
    xe = step$x;
    out->x = xe;
  }
  self->px = out->x;
  return;
}

void fun$ins$reset(struct ins *self) {
  self->k = 0;
  self->px = 0;
  fun$euler$reset(&(self->xe));
  return;
}

void fun$nav$step(struct nav *self,
                  struct fun$nav$step *out,
                  double gps, double xv, bool s) {
  struct fun$ins$step out$insr$step;
  register bool cm;
  register double insr;
  register bool alr;
  if (self->r) { fun$ins$reset(&(self->insr)); }
  self->r = s & self->c;
  if (self->c) {
    cm = !s;
    out->x = gps;
    out->alarm = false;
  } else {
    fun$ins$step(&(self->insr, &out$insr$step, gps, xv);
    insr = out$insr$step.x;
    alr = out$insr$step.alarm;
    cm = s;
    out->x = insr;
    out->alarm = alr;
  }
  self->c = cm;
  return;
}

void fun$nav$reset(struct nav *self) {
  self->c = true;
  self->r = false;
  fun$ins$reset(&(self->insr);
  return;
}

struct nav self$;
double volatile gps$;
double volatile xv$;
bool volatile s$;
double volatile x$;
bool volatile alarm$;

int main(void) {
  struct fun$nav$step out$step;
  register double gps;
  register double xv;
  register bool s;

  fun$nav$reset(&self$);

  while (true) {
    gps = volatile_load(&gps$);
    xv = volatile_load(&xv$);
    s = volatile_load(&s$);

    fun$nav$step(&self$, &out$step, gps, xv, s);

    volatile_store(&x$, out$step.x);
    volatile_store(&alarm$, out$step.alarm);
  }
}
```

Lustre

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

node ins(gps, xv: double)
  returns (x: double, alarm: bool)
  var pxa, xe: double; 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: double, s: bool)
  returns (x: double, alarm: bool)
  var r, c: bool;
let
  (x, alarm) = merge c
                 (gps when c, false)
                 ((restart ins every r)
                    ((gps, xv) whenot c));
  c = true fby (merge c (not s when c)
                        (s whenot c));
  r = false fby (s and c);
tel
```

C

```
struct euler {
  bool i;
  double px;
};
struct ins {
  int k;
  double px;
  struct euler xe;
};
struct fun$ins$step {
  double x;
  bool alarm;
};
struct nav {
  bool c;
  bool r;
  struct ins insr;
};
struct fun$nav$step {
  double x;
  bool alarm;
};

double fun$euler$step(struct euler *self,
                      double x0, double u) {
  register double x;
  if (self->i) {
    x = x0;
  } else {
    x = self->px;
  }
  self->i = false;
  self->px = x + 0.100000000000000006 * u;
  return x;
}

void fun$euler$reset(struct euler *self) {
  self->i = true;
  self->px = 0;
  return;
}

void fun$ins$step(struct ins *self,
                  struct fun$ins$step *out,
                  double gps, double xv) {
  register double step$x;
  register double xe;
  out->alarm = self->k >= 50;
  self->k = self->k + 1;
  if (out->alarm) { out->x = self->px; }
  else {
    step$x = fun$euler$step(&(self->xe), gps, xv);
    xe = step$x;
    out->x = xe;
  }
  self->px = out->x;
  return;
}

void fun$ins$reset(struct ins *self) {
  self->k = 0;
  self->px = 0;
  fun$euler$reset(&(self->xe));
  return;
}

void fun$nav$step(struct nav *self,
                  struct fun$nav$step *out,
                  double gps, double xv, bool s) {
  struct fun$ins$step out$insr$step;
  register bool cm;
  register double insr;
  register bool alr;
  if (self->r) { fun$ins$reset(&(self->insr)); }
  self->r = s & self->c;
  if (self->c) {
    cm = !s;
    out->x = gps;
    out->alarm = false;
  } else {
    fun$ins$step(&(self->insr, &out$insr$step, gps, xv);
    insr = out$insr$step.x;
    alr = out$insr$step.alarm;
    cm = s;
    out->x = insr;
    out->alarm = alr;
  }
  self->c = cm;
  return;
}

void fun$nav$reset(struct nav *self) {
  self->c = true;
  self->r = false;
  fun$ins$reset(&(self->insr);
  return;
}
```

code traduit

```
struct nav self$;
double volatile gps$;
double volatile xv$;
bool volatile s$;
double volatile x$;
bool volatile alarm$;

int main(void) {
  struct fun$nav$step out$step;
  register double gps;
  register double xv;
  register bool s;

  fun$nav$reset(&self$);

  while (true) {
    gps = volatile_load(&gps$);
    xv = volatile_load(&xv$);
    s = volatile_load(&s$);

    fun$nav$step(&self$, &out$step, gps, xv, s);

    volatile_store(&x$, out$step.x);
    volatile_store(&alarm$, out$step.alarm);
  }
}
```

Lustre

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

node ins(gps, xv: double)
  returns (x: double, alarm: bool)
  var pxa, xe: double; 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: double, s: bool)
  returns (x: double, alarm: bool)
  var r, c: bool;
let
  (x, alarm) = merge c
               (gps when c, false)
               ((restart ins every r)
                  ((gps, xv) whenot c));
  c = true fby (merge c (not s when c)
                      (s whenot c));
  r = false fby (s and c);
tel
```

C

```c
struct euler {
  bool i;
  double px;
};
struct ins {
  int k;
  double px;
  struct euler xe;
};
struct fun$ins$step {
  double x;
  bool alarm;
};
struct nav {
  bool c;
  bool r;
  struct ins insr;
};
struct fun$nav$step {
  double x;
  bool alarm;
};

double fun$euler$step(struct euler *self,
                      double x0, double u) {
  register double x;
  if (self->i) {
    x = x0;
  } else {
    x = self->px;
  }
  self->i = false;
  self->px = x + 0.10000000000000006 * u;
  return x;
}

void fun$euler$reset(struct euler *self) {
  self->i = true;
  self->px = 0;
  return;
}

void fun$ins$step(struct ins *self,
                  struct fun$ins$step *out,
                  double gps, double xv) {
  register double step$x;
  register double xe;
  out->alarm = self->k >= 50;
  self->k = self->k + 1;
  if (out->alarm) { out->x = self->px; }
  else {
    step$x = fun$euler$step(&(self->xe), gps, xv);
    xe = step$x;
    out->x = xe;
  }
  self->px = out->x;
  return;
}

void fun$ins$reset(struct ins *self) {
  self->k = 0;
  self->px = 0;
  fun$euler$reset(&(self->xe));
  return;
}
```

```c
void fun$nav$step(struct nav *self,
                  struct fun$nav$step *out,
                  double gps, double xv, bool s) {
  struct fun$ins$step out$insr$step;
  register bool cm;
  register double insr;
  register bool alr;
  if (self->r) { fun$ins$reset(&(self->insr)); }
  self->r = s & self->c;
  if (self->c) {
    cm = !s;
    out->x = gps;
    out->alarm = false;
  } else {
    fun$ins$step(&(self->insr, &out$insr$step, gps, xv);
    insr = out$insr$step.x;
    alr = out$insr$step.alarm;
    cm = s;
    out->x = insr;
    out->alarm = alr;
  }
  self->c = cm;
  return;
}

void fun$nav$reset(struct nav *self) {
  self->c = true;
  self->r = false;
  fun$ins$reset(&(self->insr));
  return;
}
```

boucle principale

```c
struct nav self$;
double volatile gps$;
double volatile xv$;
bool volatile s$;
double volatile x$;
bool volatile alarm$;

int main(void) {
  struct fun$nav$step out$step;
  register double gps;
  register double xv;
  register bool s;

  fun$nav$reset(&self$);

  while (true) {
    gps = volatile_load(&gps$);
    xv = volatile_load(&xv$);
    s = volatile_load(&s$);

    fun$nav$step(&self$, &out$step, gps, xv, s);

    volatile_store(&x$, out$step.x);
    volatile_store(&alarm$, out$step.alarm);
  }
}
```

Lustre

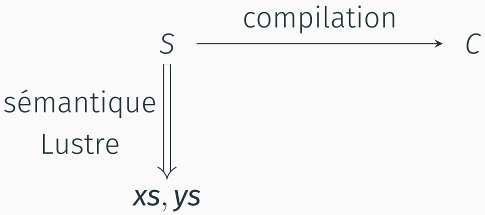
```
node euler(x0, u: double)
  returns (x: double);
let
  x = x0 fby (x + 0.1 * u);
tel

node ins(gps, xv: double)
  returns (x: double, alarm: bool)
  var pxa, xe: double; 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: double, s: bool)
  returns (x: double, alarm: bool)
  var r, c: bool;
let
  (x, alarm) = merge c
               (gps when c, false)
               ((restart ins every r)
                  ((gps, xv) whenot c));
  c = true fby (merge c (not s when c)
                        (s whenot c));
  r = false fby (s and c);
tel
```

Assembleur

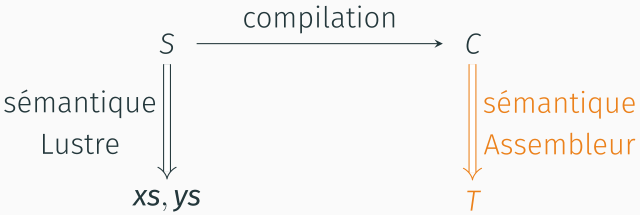
```
        .data
        .align  8
        .globl  self$
self$:
        .space  40
        .type   self$, @object
        .size   self$, . - self$
        .data
        .align  8
        .globl  x$
x$:
        .space  8
        .type   x$, @object
        .size   x$, . - x$
        .data
        .align  8
        .globl  alarm$
alarm$:
        .space  1
        .type   alarm$, @object
        .size   alarm$, . - alarm$
        .data
        .align  8
        .globl  gps$
gps$:
        .space  8
        .type   gps$, @object
        .size   gps$, . - gps$
        .data
        .align  8
        .globl  xv$
xv$:
        .space  8
        .type   xv$, @object
        .size   xv$, . - xv$
        .data
        .align  8
        .globl  s$
s$:
        .space  1
        .type   s$, @object
        .size   s$, . - s$
        .text
        .align  16
        .globl fun$euler$step
fun$euler$step:
        .cfi_startproc
        subq    $8, %rsp
        .cfi_adjust_cfa_offset  8
        leaq    16(%rsp), %rax
        movq    %rax, 0(%rsp)
        movzbl  0(%rdi), %eax
        cmpl    $0, %eax
        jne     .L100
        movsd   8(%rdi), %xmm0
.L100:
        xorl    %ecx, %ecx
        movb    %cl, 0(%rdi)
        movsd   .L101(%rip), %xmm2 # 0.100000000000000006
        mulsd   %xmm1, %xmm2
        movapd  %xmm0, %xmm1
        addsd   %xmm2, %xmm1
        movsd   %xmm1, 8(%rdi)
        addq    $8, %rsp
        ret
        .cfi_endproc
        .type   fun$euler$step, @function
        .size   fun$euler$step, . - fun$euler$step
        .section        .rodata.cst8,"aM",@progbits,8
        .align  8
.L101:  .quad   0x3fb999999999999a
        .text
        .align  16
        .globl fun$euler$reset
fun$euler$reset:
        .cfi_startproc
        subq    $8, %rsp
        .cfi_adjust_cfa_offset  8
        leaq    16(%rsp), %rax
        movq    %rax, 0(%rsp)
        movl    $1, %eax
        movb    %al, 0(%rdi)
        xorpd   %xmm0, %xmm0
        movsd   %xmm0, 8(%rdi)
        addq    $8, %rsp
        ret
        .cfi_endproc
        .type   fun$euler$reset, @function
        .size   fun$euler$reset, . - fun$euler$reset
        .text
        .align  16
        .globl fun$ins$step
fun$ins$step:
        .cfi_startproc
        subq    $24, %rsp
        .cfi_adjust_cfa_offset  24
        leaq    32(%rsp), %rax
        movq    %rax, 0(%rsp)
        movq    %rbx, 8(%rsp)
        movq    %rbp, 16(%rsp)
        movq    %rsi, %rbx
        movq    %rdi, %rbp
        movl    0(%rbp), %r9d
        cmpl    $50, %r9d
        setge   %r8b
        movzbl  %r8b, %r8d
        movb    %r8b, 8(%rbx)
        movl    0(%rbp), %ecx
        leal    1(%ecx), %eax
        movl    %eax, 0(%rbp)
        movzbl  8(%rbx), %edx
        cmpl    $0, %edx
        jne     .L102
        leaq    16(%rbp), %rdi
        call    fun$euler$step
        movsd   %xmm0, 0(%rbx)
        jmp     .L103
.L102:
        movsd   8(%rbp), %xmm2
        movsd   %xmm2, 0(%rbx)
.L103:
        movsd   0(%rbx), %xmm3
        movsd   %xmm3, 8(%rbp)
        movq    8(%rsp), %rbx
        movq    16(%rsp), %rbp
        addq    $24, %rsp
        ret
        .cfi_endproc
        .type   fun$ins$step, @function
        .size   fun$ins$step, . - fun$ins$step
        .text
        .align  16
        .globl fun$ins$reset
fun$ins$reset:
        .cfi_startproc
        subq    $8, %rsp
        .cfi_adjust_cfa_offset  8
        leaq    16(%rsp), %rax
        movq    %rax, 0(%rsp)
        xorl    %eax, %eax
        movl    %eax, 0(%rdi)
        xorpd   %xmm0, %xmm0
        movsd   %xmm0, 8(%rdi)
        leaq    16(%rdi), %rdi
        addq    $8, %rsp
        jmp     fun$euler$reset
        .cfi_endproc
        .type   fun$ins$reset, @function
        .size   fun$ins$reset, . - fun$ins$reset
        .text
        .align  16
        .globl fun$nav$step
fun$nav$step:
        .cfi_startproc
        subq    $72, %rsp
        .cfi_adjust_cfa_offset  72
        leaq    80(%rsp), %rax
        movq    %rax, 0(%rsp)
        movq    %rbx, 8(%rsp)
        movq    %rbp, 16(%rsp)
        movq    %r12, 24(%rsp)
        movq    %rdx, %rbx
        movsd   %xmm1, 40(%rsp)
        movsd   %xmm0, 32(%rsp)
        movq    %rsi, %rbp
        movq    %rdi, %r12
        movzbl  1(%r12), %edi
        cmpl    $0, %edi
        je      .L104
        leaq    8(%r12), %rdi
        call    fun$ins$reset
.L104:
        movzbl  0(%r12), %r9d
        movq    %rbx, %rax
        andl    %r9d, %eax
        cmpl    $0, %eax
        setne   %al
        movzbl  %al, %eax
        movb    %al, 1(%r12)
        movzbl  0(%r12), %r10d
        cmpl    $0, %r10d
        jne     .L105
        leaq    8(%r12), %rdi
        leaq    48(%rsp), %rsi
        movsd   40(%rsp), %xmm1
        movsd   32(%rsp), %xmm0
        call    fun$ins$step
        movsd   48(%rsp), %xmm3
        movzbl  56(%rsp), %esi
        movsd   %xmm3, 0(%rbp)
        cmpl    $0, %esi
        setne   %dl
        movzbl  %dl, %edx
        movb    %dl, 8(%rbp)
        jmp     .L106
.L105:
        cmpl    $0, %ebx
        sete    %bl
        movzbl  %bl, %ebx
        movsd   32(%rsp), %xmm0
        movsd   %xmm0, 0(%rbp)
        xorl    %r11d, %r11d
        movb    %r11b, 8(%rbp)
.L106:
        cmpl    $0, %ebx
        setne   %r8b
        movzbl  %r8b, %r8d
        movb    %r8b, 0(%r12)
        movq    8(%rsp), %rbx
        movq    16(%rsp), %rbp
        movq    24(%rsp), %r12
        addq    $72, %rsp
        ret
        .cfi_endproc
        .type   fun$nav$step, @function
        .size   fun$nav$step, . - fun$nav$step
        .text
        .align  16
        .globl fun$nav$reset
fun$nav$reset:
        .cfi_startproc
        subq    $8, %rsp
        .cfi_adjust_cfa_offset  8
        leaq    16(%rsp), %rax
        movq    %rax, 0(%rsp)
        movl    $1, %eax
        movb    %al, 0(%rdi)
        xorl    %ecx, %ecx
        movb    %cl, 1(%rdi)
        leaq    8(%rdi), %rdi
        addq    $8, %rsp
        jmp     fun$ins$reset
        .cfi_endproc
        .type   fun$nav$reset, @function
        .size   fun$nav$reset, . - fun$nav$reset
        .text
        .align  16
        .globl main_sync
main_sync:
        .cfi_startproc
        subq    $24, %rsp
        .cfi_adjust_cfa_offset  24
        leaq    32(%rsp), %rax
        movq    %rax, 0(%rsp)
        leaq    self$(%rip), %rdi
        call    fun$nav$reset
.L107:
        call    sync
        movsd   gps$(%rip), %xmm0
        movsd   xv$(%rip), %xmm1
        movzbl  s$(%rip), %ecx
        leaq    self$(%rip), %rdi
        leaq    8(%rsp), %rsi
        cmpl    $0, %ecx
        setne   %dl
        movzbl  %dl, %edx
        call    fun$nav$step
        movsd   8(%rsp), %xmm0
        movsd   %xmm0, x$(%rip)
        movzbl  16(%rsp), %eax
        cmpl    $0, %eax
        setne   %al
        movzbl  %al, %eax
        movb    %al, alarm$(%rip)
        jmp     .L107
        .cfi_endproc
        .type   main_sync, @function
        .size   main_sync, . - main_sync
        .text
        .align  16
        .globl main_proved
main_proved:
        .cfi_startproc
        subq    $24, %rsp
        .cfi_adjust_cfa_offset  24
        leaq    32(%rsp), %rax
        movq    %rax, 0(%rsp)
        leaq    self$(%rip), %rdi
        call    fun$nav$reset
.L108:
        movsd   gps$(%rip), %xmm0
        movsd   xv$(%rip), %xmm1
        movzbl  s$(%rip), %eax
        leaq    self$(%rip), %rdi
        leaq    8(%rsp), %rsi
        cmpl    $0, %eax
        setne   %dl
        movzbl  %dl, %edx
        call    fun$nav$step
        movsd   8(%rsp), %xmm0
        movsd   %xmm0, x$(%rip)
        movzbl  16(%rsp), %eax
        cmpl    $0, %eax
        setne   %al
        movzbl  %al, %eax
        movb    %al, alarm$(%rip)
        jmp     .L108
        .cfi_endproc
        .type   main_proved, @function
        .size   main_proved, . - main_proved
        .text
        .align  16
        .globl main
main:
        .cfi_startproc
        subq    $8, %rsp
        .cfi_adjust_cfa_offset  8
        leaq    16(%rsp), %rax
        movq    %rax, 0(%rsp)
        call    main_sync
        movq    %rbx, %rax
        addq    $8, %rsp
        ret
        .cfi_endproc
        .type   main, @function
        .size   main, . - main
```

Correction ?

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


compilation
S
C
sémantique
Lustre
xs, ys

Correction ?


compilation
S
C
sémantique Lustre
sémantique Assembleur
xs, ys
T

Correction ?


compilation
S
C
sémantique
Lustre
sémantique
Assembleur
xs, ys
T
« équivalence »

Remarque : on veut en réalité la direction opposée, appelée *raffinement*, c'est-à-dire les comportements observables de C sont aussi des comportements observables de S.

Mécanisation de Lustre Normalisé

4 types d'équations

$x = ce$	équation simple
$x = c$ **fby** e	équation **fby**
$\boldsymbol{x} = f(\boldsymbol{e})$	instanciation de nœud
$\boldsymbol{x} = ($**restart** f **every** $r)(\boldsymbol{e})$	instanciation avec *reset* modulaire

Sémantique

Flots comme fonctions $\mathbb{N} \mapsto$ value :

$$\begin{array}{cccc} 0 & 1 & 2 & \cdots \\ \downarrow & \downarrow & \downarrow & \cdots \\ v_0 & v_1 & v_2 & \cdots \end{array}$$

sémantique instantanée projetée

Flots comme coinductifs :

$$v_0 \cdot v_1 \cdot v_2 \cdot \cdots$$

description coinductive de la sémantique

Sémantique Instantanée

$$\frac{}{R \vdash x \downarrow R(x)} \qquad \frac{R \vdash e_1 \downarrow \langle v_1 \rangle \quad R \vdash e_2 \downarrow \langle v_2 \rangle}{R \vdash e_1 + e_2 \downarrow \langle [\![+]\!](v_1, v_2) \rangle} \qquad \frac{R \vdash e_1 \downarrow \langle\ \rangle \quad R \vdash e_2 \downarrow \langle\ \rangle}{R \vdash e_1 + e_2 \downarrow \langle\ \rangle}$$

Sémantique Projetée

$$\frac{\forall i,\ H_i(x) = s_i \quad \forall i,\ H_i \vdash e \downarrow s_i}{H \vdash x\ =\ e} \qquad \frac{\forall i,\ H_i \vdash e \downarrow s_i \quad \forall i,\ H_i(x) = \mathrm{fby}(c, s)_i}{H \vdash x\ =\ c\ \texttt{fby}\ e}$$

$$\frac{\forall i,\ H_i \vdash \mathbf{e} \downarrow xs_i \quad \vdash f(xs) \Downarrow ys \quad \forall i,\ H_i(\mathbf{x}) = ys_i}{H \vdash \mathbf{x}\ =\ f(\,\mathbf{e}\,)}$$

Sémantique Instantanée

$$\frac{}{R \vdash x \downarrow R(x)} \qquad \frac{R \vdash e_1 \downarrow \langle v_1 \rangle \quad R \vdash e_2 \downarrow \langle v_2 \rangle}{R \vdash e_1 + e_2 \downarrow \langle [\![+]\!](v_1, v_2) \rangle} \qquad \frac{R \vdash e_1 \downarrow \langle\,\rangle \quad R \vdash e_2 \downarrow \langle\,\rangle}{R \vdash e_1 + e_2 \downarrow \langle\,\rangle}$$

Sémantique Projetée

$$\frac{\forall i,\ H_i(x) = s_i \quad \forall i,\ H_i \vdash e \downarrow s_i}{H \vdash x = e} \qquad \frac{\forall i,\ H_i \vdash e \downarrow s_i \quad \forall i,\ H_i(x) = \mathrm{fby}(c, s)_i}{H \vdash x = c\ \texttt{fby}\ e}$$

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Sémantique Instantanée

$$\frac{}{R \vdash x \downarrow R(x)} \qquad \frac{R \vdash e_1 \downarrow \langle v_1 \rangle \quad R \vdash e_2 \downarrow \langle v_2 \rangle}{R \vdash e_1 + e_2 \downarrow \langle [\![+]\!](v_1, v_2) \rangle} \qquad \frac{R \vdash e_1 \downarrow \langle\, \rangle \quad R \vdash e_2 \downarrow \langle\, \rangle}{R \vdash e_1 + e_2 \downarrow \langle\, \rangle}$$

Sémantique Projetée

$$\frac{\forall i,\ H_i(x) = s_i \quad \forall i,\ H_i \vdash e \downarrow s_i}{H \vdash x = e} \qquad \frac{\forall i,\ H_i \vdash e \downarrow s_i \quad \forall i,\ H_i(x) = \mathrm{fby}(c, s)_i}{H \vdash x = c \ \texttt{fby}\ e}$$

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$$\frac{}{R \vdash x \downarrow R(x)} \qquad \frac{R \vdash e_1 \downarrow \langle v_1 \rangle \quad R \vdash e_2 \downarrow \langle v_2 \rangle}{R \vdash e_1 + e_2 \downarrow \langle [\![+]\!](v_1, v_2) \rangle} \qquad \frac{R \vdash e_1 \downarrow \langle\, \rangle \quad R \vdash e_2 \downarrow \langle\, \rangle}{R \vdash e_1 + e_2 \downarrow \langle\, \rangle}$$

Sémantique Projetée

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Sémantique de Nœud

$$\frac{\text{node}(G, f) = n \quad \forall i,\ H_i(n.\textbf{in}) = xs_i \quad \forall i,\ H_i(n.\textbf{out}) = ys_i \qquad \forall eq \in n.\textbf{eqs},\ H \vdash eq}{\vdash f(xs) \Downarrow ys}$$

Sémantique de Nœud

$$\frac{\text{node}(G, f) = n \quad \forall i,\ H_i(n.\mathbf{in}) = xs_i \quad \forall i,\ H_i(n.\mathbf{out}) = ys_i \quad \forall eq \in n.\mathbf{eqs},\ H \vdash eq}{\vdash f(xs) \Downarrow ys}$$

Sémantique de Nœud

$$\frac{\text{node}(G, f) = n \quad \forall i,\ H_i(n.\mathbf{in}) = xs_i \quad \forall i,\ H_i(n.\mathbf{out}) = ys_i \quad \forall eq \in n.\mathbf{eqs},\ H \vdash eq}{\vdash f(xs) \Downarrow ys}$$

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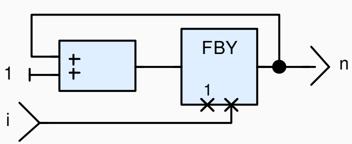
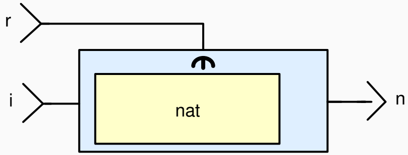
Sémantique de Nœud

$$\frac{\text{node}(G, f) = n \quad \forall i,\ H_i(n.\mathbf{in}) = xs_i \quad \forall i,\ H_i(n.\mathbf{out}) = ys_i \qquad \forall eq \in n.\mathbf{eqs},\ H \vdash eq}{\vdash f(xs) \Downarrow ys}$$

Exemple Plus Simple : Sémantique Intuitive du Reset Modulaire

```
node nat(i: int)
  returns (n: int)
let
  n = i fby (n + 1);
tel
```





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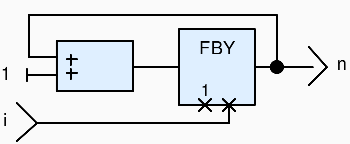
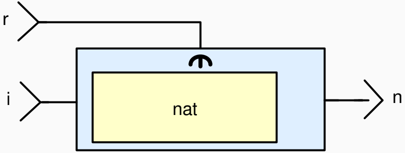
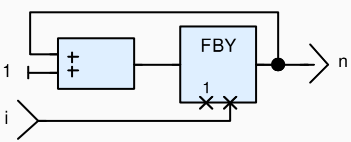
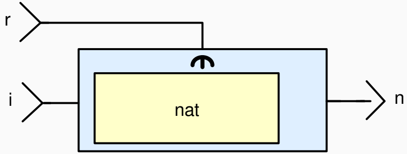




r	F
i	0
$nat(i)$	0
$(\texttt{restart}\ nat\ \texttt{every}\ r)(i)$	0

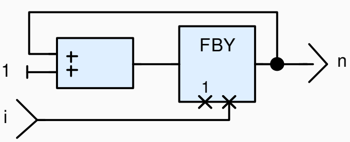
```
node nat(i: int)
  returns (n: int)
let
  n = i fby (n + 1);
tel
```

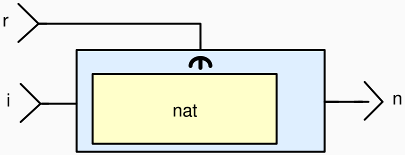




r	F	F
i	0	5
$nat(i)$	0	1
$(\texttt{restart}\ nat\ \texttt{every}\ r)(i)$	0	1

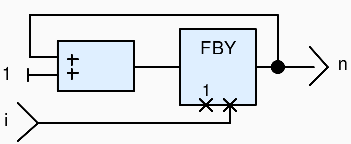
```
node nat(i: int)
  returns (n: int)
let
  n = i fby (n + 1);
tel
```

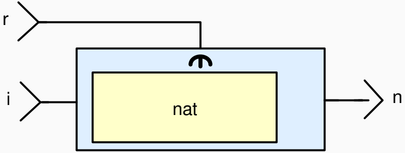




r	F	F	T
i	0	5	10
$nat(i)$	0	1	2
$(\texttt{restart}\ nat\ \texttt{every}\ r)(i)$	0	1	10

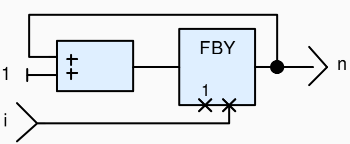
```
node nat(i: int)
  returns (n: int)
let
  n = i fby (n + 1);
tel
```

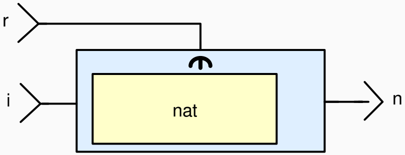




r	F	F	T	F
i	0	5	10	15
$nat(i)$	0	1	2	3
(**restart** nat **every** r)(i)	0	1	10	11

```
node nat(i: int)
  returns (n: int)
let
  n = i fby (n + 1);
tel
```





r	F	F	T	F	F
i	0	5	10	15	20
$nat(i)$	0	1	2	3	4
$($**restart** nat **every** $r)(i)$	0	1	10	11	12

Exemple Plus Simple : Sémantique Intuitive du Reset Modulaire

```
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```

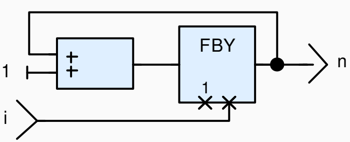

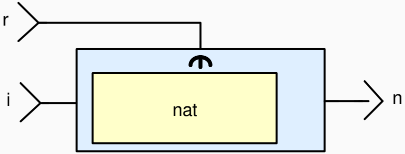

r	F	F	T	F	F	T
i	0	5	10	15	20	25
nat(*i*)	0	1	2	3	4	5
(**restart** *nat* **every** *r*)(*i*)	0	1	10	11	12	25

```
node nat(i: int)
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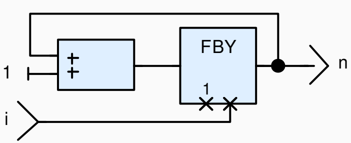

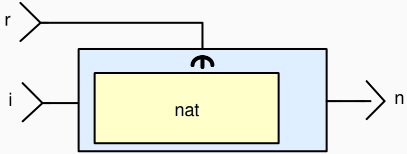

r	F	F	T	F	F	T	F
i	0	5	10	15	20	25	30
$nat(i)$	0	1	2	3	4	5	6
(**restart** nat **every** r)(i)	0	1	10	11	12	25	26

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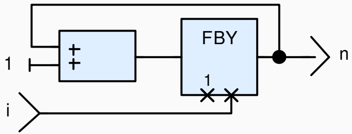

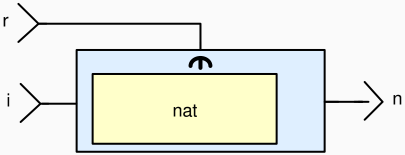

r	F	F	T	F	F	T	F	$\cdots$
i	0	5	10	15	20	25	30	$\cdots$
$nat(i)$	0	1	2	3	4	5	6	$\cdots$
(**restart** nat **every** r)(i)	0	1	10	11	12	25	26	$\cdots$

Exemple Plus Simple : Sémantique Intuitive du Reset Modulaire

Caspi 1994
Hamon et Pouzet 2000

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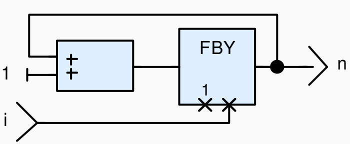

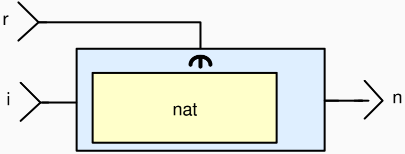

r	F	F	T	F	F	T	F	...
i	0	5	10	15	20	25	30	...
nat(*i*)	0	1	2	3	4	5	6	...
(**restart** *nat* **every** *r*)(*i*)	0	1	10	11	12	25	26	...

Peut être implémenté dans un langage récursif d'ordre supérieur

Exemple Plus Simple : Sémantique Intuitive du Reset Modulaire

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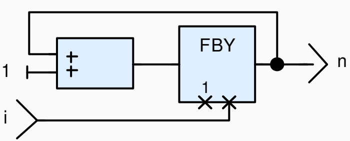

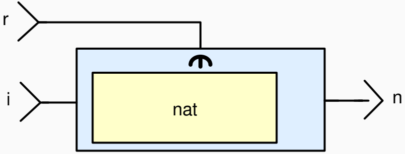

r	F	F	T	F	F	T	F	...
i	0	5	10	15	20	25	30	...
$nat(i)$	0	1	2	3	4	5	6	...
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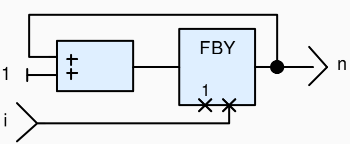

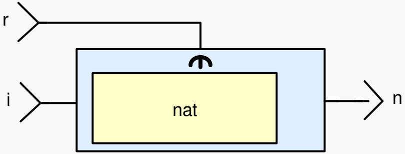

r	F	F	T	F	F	T	F	...
i	0	5	10	15	20	25	30	...
$nat(i)$	0	1	2	3	4	5	6	...
(**restart** nat **every** r)(i)	0	1	10	11	12	25	26	...

Peut être implémenté dans un langage récursif d'ordre supérieur

Exemple Plus Simple : Sémantique Intuitive du Reset Modulaire

r	F	F	T	F	F	T	F	$\cdots$
i	0	5	10	15	20	25	30	$\cdots$
(`restart` *nat* `every` *r*)(*i*)	0	1	10	11	12	25	26	$\cdots$

Exemple Plus Simple : Sémantique Intuitive du Reset Modulaire

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count r	0	0	1	1	1	2	2	$\cdots$
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i	0	5	10	15	20	25	30	$\cdots$
$\text{mask}_r^0\ i$	0	5						$\cdots$
(restart *nat* every r)(i)	0	1	10	11	12	25	26	$\cdots$

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r	F	F	T	F	F	T	F	$\cdots$
count r	0	0	1	1	1	2	2	$\cdots$
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$\text{mask}_r^0\ i$	0	5						$\cdots$
$nat(\text{mask}_r^0\ i)$	0	1						$\cdots$
(`restart` nat `every` r)(i)	0	1	10	11	12	25	26	$\cdots$

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$\text{mask}_r^0\ i$	0	5						$\cdots$
$nat(\text{ mask}_r^0\ i)$	0	1						$\cdots$
$\text{mask}_r^1\ i$			10	15	20			$\cdots$
(**restart** *nat* **every** r)(i)	0	1	10	11	12	25	26	$\cdots$

Exemple Plus Simple : Sémantique Intuitive du Reset Modulaire

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count r	0	0	1	1	1	2	2	$\cdots$
i	0	5	10	15	20	25	30	$\cdots$
$\text{mask}_r^0\ i$	0	5						$\cdots$
$nat(\ \text{mask}_r^0\ i\ )$	0	1						$\cdots$
$\text{mask}_r^1\ i$			10	15	20			$\cdots$
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$(\texttt{restart}\ nat\ \texttt{every}\ r)(i)$	0	1	10	11	12	25	26	$\cdots$

Exemple Plus Simple : Sémantique Intuitive du Reset Modulaire

r	F	F	T	F	F	T	F	$\cdots$
count r	0	0	1	1	1	2	2	$\cdots$
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$\text{mask}_r^0\ i$	0	5						$\cdots$
$nat(\text{ mask}_r^0\ i)$	0	1						$\cdots$
$\text{mask}_r^1\ i$			10	15	20			$\cdots$
$nat(\text{ mask}_r^1\ i)$			10	11	12			$\cdots$
$\text{mask}_r^2\ i$						25	30	$\cdots$
(`restart` nat `every` r)(i)	0	1	10	11	12	25	26	$\cdots$

Exemple Plus Simple : Sémantique Intuitive du Reset Modulaire

r	F	F	T	F	F	T	F	$\cdots$
count r	0	0	1	1	1	2	2	$\cdots$
i	0	5	10	15	20	25	30	$\cdots$
$\text{mask}_r^0\ i$	0	5						$\cdots$
$nat(\text{mask}_r^0\ i)$	0	1						$\cdots$
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i	0	5	10	15	20	25	30	$\cdots$
$\text{mask}_r^0\ i$	0	5						$\cdots$
$nat(\ \text{mask}_r^0\ i\,)$	0	1						$\cdots$
$\text{mask}_r^1\ i$			10	15	20			$\cdots$
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$\vdots$								
(`restart` nat `every` r)(i)	0	1	10	11	12	25	26	$\cdots$

Instanciation de nœud

$$\frac{\forall i,\ H_i \vdash \boldsymbol{e} \downarrow xs_i \quad \vdash f(xs) \Downarrow ys \quad \forall i,\ H_i(\boldsymbol{x}) = ys_i}{H \vdash \boldsymbol{x} = f(\boldsymbol{e})}$$

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$$\frac{\forall i,\ H_i \vdash \mathbf{e} \downarrow xs_i \quad \vdash f\,(xs) \Downarrow ys \quad \forall i,\ H_i(\mathbf{x}) = ys_i}{H \vdash \mathbf{x} = f(\mathbf{e})}$$

Reset modulaire

$$\frac{\begin{array}{c}\forall i,\ H_i(y) = rs_i \quad r = \text{bools-of } rs \\ \forall i,\ H_i \vdash \mathbf{e} \downarrow xs_i \quad \forall k,\ \vdash f\left(\text{mask}_r^k\, \mathbf{xs}\right) \Downarrow \text{mask}_r^k\, \mathbf{ys} \quad \forall i,\ H_i(\mathbf{x}) = ys_i\end{array}}{H \vdash \mathbf{x} = (\texttt{restart}\ f\ \texttt{every}\ y)(\mathbf{e})}$$

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Relation universellement quantifiée : nombre non borné de contraintes

Compilation du Reset Modulaire : de NLustre vers Stc

Un Problème avec la Compilation de NLustre vers Obc

```
node driver(x0, y0, u, v: double, r: bool)
  returns (x, y: double)
  var ax, ay: bool;
let
  x, ax = (restart ins every r)(x0, u);
  y, ay = (restart ins every r)(y0, v);
tel
```

```
class driver {
  instance x: ins, y: ins;

  reset() { ins(x).reset();
            ins(y).reset() }

  step(x0, y0, u, v: double, r: bool)
    returns (x, y: double)
    var ax, ay: bool
  {
    if r { ins(x).reset() };
    x, ax := ins(x).step(x0, u);
    if r { ins(y).reset() };
    y, ay := ins(y).step(y0, v)
  }
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```

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ordonnancer *et* introduire l'état

VS

introduire l'état *puis* ordonnancer

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STC : SYNCHRONOUS TRANSITION CODE

Proposer un nouveau langage intermédiaire

- Sémantique invariante par permutation
- Reset séparé
- Variables d'état et instances explicites

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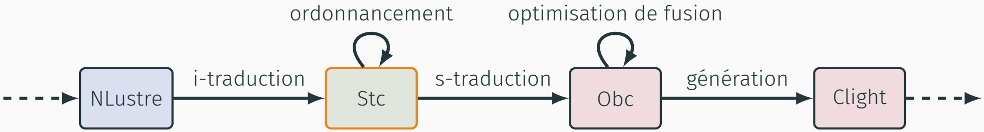

```
node ins(gps, xv: double)
  returns (x: double, alarm: bool)
  var k: int, px: double,
      xe: double when not alarm;
let
  k = 0 fby k + 1;
  alarm = (k >= 50);
  xe = euler(gps when not alarm,
             xv when not alarm);
  x = merge alarm (px when alarm) xe;
  px = 0. fby x;
tel
```

```
system ins {
  init k = 0, px = 0.;
  sub xe: euler;

  transition(gps, xv: double)
    returns (x: double, alarm: bool)
    var xe: double when not alarm;
  {
    next k = k + 1;
    alarm = (k >= 50);
    xe = euler<xe>(gps when not alarm,
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    x = merge alarm (px when alarm) xe;
    next px = x;
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```

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node ins(gps, xv: double)
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introduire l'état uniquement

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introduire l'état uniquement

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introduire l'état uniquement

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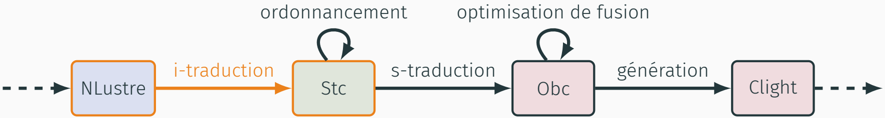
Compilation de l'Exemple du Reset




```
node driver(x0, y0, u, v: double, r: bool)
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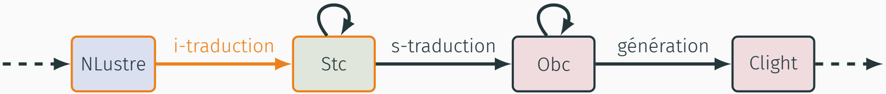
  var ax, ay: bool;
let
  x, ax = (restart ins every r)(x0, u);
  y, ay = (restart ins every r)(y0, v);
tel
```

```
system driver {
  sub x: ins, y: ins;

  transition(x0, y0, u, v: double, r: bool)
    returns (x, y: double)
    var ax, ay: bool;
  {
    x, ax = ins<x>(x0, u);
    reset ins<x> every (. on r);
    y, ay = ins<y>(y0, v);
    reset ins<y> every (. on r);
  }
}
```

introduire l'état uniquement

Compilation de l'Exemple du Reset

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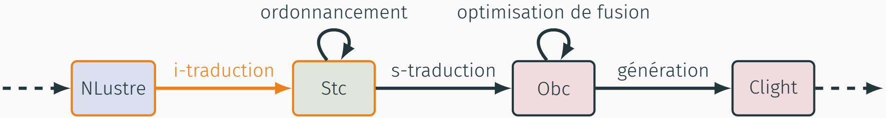
introduire l'état uniquement

Compilation de l'Exemple du Reset

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introduire l'état uniquement

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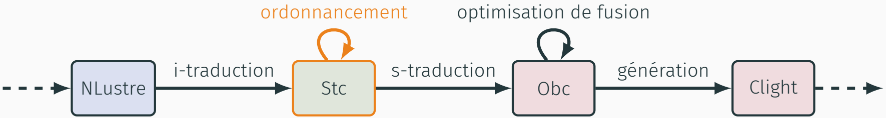


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ordonnancer uniquement

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Système de transitions

- États de départ S, d'arrivée S'
- Contraintes de transition
- État intermédiaire I

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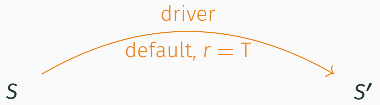

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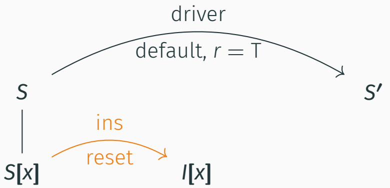
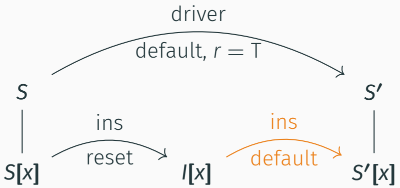


Système de transitions

- États de départ S, d'arrivée S'
- Contraintes de transition
- État intermédiaire I

```
system driver {
  sub x: ins, y: ins;

  transition(x0, y0, u, v: double, r: bool)
    returns (x, y: double)
    var ax, ay: bool;
  {
    x, ax = ins<x>(x0, u);
    reset ins<x> every (. on r);
    y, ay = ins<y>(y0, v);
    reset ins<y> every (. on r);
  }
}
```



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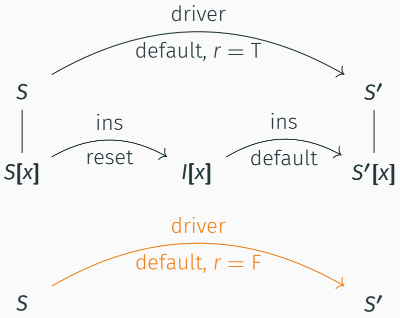

Système de transitions

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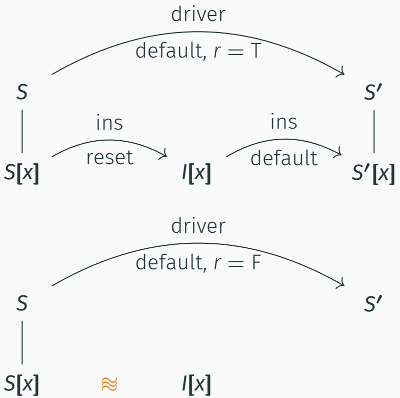

Sémantique Intuitive de Stc

Système de transitions

- États de départ S, d'arrivée S'
- Contraintes de transition
- État intermédiaire I

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```

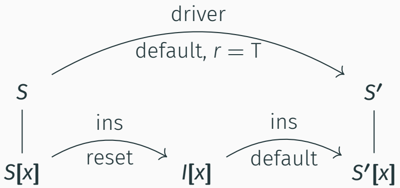

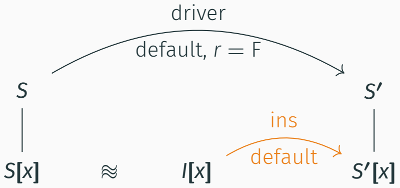

Contrainte de transition basique

$$\frac{R \vdash e \downarrow R(x)}{R, S, I, S' \vdash x = e}$$

Contrainte de transition *next*

$$\frac{R \vdash e \downarrow \langle v \rangle \quad R(x) = \langle S(x) \rangle \quad S'(x) = v}{R, S, I, S' \vdash \texttt{next}\ x = e} \qquad \frac{R \vdash e \downarrow \langle\, \rangle \quad R(x) = \langle\, \rangle \quad S'(x) = S(x)}{R, S, I, S' \vdash \texttt{next}\ x = e}$$

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\qquad
\frac{R \vdash e \downarrow \langle\,\rangle \quad R(x) = \langle\,\rangle \quad S'(x) = S(x)}{R, S, I, S' \vdash \texttt{next}\ x = e}$$

Contrainte de transition basique

$$\frac{R \vdash e \downarrow R(x)}{R, S, I, S' \vdash x = e}$$

Contrainte de transition *next*

$$\frac{R \vdash e \downarrow \langle v \rangle \quad R(x) = \langle S(x) \rangle \quad S'(x) = v}{R, S, I, S' \vdash \texttt{next}\ x = e} \qquad \frac{R \vdash e \downarrow \langle\ \rangle \quad R(x) = \langle\ \rangle \quad S'(x) = S(x)}{R, S, I, S' \vdash \texttt{next}\ x = e}$$

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Transition par défaut

$$\frac{R \vdash \mathbf{e} \downarrow \mathbf{v} \quad I[i]\,, S'[i] \vdash f\,(\mathbf{v}) \Downarrow R(\mathbf{x}) \quad \text{if } (k = 0) \text{ then } I[i] \approx S[i]}{R, S, I, S' \vdash \mathbf{x} = f\texttt{<}i, k\texttt{>}(\,\mathbf{e}\,)}$$

Transition *reset*

$$\frac{R \vdash ck \downarrow \text{true} \quad \text{initial-state}\, f\ I[i]}{R, S, I, S' \vdash \texttt{reset}\ f\texttt{<}i\texttt{>}\ \texttt{every}\ ck}
\qquad
\frac{R \vdash ck \downarrow \text{false} \quad I[i] \approx S[i]}{R, S, I, S' \vdash \texttt{reset}\ f\texttt{<}i\texttt{>}\ \texttt{every}\ ck}$$

Transition par défaut

$$\frac{R \vdash e \downarrow v \quad I[i], S'[i] \vdash f(v) \Downarrow R(x) \quad \text{if } (k = 0) \text{ then } I[i] \approx S[i]}{R, S, I, S' \vdash \mathtt{x = f<i, k>(e)}}$$

Transition *reset*

$$\frac{R \vdash ck \downarrow \text{true} \quad \text{initial-state}\, f\ I[i]}{R, S, I, S' \vdash \mathtt{reset}\ f\texttt{<}i\texttt{>}\ \mathtt{every}\ ck}$$

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Transition par défaut

$$\frac{R \vdash e \downarrow v \quad I[i]\,,S'[i] \vdash f\,(v) \Downarrow R(x) \qquad \text{if } \ (k = 0) \ \text{ then } I[i] \approx S[i]}{R, S, I, S' \vdash x \texttt{ = } f\texttt{<}i, k\texttt{>(}\,e\,\texttt{)}}$$

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Système

$$\frac{\text{system}(P, f) = s \quad R(s.\mathbf{in}) = \boldsymbol{xs} \quad R(s.\mathbf{out}) = \boldsymbol{ys} \\ \forall tc \in s.\mathbf{tcs}\ , R, S, I, S' \vdash tc}{S, S' \vdash f(\boldsymbol{xs}) \Downarrow \boldsymbol{ys}}$$

Système

$$\frac{\text{system}(P, f) = s \quad R(s.\mathbf{in}) = \mathbf{xs} \quad R(s.\mathbf{out}) = \mathbf{ys} \qquad \forall tc \in s.\mathbf{tcs}\ , R, S, I, S' \vdash tc}{S, S' \vdash f\,(\mathbf{xs}) \Downarrow \mathbf{ys}}$$

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Système

$$\frac{\text{system}(P, f) = s \quad R(s.\mathsf{in}) = xs \quad R(s.\mathsf{out}) = ys \qquad \forall tc \in s.\mathbf{tcs}\ , R, S, I, S' \vdash tc}{S, S' \vdash f\,(xs) \Downarrow ys}$$

Exécution en boucle

$$\frac{S, S' \vdash f(xs_n) \Downarrow ys_n \qquad S' \vdash f(xs) \overset{n+1}{\circlearrowleft} ys}{S \vdash f(xs) \overset{n}{\circlearrowleft} ys}$$

Exécution en boucle

$$\dfrac{S, S' \vdash f(xs_n) \downdownarrows ys_n \qquad S' \vdash f(xs) \overset{n+1}{\circlearrowleft} ys}{S \vdash f(xs) \overset{n}{\circlearrowleft} ys}$$

Exécution en boucle

$$\dfrac{S, S' \vdash f(xs_n) \Downarrow ys_n \qquad \dfrac{S', S'' \vdash f(xs_{n+1}) \Downarrow ys_{n+1} \qquad S'' \vdash f(xs) \overset{n+2}{\circlearrowleft} ys}{S' \vdash f(xs) \overset{n+1}{\circlearrowleft} ys}}{S \vdash f(xs) \overset{n}{\circlearrowleft} ys}$$

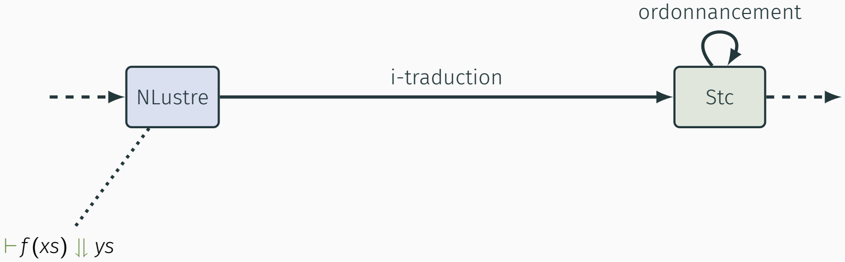
Exécution en boucle

$$\dfrac{S, S' \vdash f(xs_n) \Downarrow ys_n \qquad \dfrac{S', S'' \vdash f(xs_{n+1}) \Downarrow ys_{n+1} \qquad \dfrac{S'', S''' \vdash f(xs_{n+2}) \Downarrow ys_{n+2} \qquad S''' \vdash f(xs) \overset{n+3}{\circlearrowright} ys}{S'' \vdash f(xs) \overset{n+2}{\circlearrowright} ys}}{S' \vdash f(xs) \overset{n+1}{\circlearrowright} ys}}{S \vdash f(xs) \overset{n}{\circlearrowright} ys}$$

Exécution en boucle

$$\dfrac{S, S' \vdash f(xs_n) \downdownarrows ys_n \qquad \dfrac{S', S'' \vdash f(xs_{n+1}) \downdownarrows ys_{n+1} \qquad \dfrac{S'', S''' \vdash f(xs_{n+2}) \downdownarrows ys_{n+2} \qquad \dfrac{\vdots}{S''' \vdash f(xs) \overset{n+3}{\circlearrowright} ys}}{S'' \vdash f(xs) \overset{n+2}{\circlearrowright} ys}}{S' \vdash f(xs) \overset{n+1}{\circlearrowright} ys}}{S \vdash f(xs) \overset{n}{\circlearrowright} ys}$$

Correction : Préservation de la Sémantique



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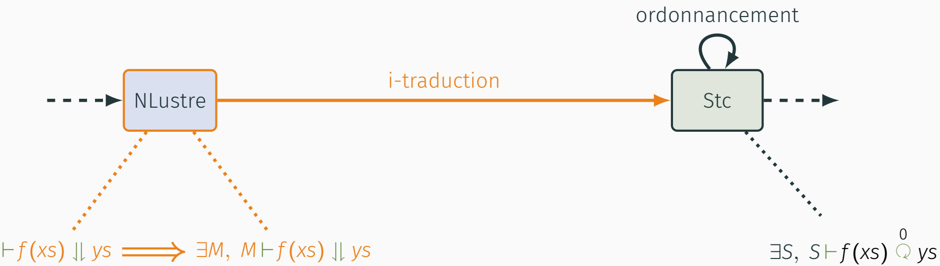
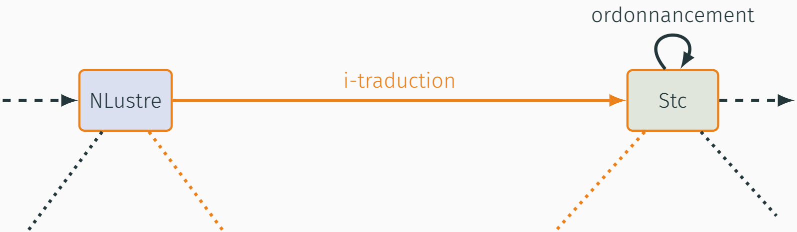
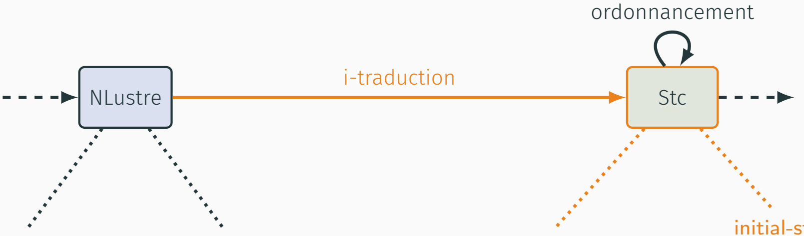
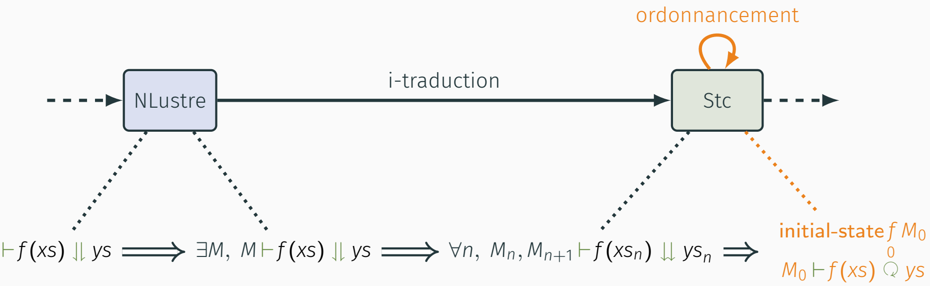




$\vdash f(xs) \Downarrow ys \implies \exists M,\ M \vdash f(xs) \Downarrow ys \implies \forall n,\ M_n, M_{n+1} \vdash f(xs_n) \Downarrow ys_n$ $\qquad \exists S,\ S \vdash f(xs) \overset{0}{\circlearrowleft} ys$



$\vdash f(xs) \Downarrow ys \implies \exists M,\ M \vdash f(xs) \Downarrow ys \implies \forall n,\ M_n, M_{n+1} \vdash f(xs_n) \Downarrow ys_n \implies$ initial-state $f\ M_0$ / $M_0 \vdash f(xs) \overset{0}{\circlearrowleft} ys$


ordonnancement
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NLustre
Stc
$\vdash f(xs) \Downarrow ys \implies \exists M,\ M \vdash f(xs) \Downarrow ys \implies \forall n,\ M_n, M_{n+1} \vdash f(xs_n) \Downarrow ys_n \implies$
initial-state $f\ M_0$
$M_0 \vdash f(xs) \overset{0}{\circlearrowleft} ys$

Production de Code Impératif : de Stc vers Obc

Stc

```
system ins {
  init k = 0, px = 0.;
  sub xe: euler;

  transition(gps, xv: double)
    returns (x: double, alarm: bool)
    var xe: double when not alarm;
  {
    alarm = (k >= 50);
    next k = k + 1;
    xe = euler<xe>(gps when not alarm,
                   xv when not alarm);
    x = merge alarm (px when alarm) xe;
    next px = x;
  }
}
```

Obc

```
class ins {
  state k: int, px: double;
  instance xe: euler;

  reset() { state(k) := 0;
            state(px) := 0.;
            euler(xe).reset() }

  step(gps, xv: double)
    returns (x: double, alarm: bool)
    var xe: double
  {
    alarm := state(k) >= 50;
    state(k) := state(k) + 1;
    if alarm { }
    else { xe := euler(xe).step(gps, xv) };
    if alarm { x := state(px) }
    else { x := xe };
    state(px) := x
  }
}
```

Stc

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Stc

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    state(k) := state(k) + 1;
    if alarm { }
    else { xe := euler(xe).step(gps, xv) };
    if alarm { x := state(px) }
    else { x := xe };
    state(px) := x
  }
}
```

Stc

```
system ins {
  init k = 0, px = 0.;
  sub xe: euler;

  transition(gps, xv: double)
    returns (x: double, alarm: bool)
    var xe: double when not alarm;
  {
    alarm = (k >= 50);
    next k = k + 1;
    xe = euler<xe>(gps when not alarm,
                   xv when not alarm);
    x = merge alarm (px when alarm) xe;
    next px = x;
  }
}
```

Obc

```
class ins {
  state k: int, px: double;
  instance xe: euler;

  reset() { state(k) := 0;
            state(px) := 0.;
            euler(xe).reset() }

  step(gps, xv: double)
    returns (x: double, alarm: bool)
    var xe: double
  {
    alarm := state(k) >= 50;
    state(k) := state(k) + 1;
    if alarm { }
    else { xe := euler(xe).step(gps, xv) };
    if alarm { x := state(px) }
    else { x := xe };
    state(px) := x
  }
```

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                   xv when not alarm);
    x = merge alarm (px when alarm) xe;
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}
```

Obc

```
class ins {
  state k: int, px: double;
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            state(px) := 0.;
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    returns (x: double, alarm: bool)
    var xe: double
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    alarm := state(k) >= 50;
    state(k) := state(k) + 1;
    if alarm { }
    else { xe := euler(xe).step(gps, xv) };
    if alarm { x := state(px) }
    else { x := xe };
    state(px) := x
  }
}
```
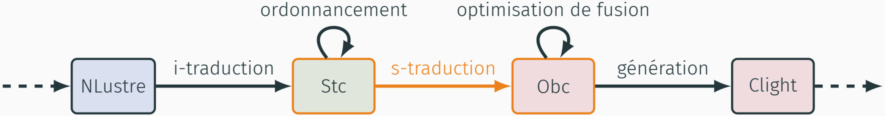
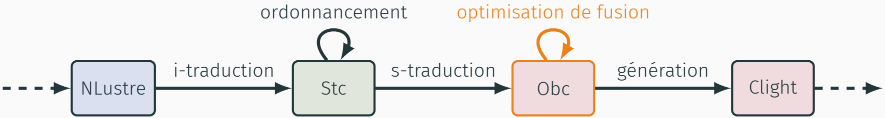

Compilation de l'Exemple du Reset




```
system driver {
  sub x: ins, y: ins;

  transition(x0, y0, u, v: double, r: bool)
    returns (x, y: double)
    var ax, ay: bool;
  {
    reset ins<x> every (. on r);
    reset ins<y> every (. on r);
    x, ax = ins<x>(x0, u);
    y, ay = ins<y>(y0, v);
  }
}
```

```
class driver {
  instance x: ins, y: ins;

  reset() { ins(x).reset();
            ins(y).reset() }

  step(x0, y0, u, v: double, r: bool)
    returns (x, y: double)
    var ax, ay: bool
  {
    if r { ins(x).reset() };
    if r { ins(y).reset() };
    x, ax := ins(x).step(x0, u);
    y, ay := ins(y).step(y0, v)
  }
}
```

Compilation de l'Exemple du Reset




```
system driver {
  sub x: ins, y: ins;

  transition(x0, y0, u, v: double, r: bool)
    returns (x, y: double)
    var ax, ay: bool;
  {
    reset ins<x> every (. on r);
    reset ins<y> every (. on r);
    x, ax = ins<x>(x0, u);
    y, ay = ins<y>(y0, v);
  }
}
```

```
class driver {
  instance x: ins, y: ins;

  reset() { ins(x).reset();
            ins(y).reset() }

  step(x0, y0, u, v: double, r: bool)
    returns (x, y: double)
    var ax, ay: bool
  {
    if r { ins(x).reset();
           ins(y).reset() };
    x, ax := ins(x).step(x0, u);
    y, ay := ins(y).step(y0, v)
  }
}
```

Expressions

$$\frac{}{me, ve \vdash x \Downarrow ve(x)} \qquad \frac{}{me, ve \vdash \texttt{state}(x) \Downarrow me(x)} \qquad \frac{me, ve \vdash e_1 \Downarrow v_1 \quad me, ve \vdash e_2 \Downarrow v_2}{me, ve \vdash e_1 + e_2 \Downarrow [\![+]\!](v_1, v_2)}$$

Instructions

$$\frac{me, ve \vdash e \Downarrow v}{me, ve \vdash x \texttt{ := } e \Downarrow (me, ve\{x \mapsto v\})} \qquad \frac{me, ve \vdash e \Downarrow v}{me, ve \vdash \texttt{state}(x) \texttt{ := } e \Downarrow (me\{x \mapsto v\}, ve)}$$

$$\frac{\begin{array}{c} me, ve \vdash s_1 \Downarrow (me_1, ve_1) \\ me_1, ve_1 \vdash s_2 \Downarrow (me_2, ve_2) \end{array}}{me, ve \vdash s_1 \texttt{ ; } s_2 \Downarrow (me_2, ve_2)} \qquad \frac{me, ve \vdash \mathbf{e} \Downarrow \mathbf{v} \quad me[i] \vdash c.f(\mathbf{v}) \overset{\mathbf{w}}{\Downarrow} me'_i}{me, ve \vdash \mathbf{x} \texttt{ := } c(i)\texttt{.}f(\mathbf{e}) \Downarrow (me\{i \mapsto me'_i\}, ve\{\mathbf{x} \mapsto \mathbf{w}\})}$$

Expressions

$$\frac{}{me, ve \vdash x \Downarrow ve(x)} \qquad \frac{}{me, ve \vdash \mathtt{state}(x) \Downarrow me(x)} \qquad \frac{me, ve \vdash e_1 \Downarrow v_1 \quad me, ve \vdash e_2 \Downarrow v_2}{me, ve \vdash e_1 + e_2 \Downarrow [\![+]\!](v_1, v_2)}$$

Instructions

$$\frac{me, ve \vdash e \Downarrow v}{me, ve \vdash x \mathrel{\mathtt{:=}} e \Downarrow (me, ve\{x \mapsto v\})} \qquad \frac{me, ve \vdash e \Downarrow v}{me, ve \vdash \mathtt{state}(x) \mathrel{\mathtt{:=}} e \Downarrow (me\{x \mapsto v\}, ve)}$$

$$\frac{\begin{array}{c} me, ve \vdash s_1 \Downarrow (me_1, ve_1) \\ me_1, ve_1 \vdash s_2 \Downarrow (me_2, ve_2) \end{array}}{me, ve \vdash s_1 \mathbin{\mathtt{;}} s_2 \Downarrow (me_2, ve_2)} \qquad \frac{me, ve \vdash \mathbf{e} \Downarrow \mathbf{v} \quad me[i] \vdash c.f(\mathbf{v}) \overset{\mathbf{w}}{\Downarrow} me_i'}{me, ve \vdash \mathbf{x} \mathrel{\mathtt{:=}} c(i)\mathtt{.}f(\mathbf{e}) \Downarrow (me\{i \mapsto me_i'\}, ve\{\mathbf{x} \mapsto \mathbf{w}\})}$$

Expressions

$$\frac{}{me, ve \vdash x \Downarrow ve(x)} \qquad \frac{}{me, ve \vdash \texttt{state}(x) \Downarrow me(x)} \qquad \frac{me, ve \vdash e_1 \Downarrow v_1 \quad me, ve \vdash e_2 \Downarrow v_2}{me, ve \vdash e_1 + e_2 \Downarrow [\![+]\!](v_1, v_2)}$$

Instructions

$$\frac{me, ve \vdash e \Downarrow v}{me, ve \vdash x \texttt{ := } e \Downarrow (me, ve\{x \mapsto v\})} \qquad \frac{me, ve \vdash e \Downarrow v}{me, ve \vdash \texttt{state}(x) \texttt{ := } e \Downarrow (me\{x \mapsto v\}, ve)}$$

$$\frac{\begin{array}{c} me, ve \vdash s_1 \Downarrow (me_1, ve_1) \\ me_1, ve_1 \vdash s_2 \Downarrow (me_2, ve_2) \end{array}}{me, ve \vdash s_1 \texttt{ ; } s_2 \Downarrow (me_2, ve_2)} \qquad \frac{me, ve \vdash \boldsymbol{e} \Downarrow \boldsymbol{v} \quad me[i] \vdash c.f(\boldsymbol{v}) \overset{\boldsymbol{w}}{\Downarrow} me_i'}{me, ve \vdash \boldsymbol{x} \texttt{ := } c(i)\texttt{.}f(\boldsymbol{e}) \Downarrow (me\{i \mapsto me_i'\}, ve\{\boldsymbol{x} \mapsto \boldsymbol{w}\})}$$

Expressions

$$\frac{}{me, ve \vdash x \Downarrow ve(x)} \qquad \frac{}{me, ve \vdash \texttt{state}(x) \Downarrow me(x)} \qquad \frac{me, ve \vdash e_1 \Downarrow v_1 \quad me, ve \vdash e_2 \Downarrow v_2}{me, ve \vdash e_1 + e_2 \Downarrow [\![+]\!](v_1, v_2)}$$

Instructions

$$\frac{me, ve \vdash e \Downarrow v}{me, ve \vdash x := e \Downarrow (me, ve\{x \mapsto v\})} \qquad \frac{me, ve \vdash e \Downarrow v}{me, ve \vdash \texttt{state}(x) := e \Downarrow (me\{x \mapsto v\}, ve)}$$

$$\frac{\begin{array}{c} me, ve \vdash s_1 \Downarrow (me_1, ve_1) \\ me_1, ve_1 \vdash s_2 \Downarrow (me_2, ve_2) \end{array}}{me, ve \vdash s_1 \ ; \ s_2 \Downarrow (me_2, ve_2)} \qquad \frac{me, ve \vdash \mathbf{e} \Downarrow \mathbf{v} \quad me[i] \vdash c.f(\mathbf{v}) \overset{\mathbf{w}}{\Downarrow} me'_i}{me, ve \vdash \mathbf{x} := c(i).f(\mathbf{e}) \Downarrow (me\{i \mapsto me'_i\}, ve\{\mathbf{x} \mapsto \mathbf{w}\})}$$

Expressions

$$\frac{}{me, ve \vdash x \Downarrow ve(x)} \qquad \frac{}{me, ve \vdash \mathtt{state}(x) \Downarrow me(x)} \qquad \frac{me, ve \vdash e_1 \Downarrow v_1 \quad me, ve \vdash e_2 \Downarrow v_2}{me, ve \vdash e_1 + e_2 \Downarrow [\![+]\!](v_1, v_2)}$$

Instructions

$$\frac{me, ve \vdash e \Downarrow v}{me, ve \vdash x := e \Downarrow (me, ve\{x \mapsto v\})} \qquad \frac{me, ve \vdash e \Downarrow v}{me, ve \vdash \mathtt{state}(x) := e \Downarrow (me\{x \mapsto v\}, ve)}$$

$$\frac{\begin{array}{c} me, ve \vdash s_1 \Downarrow (me_1, ve_1) \\ me_1, ve_1 \vdash s_2 \Downarrow (me_2, ve_2) \end{array}}{me, ve \vdash s_1 \,;\, s_2 \Downarrow (me_2, ve_2)} \qquad \frac{me, ve \vdash \mathbf{e} \Downarrow \mathbf{v} \quad me[i] \vdash c.f(\mathbf{v}) \overset{\mathbf{w}}{\Downarrow} me'_i}{me, ve \vdash \mathbf{x} := c(i).f(\mathbf{e}) \Downarrow (me\{i \mapsto me'_i\}, ve\{\mathbf{x} \mapsto \mathbf{w}\})}$$

Règles Sémantiques

Expressions

$$\frac{}{me, ve \vdash x \Downarrow ve(x)} \qquad \frac{}{me, ve \vdash \texttt{state}(x) \Downarrow me(x)} \qquad \frac{me, ve \vdash e_1 \Downarrow v_1 \quad me, ve \vdash e_2 \Downarrow v_2}{me, ve \vdash e_1 + e_2 \Downarrow [\![+]\!](v_1, v_2)}$$

Instructions

$$\frac{me, ve \vdash e \Downarrow v}{me, ve \vdash x \texttt{ := } e \Downarrow (me, ve\{x \mapsto v\})} \qquad \frac{me, ve \vdash e \Downarrow v}{me, ve \vdash \texttt{state}(x) \texttt{ := } e \Downarrow (me\{x \mapsto v\}, ve)}$$

$$\frac{\begin{array}{c} me, ve \vdash s_1 \Downarrow (me_1, ve_1) \\ me_1, ve_1 \vdash s_2 \Downarrow (me_2, ve_2) \end{array}}{me, ve \vdash s_1 \texttt{ ; } s_2 \Downarrow (me_2, ve_2)} \qquad \frac{me, ve \vdash \mathbf{e} \Downarrow \mathbf{v} \quad me[i] \vdash c.f(\mathbf{v}) \overset{\mathbf{w}}{\Downarrow} me_i'}{me, ve \vdash \mathbf{x} \texttt{ := } c(i)\texttt{.}f(\mathbf{e}) \Downarrow (me\{i \mapsto me_i'\}, ve\{\mathbf{x} \mapsto \mathbf{w}\})}$$

Expressions

$$\frac{}{me, ve \vdash x \Downarrow ve(x)} \qquad \frac{}{me, ve \vdash \texttt{state}(x) \Downarrow me(x)} \qquad \frac{me, ve \vdash e_1 \Downarrow v_1 \quad me, ve \vdash e_2 \Downarrow v_2}{me, ve \vdash e_1 + e_2 \Downarrow [\![+]\!](v_1, v_2)}$$

Instructions

$$\frac{me, ve \vdash e \Downarrow v}{me, ve \vdash x := e \Downarrow (me, ve\{x \mapsto v\})} \qquad \frac{me, ve \vdash e \Downarrow v}{me, ve \vdash \texttt{state}(x) := e \Downarrow (me\{x \mapsto v\}, ve)}$$

$$\frac{me, ve \vdash s_1 \Downarrow (me_1, ve_1) \quad me_1, ve_1 \vdash s_2 \Downarrow (me_2, ve_2)}{me, ve \vdash s_1 \,;\, s_2 \Downarrow (me_2, ve_2)} \qquad \frac{me, ve \vdash \mathbf{e} \Downarrow \mathbf{v} \quad me[i] \vdash c.f(\mathbf{v}) \overset{\mathbf{w}}{\Downarrow} me'_i}{me, ve \vdash \mathbf{x} := c(i).f(\mathbf{e}) \Downarrow (me\{i \mapsto me'_i\}, ve\{\mathbf{x} \mapsto \mathbf{w}\})}$$

Expressions

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$$\frac{me, ve \vdash e \Downarrow v}{me, ve \vdash x := e \Downarrow (me, ve\{x \mapsto v\})} \qquad \frac{me, ve \vdash e \Downarrow v}{me, ve \vdash \mathtt{state}(x) := e \Downarrow (me\{x \mapsto v\}, ve)}$$

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Expressions

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Instructions

$$\frac{me, ve \vdash e \Downarrow v}{me, ve \vdash x \mathtt{:=} e \Downarrow (me, ve\{x \mapsto v\})} \qquad \frac{me, ve \vdash e \Downarrow v}{me, ve \vdash \mathtt{state}(x) \mathtt{:=} e \Downarrow (me\{x \mapsto v\}, ve)}$$

$$\frac{me, ve \vdash s_1 \Downarrow (me_1, ve_1) \quad me_1, ve_1 \vdash s_2 \Downarrow (me_2, ve_2)}{me, ve \vdash s_1 \mathtt{;}\ s_2 \Downarrow (me_2, ve_2)} \qquad \frac{me, ve \vdash \mathbf{e} \Downarrow \mathbf{v} \quad me[i] \vdash c.f(\mathbf{v}) \overset{\mathbf{w}}{\Downarrow} me'_i}{me, ve \vdash \mathbf{x} \mathtt{:=} c(i)\mathtt{.}f(\mathbf{e}) \Downarrow (me\{i \mapsto me'_i\}, ve\{\mathbf{x} \mapsto \mathbf{w}\})}$$

Expressions

$$\frac{}{me, ve \vdash x \Downarrow ve(x)} \qquad \frac{}{me, ve \vdash \texttt{state}(x) \Downarrow me(x)} \qquad \frac{me, ve \vdash e_1 \Downarrow v_1 \quad me, ve \vdash e_2 \Downarrow v_2}{me, ve \vdash e_1 + e_2 \Downarrow [\![+]\!](v_1, v_2)}$$

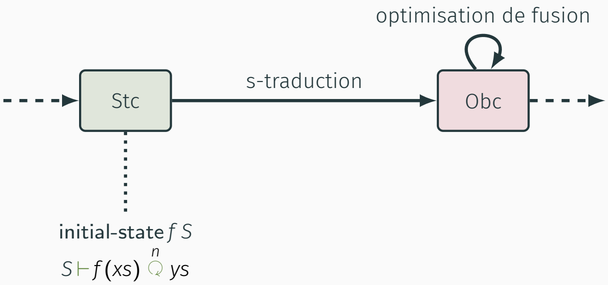
Instructions

$$\frac{me, ve \vdash e \Downarrow v}{me, ve \vdash x := e \Downarrow (me, ve\{x \mapsto v\})} \qquad \frac{me, ve \vdash e \Downarrow v}{me, ve \vdash \texttt{state}(x) := e \Downarrow (me\{x \mapsto v\}, ve)}$$

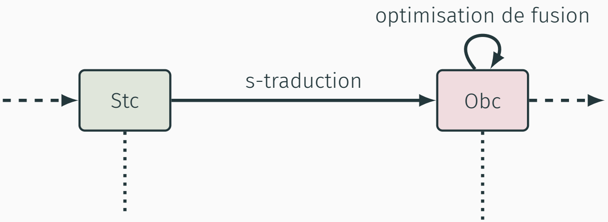
$$\frac{\begin{array}{c} me, ve \vdash s_1 \Downarrow (me_1, ve_1) \\ me_1, ve_1 \vdash s_2 \Downarrow (me_2, ve_2) \end{array}}{me, ve \vdash s_1 \; ; \; s_2 \Downarrow (me_2, ve_2)} \qquad \frac{me, ve \vdash \mathbf{e} \Downarrow \mathbf{v} \quad me[i] \vdash c.f(\mathbf{v}) \overset{\mathbf{w}}{\Downarrow} me'_i}{me, ve \vdash \mathbf{x} := c(i).f(\mathbf{e}) \Downarrow (me\{i \mapsto me'_i\}, ve\{\mathbf{x} \mapsto \mathbf{w}\})}$$

Exécution en boucle

$$\frac{me \vdash c.f(xs_n) \overset{ys_n}{\Downarrow} me' \quad me' \vdash c.f(xs) \overset{n+1}{\circlearrowleft} ys}{me \vdash c.f(xs) \overset{n}{\circlearrowleft} ys}$$


optimisation de fusion
s-traduction
Stc
Obc
initial-state f S
S ⊢ f (xs) ↻ⁿ ys

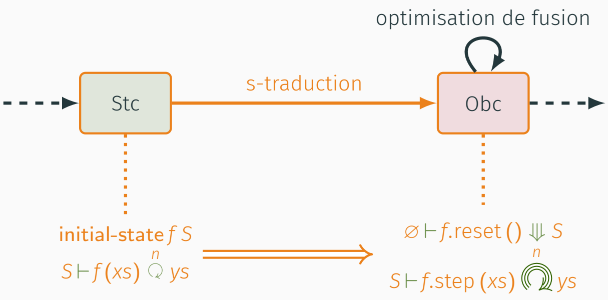
Correction

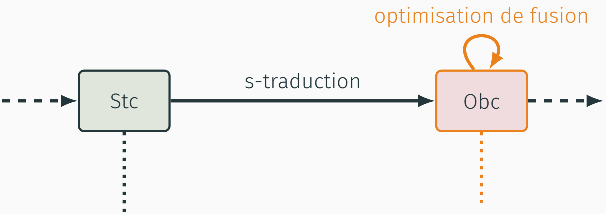


initial-state f S

$S \vdash f\,(xs) \overset{n}{\circlearrowleft} ys$

$\exists me,\ me \vdash f.\mathsf{step}\,(xs) \overset{n}{\circlearrowleft} ys$


optimisation de fusion
Stc
s-traduction
Obc
initial-state f S
S ⊢ f (xs) ys
∅ ⊢ f.reset () ⇓ S
S ⊢ f.step (xs) ys
n
n



$$\begin{array}{c} \textbf{initial-state}\ f\ S \\ S \vdash f\,(xs) \overset{n}{\circlearrowleft} ys \end{array} \Longrightarrow \begin{array}{c} \varnothing \vdash f.\mathrm{reset}\ () \Downarrow S \\ S \vdash f.\mathrm{step}\ (xs) \overset{n}{\circlearrowleft} ys \end{array}$$

Generation de code Clight

CompCert

Mécanisation en Coq de la syntaxe, de la sémantique et des algorithmes de compilation du langage C.

Clight

- langage intermédiaire de CompCert
- très proche de C
- opérations de bas niveau (adresses, structures, ...)

Obc

```
class ins {
  state k: int, px: double;
  instance xe: euler;

  reset() { state(k) := 0;
            state(px) := 0.;
            euler(xe).reset() }

  step(gps, xv: double)
    returns (x: double, alarm: bool)
    var xe: double
  {
    alarm := state(k) >= 50;
    state(k) := state(k) + 1;
    if alarm { x := state(px) }
    else {
      xe := euler(xe).step(gps, xv);
      x := xe };
    state(px) := x
  }
}
```

Clight

```
struct ins {
  int k;
  double px;
  struct euler xe;
};

void fun$ins$reset(struct ins *self) {
  self->k = 0;
  self->px = 0;
  fun$euler$reset(&(self->xe));
  return;
}
```

Obc

```
class ins {
  state k: int, px: double;
  instance xe: euler;

  reset() { state(k) := 0;
            state(px) := 0.;
            euler(xe).reset() }

  step(gps, xv: double)
    returns (x: double, alarm: bool)
    var xe: double
  {
    alarm := state(k) >= 50;
    state(k) := state(k) + 1;
    if alarm { x := state(px) }
    else {
      xe := euler(xe).step(gps, xv);
      x := xe };
    state(px) := x
  }
}
```

Clight

```
struct ins {
  int k;
  double px;
  struct euler xe;
};

void fun$ins$reset(struct ins *self) {
  self->k = 0;
  self->px = 0;
  fun$euler$reset(&(self->xe));
  return;
}
```

Obc

Clight

```
class ins {
  state k: int, px: double;
  instance xe: euler;

  reset() { state(k) := 0;
            state(px) := 0.;
            euler(xe).reset() }

  step(gps, xv: double)
    returns (x: double, alarm: bool)
    var xe: double
  {
    alarm := state(k) >= 50;
    state(k) := state(k) + 1;
    if alarm { x := state(px) }
    else {
      xe := euler(xe).step(gps, xv);
      x := xe };
    state(px) := x
  }
}
```

```
struct ins {
  int k;
  double px;
  struct euler xe;
};

void fun$ins$reset(struct ins *self) {
  self->k = 0;
  self->px = 0;
  fun$euler$reset(&(self->xe));
  return;
}
```

Obc

```
class ins {
  state k: int, px: double;
  instance xe: euler;

  reset() { state(k) := 0;
            state(px) := 0.;
            euler(xe).reset() }

  step(gps, xv: double)
    returns (x: double, alarm: bool)
    var xe: double
  {
    alarm := state(k) >= 50;
    state(k) := state(k) + 1;
    if alarm { x := state(px) }
    else {
      xe := euler(xe).step(gps, xv);
      x := xe };
    state(px) := x
  }
```

Clight

```
struct fun$ins$step {
  double x;
  bool alarm;
};
void fun$ins$step(struct ins *self,
                  struct fun$ins$step *out,
                  double gps, double xv) {
  register double step$x;
  register double xe;
  out->alarm = self->k >= 50;
  self->k = self->k + 1;
  if (out->alarm) { out->x = self->px; }
  else {
    step$x = fun$euler$step(&(self->xe), gps, xv);
    xe = step$x;
    out->x = xe;
  }
  self->px = out->x;
  return;
}
```

Obc

```
class ins {
  state k: int, px: double;
  instance xe: euler;

  reset() { state(k) := 0;
            state(px) := 0.;
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  step(gps, xv: double)
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    xe = step$x;
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  }
  self->px = out->x;
  return;
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```

Boucle Principale

```
struct nav {
  bool c;
  bool r;
  struct ins insr;
};

struct fun$nav$step {
  double x;
  bool alarm;
};

struct nav self$;
double volatile gps$;
double volatile xv$;
bool volatile s$;
double volatile x$;
bool volatile alarm$;
```

```
int main(void) {
  struct fun$nav$step out$step;
  register double gps;
  register double xv;
  register bool s;

  fun$nav$reset(&self$);

  while (true) {
    gps = volatile_load(&gps$);
    xv = volatile_load(&xv$);
    s = volatile_load(&s$);

    fun$nav$step(&self$, &out$step, gps, xv, s);

    volatile_store(&x$, out$step.x);
    volatile_store(&alarm$, out$step.alarm);
  }
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Boucle Principale

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}
```

Modèle Sémantique de Clight

- modèle mémoire : blocs contigus
- variables et registres
- état sémantique (E, L, M)

  E environnement de variables : identifiants vers adresses mémoire

  L environnement de registres : identifiants vers valeurs

  M mémoire : adresses vers octets

Conséquences du modèle mémoire de CompCert

- *aliasing*
- alignement
- permissions
- tailles de types

Manipulation de structures et de pointeurs

Conséquences du modèle mémoire de CompCert

- *aliasing*
- alignement
- permissions
- tailles de types

Manipulation de structures et de pointeurs

Solution : utiliser des assertions de Logique de Séparation

Logique de Séparation

Une extension de la logique de Hoare pour raisonner sur des programmes qui manipulent des structures et des pointeurs.

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Le prédicat $M \models P * Q$ stipule que M peut être partitionnée en deux zones distinctes sur lesquelles P et Q sont vraies respectivement.

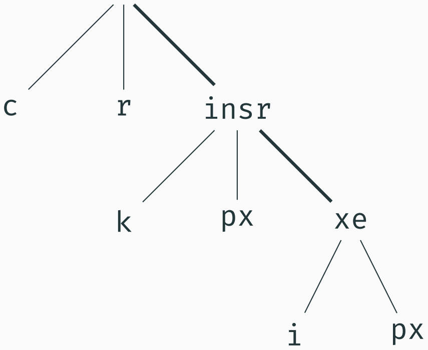
Logique de Séparation

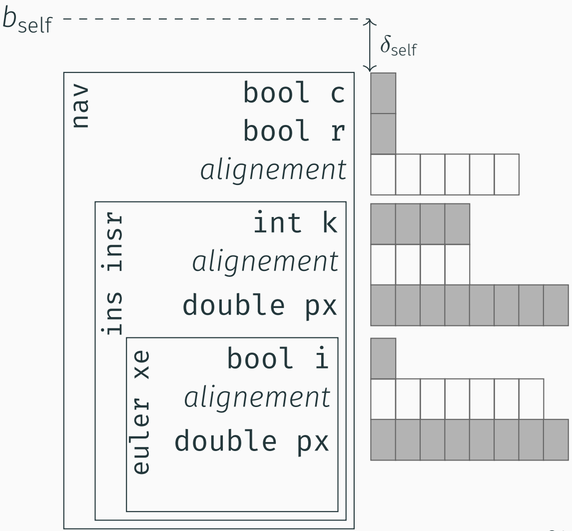
Une extension de la logique de Hoare pour raisonner sur des programmes qui manipulents des structures et des pointeurs.

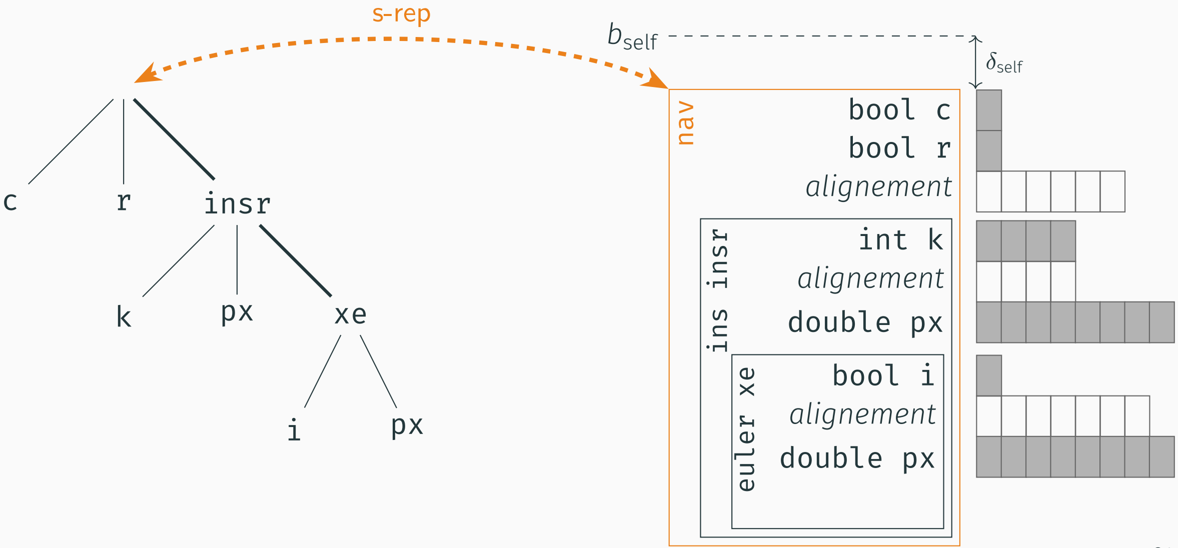
Le prédicat $M \vDash P * Q$ stipule que M peut être partitionnée en deux zones distinctes sur lesquelles P et Q sont vraies respectivement.

CompCert utilise déjà une librairie légère de Logique de Séparation pour l'une de ses passes.

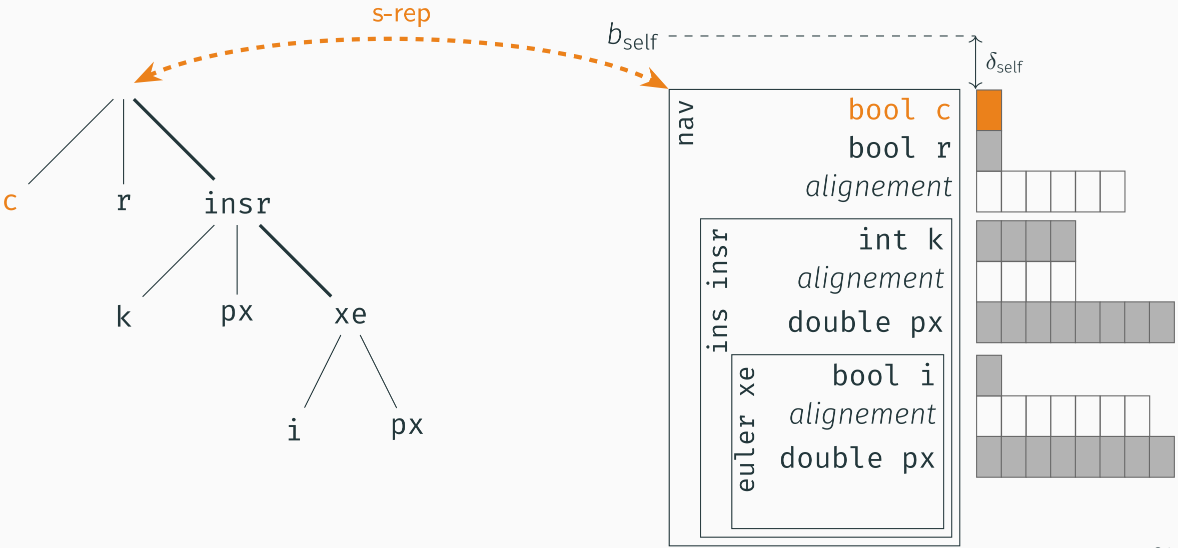
Prédicat de Correspondance d'État

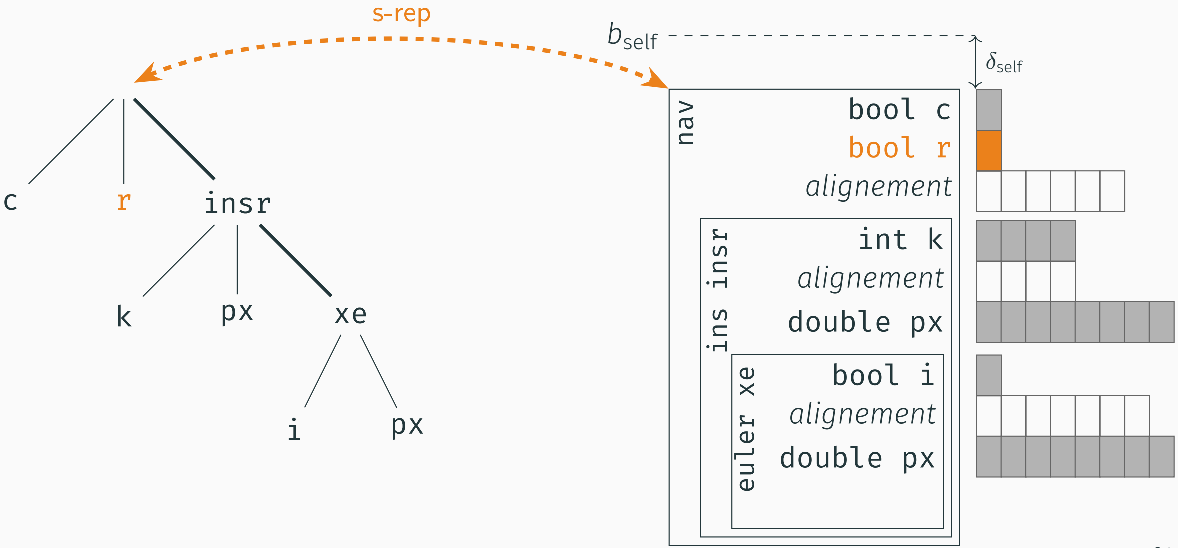





s-rep
b_{self}
δ_{self}
c
r
insr
k
px
xe
i
px
nav
bool c
bool r
alignement
ins insr
int k
alignement
double px
euler xe
bool i
alignement
double px

Prédicat de Correspondance d'État

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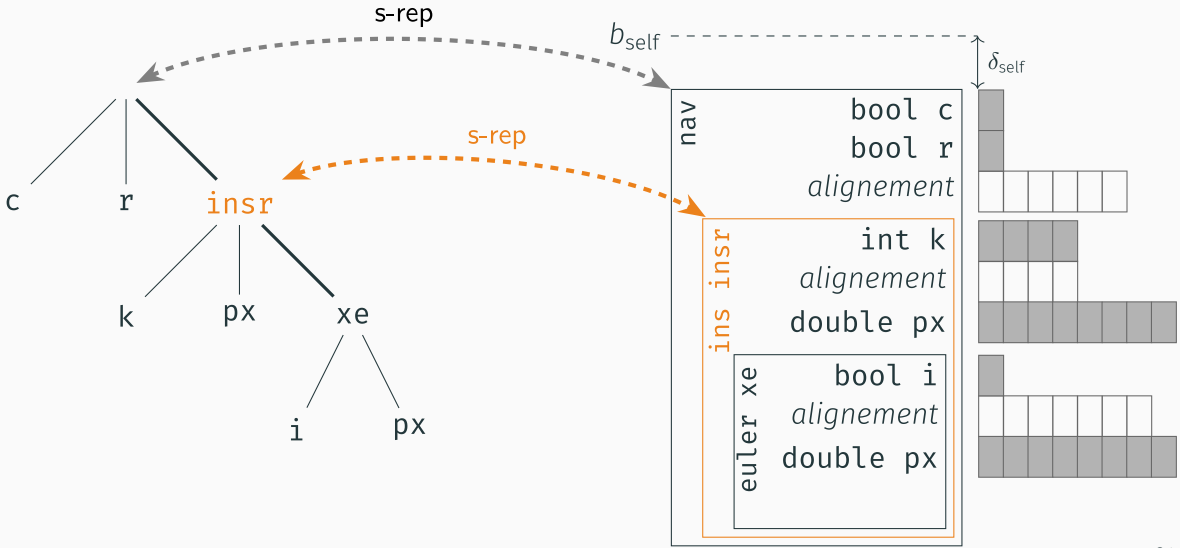
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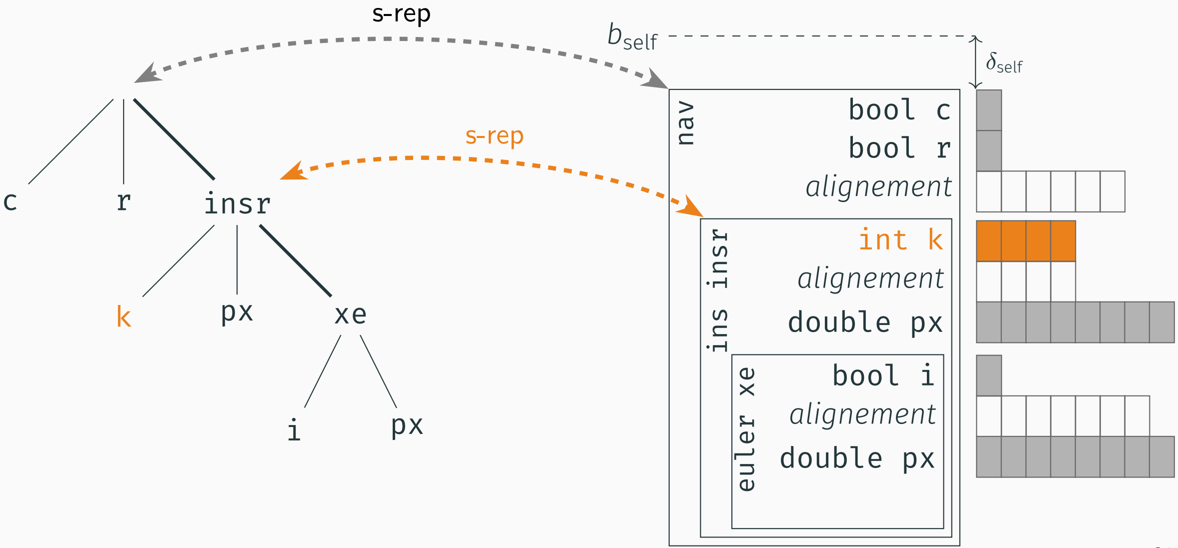

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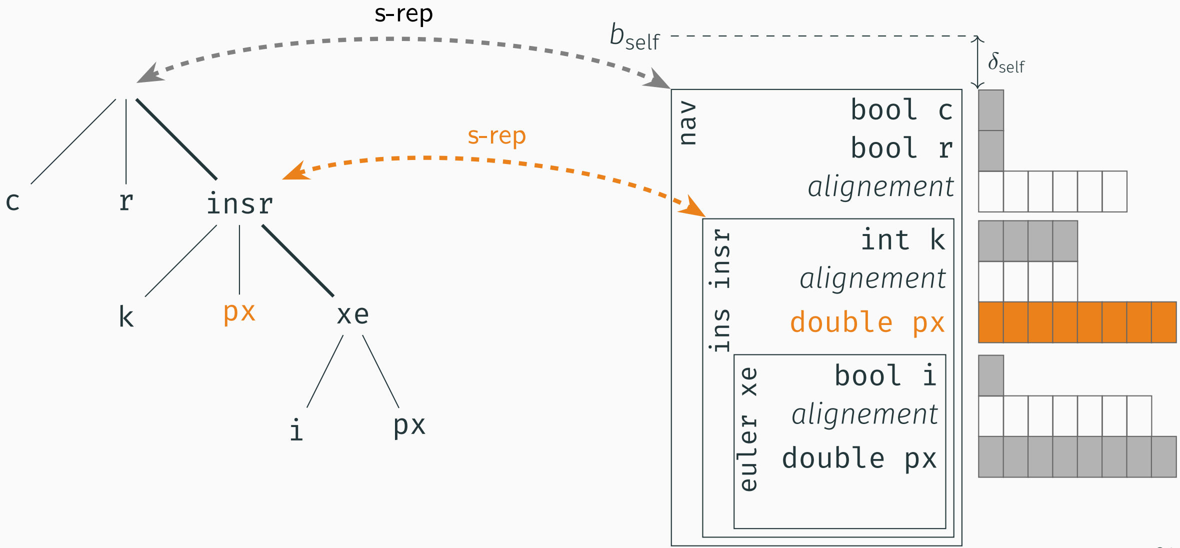

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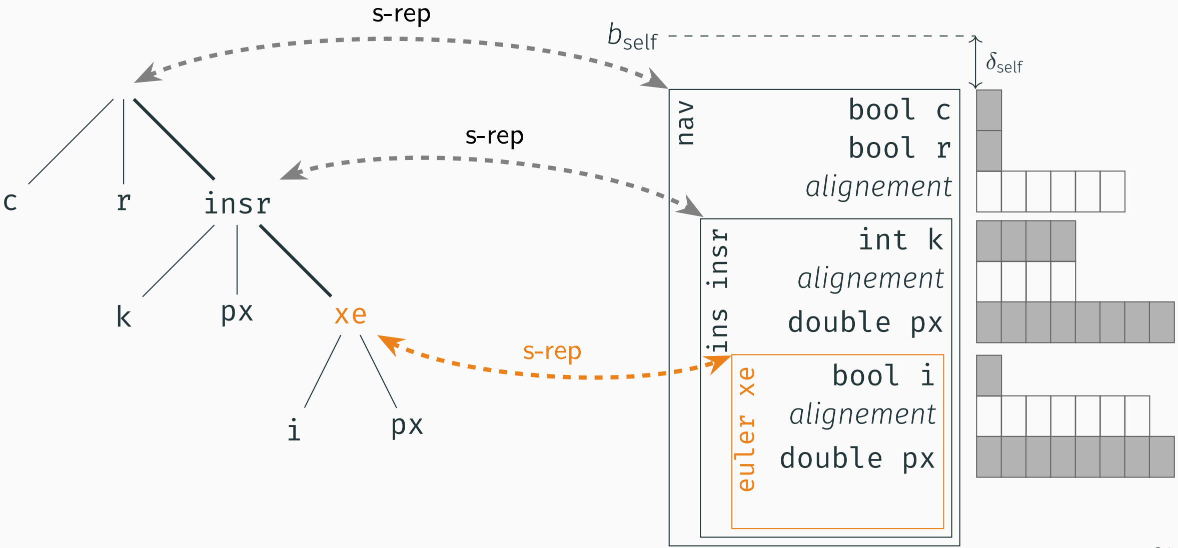

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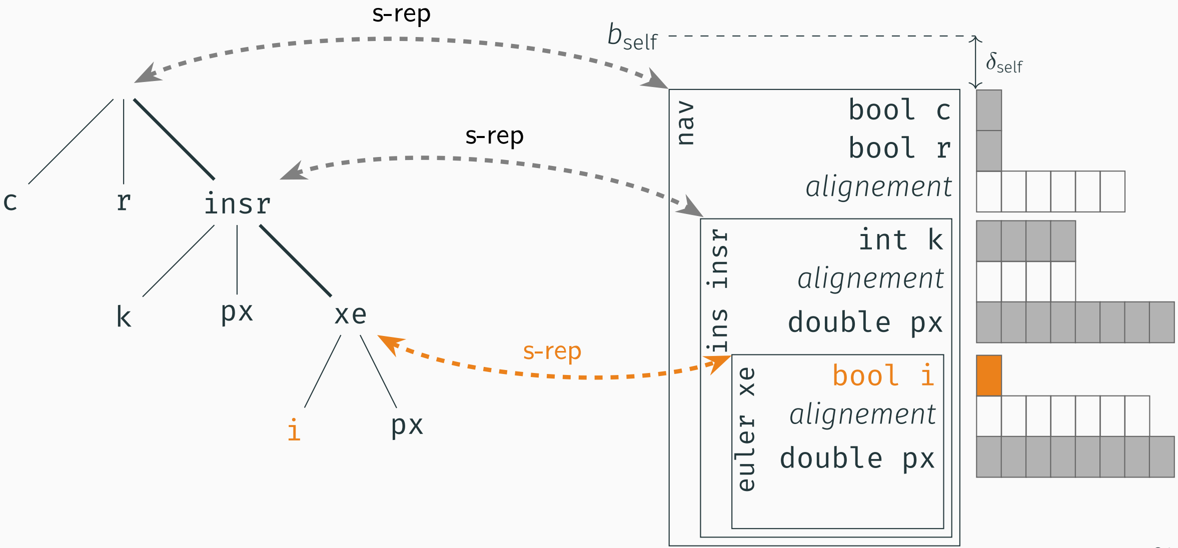

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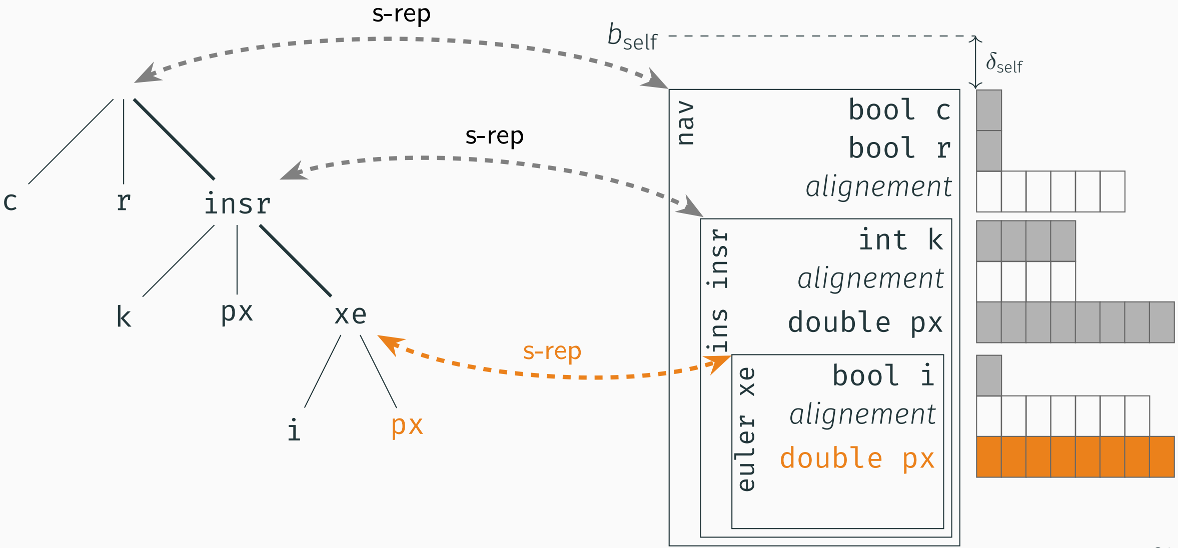
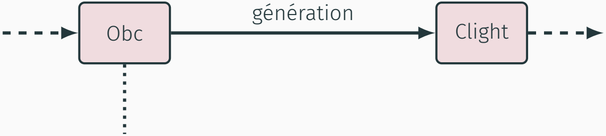
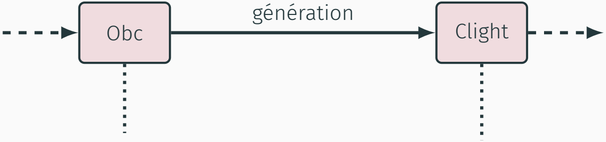




$$\varnothing \vdash f.\text{reset}\,() \Downarrow me_0$$

$$me_0 \vdash f.\text{step}\,(xs) \overset{0}{\circlearrowleft} ys$$



$\varnothing \vdash f.\mathrm{reset}\,() \Downarrow me_0$

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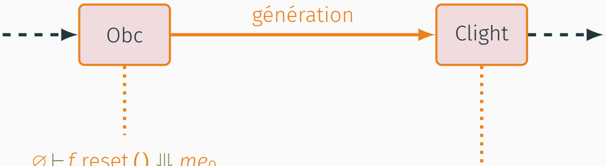
$\exists T,\ P \Downarrow \mathbf{Reacts}(T)$

T et (xs, ys) sont « équivalents »



$$\frac{\varnothing \vdash f.\text{reset}\,() \Downarrow me_0 \qquad me_0 \vdash f.\text{step}\,(xs) \overset{0}{\circlearrowleft} ys}{} \Longrightarrow P \Downarrow \textbf{Reacts}(\textbf{trace-step}\; f\; xs\; ys)$$

Correction de Vélus

Théorème (correction de Vélus)

Soient une liste de déclarations D, un nom f, deux listes de flots de valeurs $\boldsymbol{xs}$ *et* $\boldsymbol{ys}$*, un programme NLustre G et un programme Assembleur P tels que* $\mathsf{compile}\, D\, f = \mathsf{OK}\,(G, P)$ *et* $G \vdash f\,(\boldsymbol{xs}) \Downarrow \boldsymbol{ys}$*, alors, il existe une trace infinie d'événements T telle que*

$$P \Downarrow_{ASM} \mathsf{Reacts}(T) \quad \textit{et} \quad \mathsf{bisim\text{-}IO}^{G}\, f\, \boldsymbol{xs}\, \boldsymbol{ys}\, T$$

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Théorème Final

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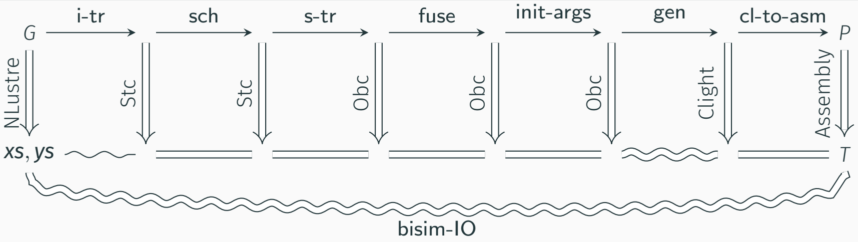


Conclusion

Résumé

- Un compilateur vérifié Lustre vers Assembleur
- Une seule règle sémantique pour le *reset*
- Un langage de systèmes de transitions intermédiaire : Stc

`velus.inria.fr`
`github.com/INRIA/velus`

Futur

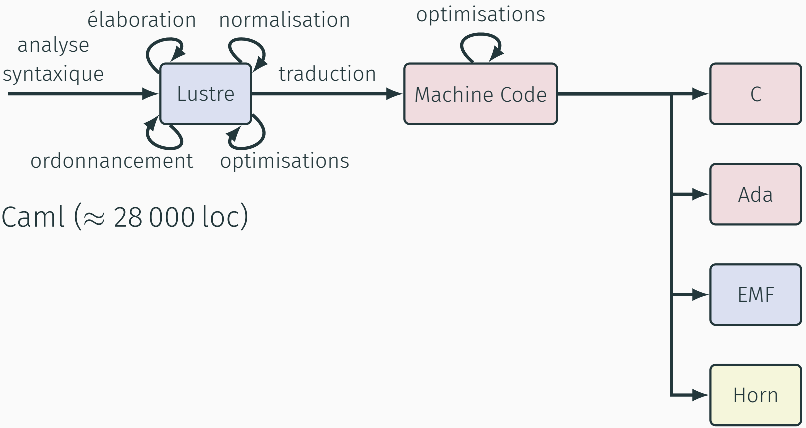
- Normalisation (fait !)
- Machines à états (en cours !)
- *Raffinement*
- Optimisations

Perspectives et discussion

- 42 000 loc et 3% de code fonctionnel
- Extensibilité
- Maintenance
- Axiomes
- Applicabilité industrielle

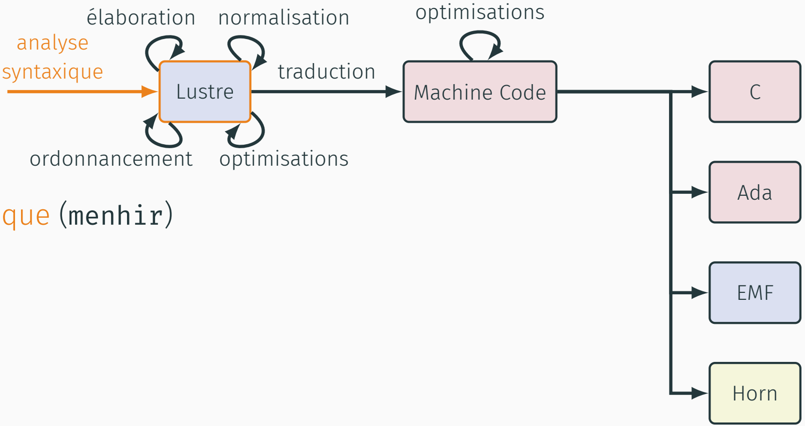
LustreC et compilation certifiante

LustreC : un Compilateur Lustre



Implémenté en OCaml (≈ 28 000 loc)

LustreC : un Compilateur Lustre



- analyse syntaxique (`menhir`)

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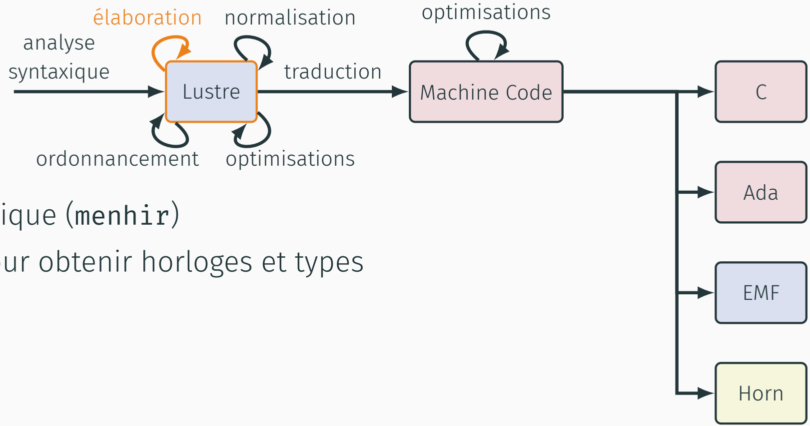

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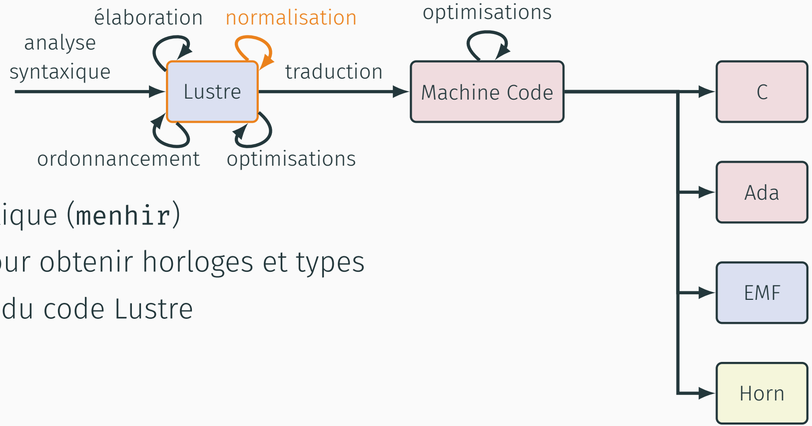
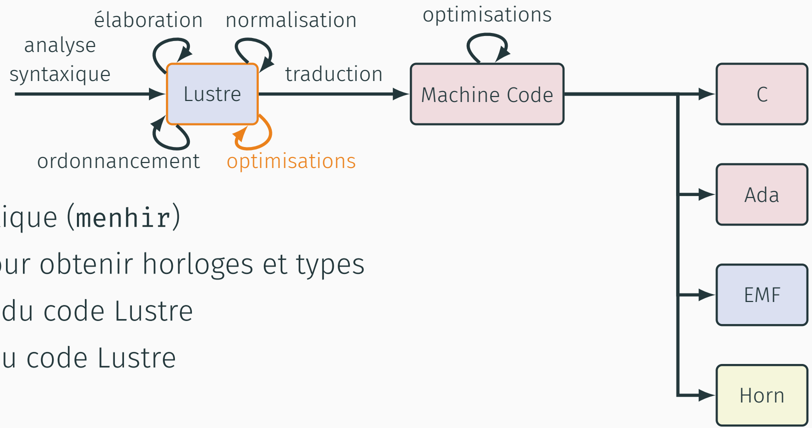


- analyse syntaxique (`menhir`)
- élaboration pour obtenir horloges et types
- normalisation du code Lustre



- analyse syntaxique (`menhir`)
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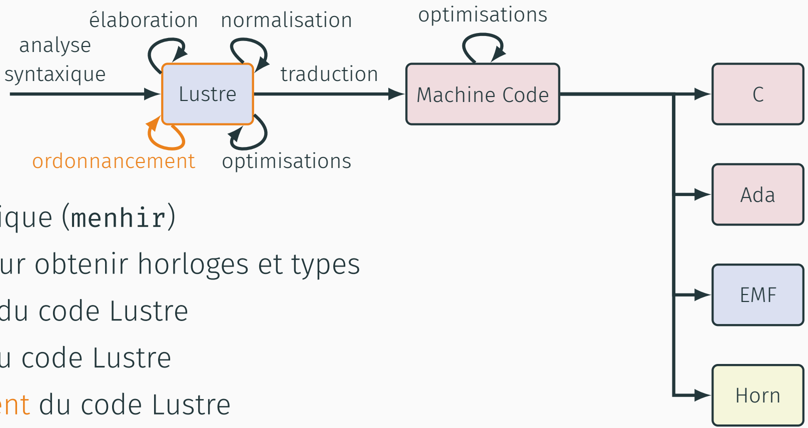
- optimisation du code Lustre

LustreC : un Compilateur Lustre



- analyse syntaxique (`menhir`)
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- optimisation du code Lustre
- ordonnancement du code Lustre

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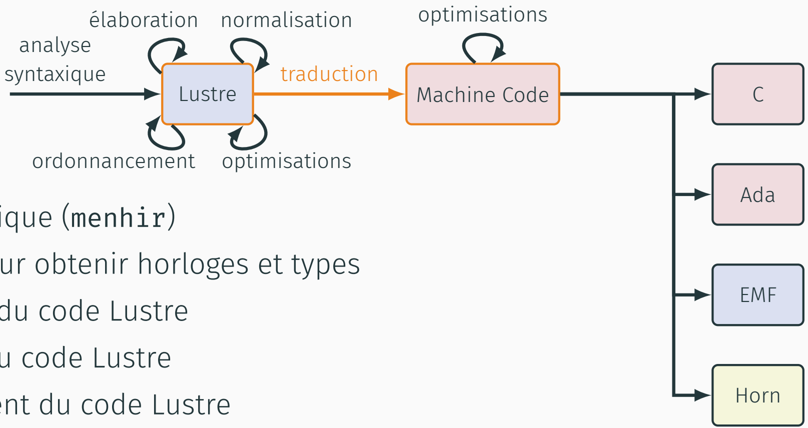

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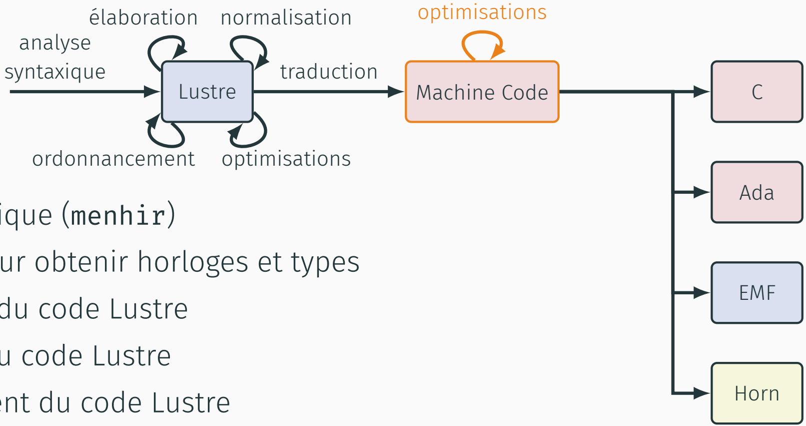

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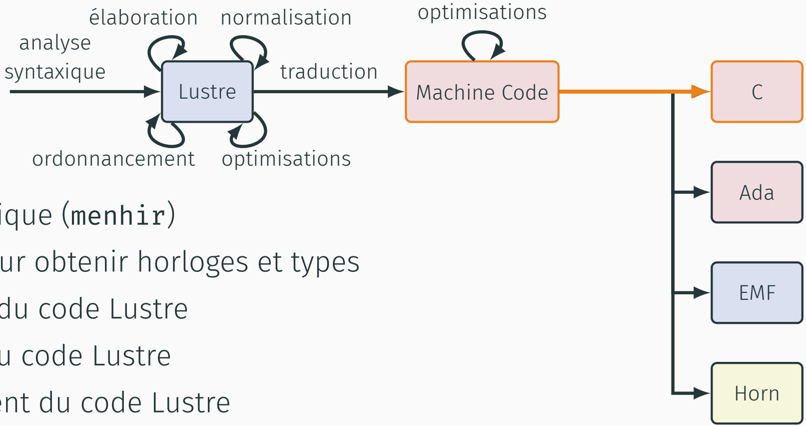

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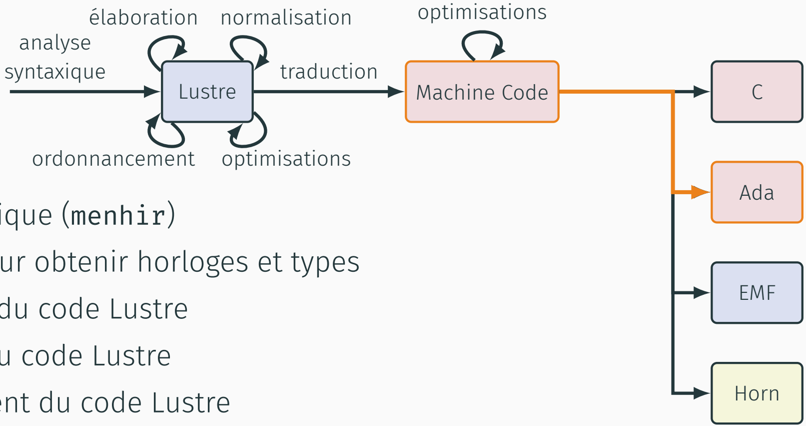

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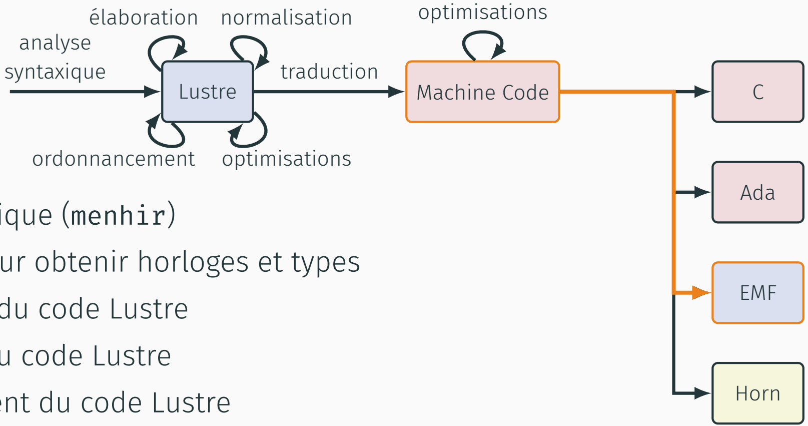

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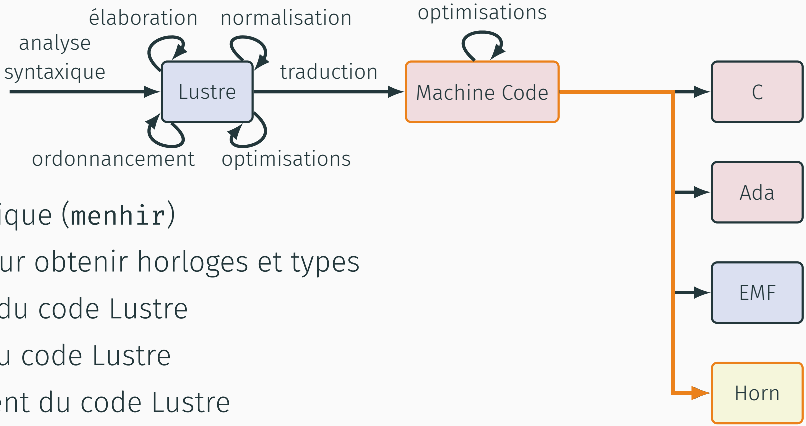

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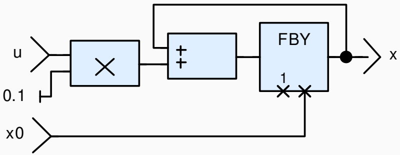
Objectif : Compilateur Certifiant

- Génération de spécification ACSL
- Encodage du résultat de correction
- À terme : transport automatique de spécification haut niveau

frama C
Software Analyzers

- Approche plus souple
- Autres *backends* envisageables (ex. SPARK / Ada)
- Incomparables en termes de fonctionnalités (2K loc vs 28K loc)
- SCADE vs Simulink
- Transport de spécifications et vérification




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

Exemple

```c
struct euler {
  bool i;
  double px;
};
```

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

void _arrow_reset(struct _arrow_mem *self) {
  self->_reg._first = true;
  return;
}

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

Exemple

```c
struct euler {
  bool i;
  double px;
};
```

```c
struct euler_mem {
  _Bool euler_reset;
  struct euler_reg {double __euler_2;} _reg;
  struct _arrow_mem *ni_9;
};
```

Exemple

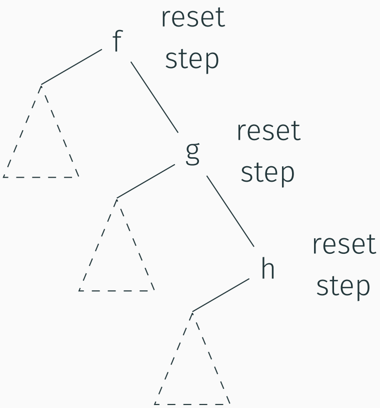
```
void fun$euler$reset(struct euler *self) {
  self->i = true;
  self->px = 0;
  return;
}
```

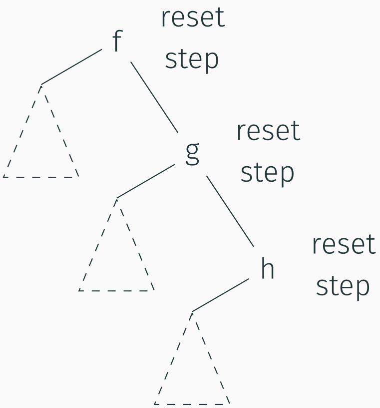
```
void euler_set_reset(struct euler_mem *self) {
  self->euler_reset = 1;
  return;
}

void euler_clear_reset(struct euler_mem *self) {
  if (self->euler_reset) {
    self->euler_reset = 0;
    _arrow_reset(self->ni_9);
  }
  return;
}
```

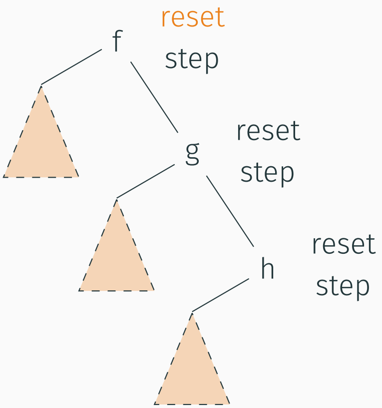
```c
double fun$euler$step(struct euler *self,
                      double x0, double u) {
  register double x;
  if (self->i) {
    x = x0;
  } else {
    x = self->px;
  }
  self->i = false;
  self->px = x + 0.10000000000000006 * u;
  return x;
}
```

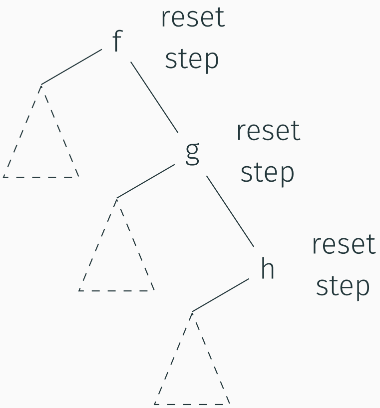
```c
void euler_step(double x0, double u,
                double (*x),
                struct euler_mem *self) {
  _Bool __euler_1;
  euler_clear_reset(self);
  __euler_1 = _arrow_step(self->ni_9);
  if (__euler_1) {
    *x = x0;
  } else {
    *x = self->_reg.__euler_2;
  }
  self->_reg.__euler_2 = (*x + (0.1 * u));
  return;
}
```

Compilation du reset






reset
f
step
reset
g
step
reset
h
step


reset
f
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g
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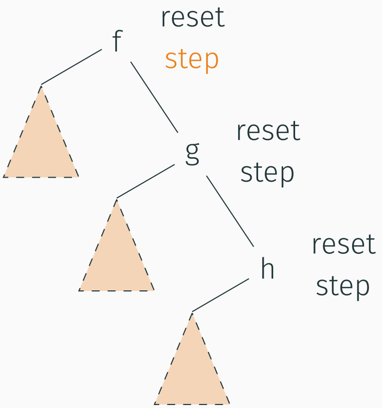
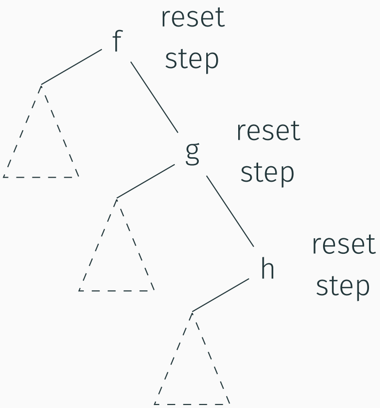
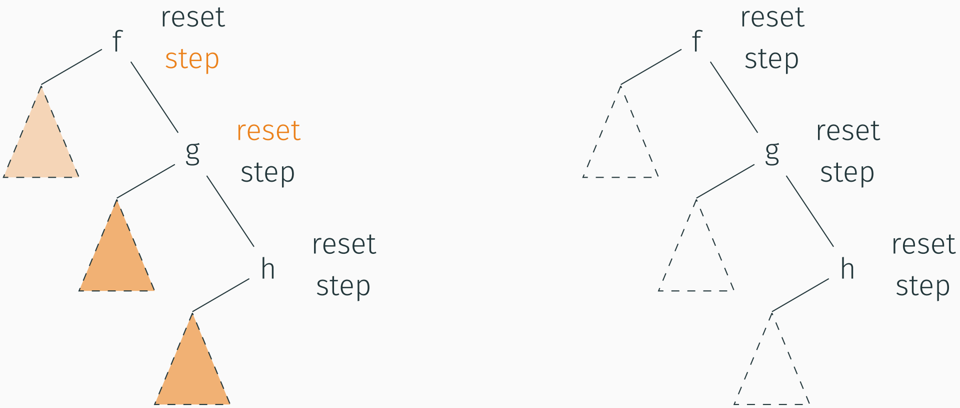
step

Compilation du reset







f
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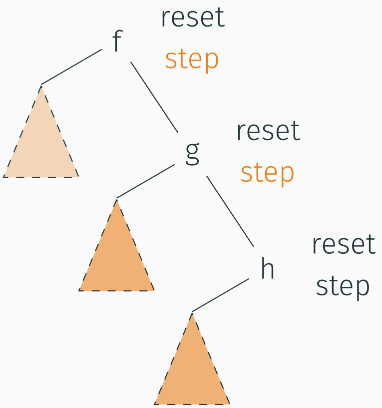
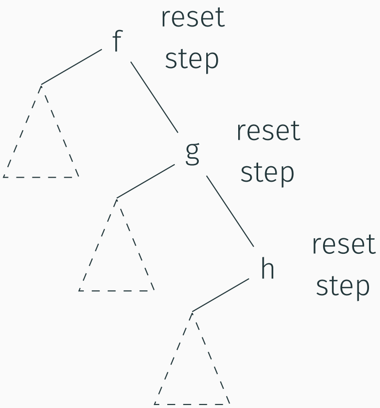
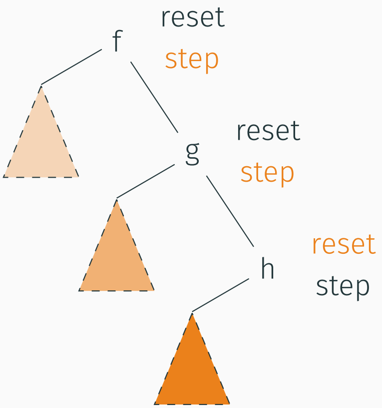
Compilation du reset






f
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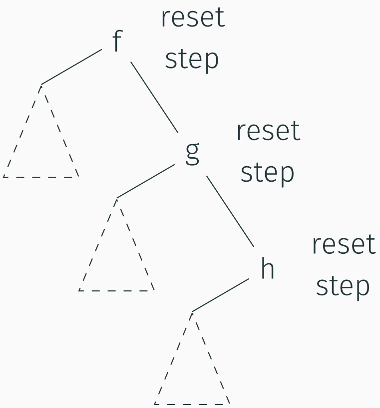
f
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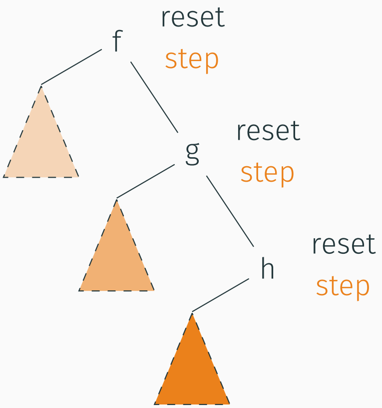
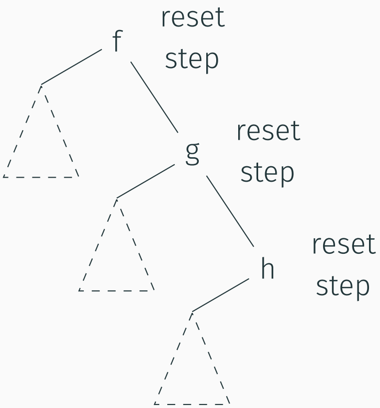
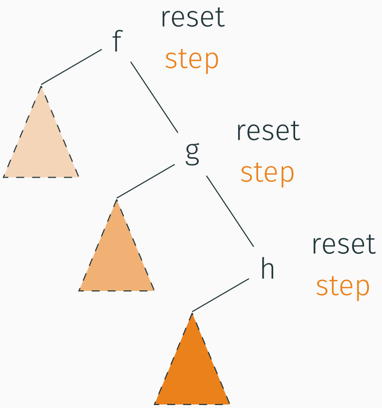
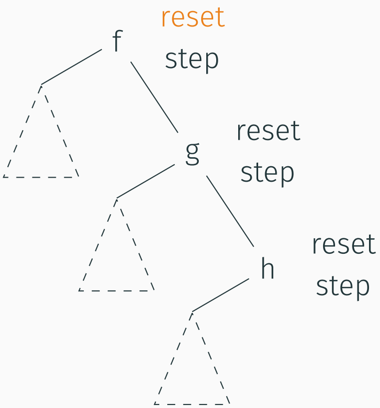
Compilation du reset





Compilation du reset





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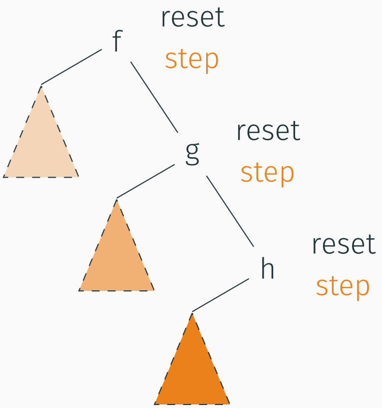

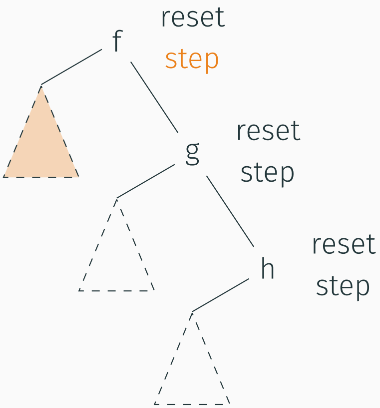

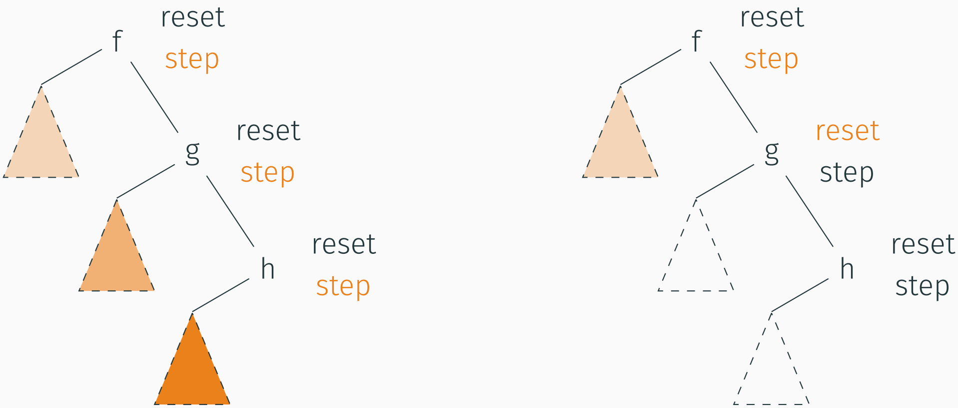
reset
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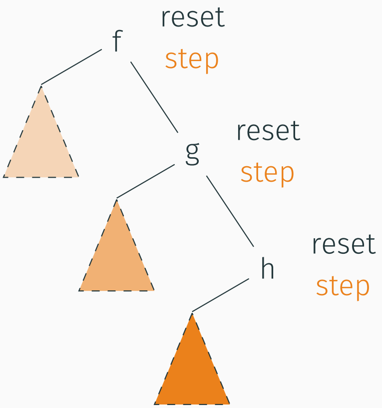
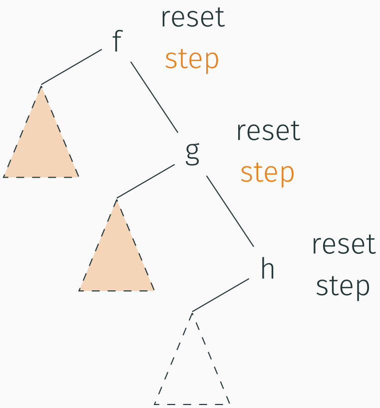
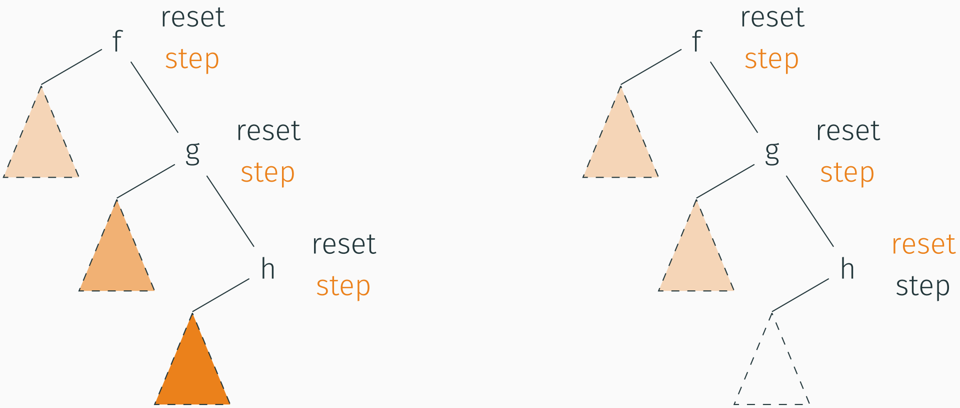
Compilation du reset

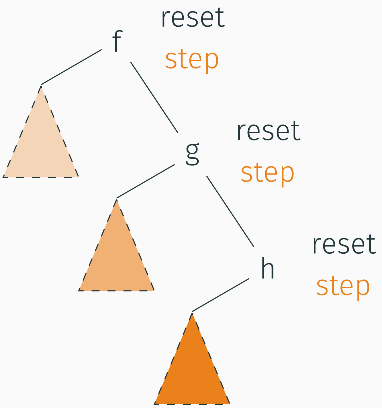


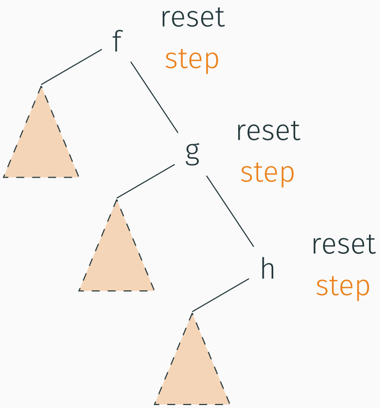


Compilation du reset



Compilation du reset





Principe de la spécification

Prédicats ACSL

- correspondance d'état (mémoire fantôme, principe de `s-rep`)
- relations de transition

Exemple avec Spécification

```
/*@ requires \separated(self, mem, self->ni_9, x);
    requires euler_ghost(*mem, self);
    ensures euler_ghost(*mem, self);
    ensures euler_transition(\old(*mem), x0, u, *mem, *x);
    assigns *x;
    assigns self->_reg.__euler_2;
    assigns self->ni_9->_reg._first;
    assigns self->euler_reset;
    assigns mem->_reg.__euler_2;
    assigns mem->ni_9._reg._first;
    assigns mem->euler_reset;
*/
void euler_step(double x0, double u,
                 double (*x),
                 struct euler_mem *self)
      /*@ ghost (struct euler_mem_ghost \ghost *mem) */ {
```

Exemple avec Spécification

```
  _Bool __euler_1;
  euler_clear_reset(self) /*@ ghost (mem) */;
  //@ assert euler_ghost0(*mem, self);
  //@ assert euler_transition0(*mem, x0, u, *mem);
  Reset:

  __euler_1 = _arrow_step(self->ni_9) /*@ ghost (&mem->ni_9) */;
  //@ assert euler_ghost1(*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_ghost2(*mem, self);
  //@ assert euler_transition2(\at(*mem, Reset), x0, u, *mem, *x);

  self->_reg.__euler_2 = (*x + (0.1 * u));
  //@ ghost mem->_reg.__euler_2 = (*x + (0.1 * u));
  //@ assert euler_ghost3(*mem, self);
  //@ assert euler_transition3(\at(*mem, Reset), x0, u, *mem, *x);

  return;
}
```

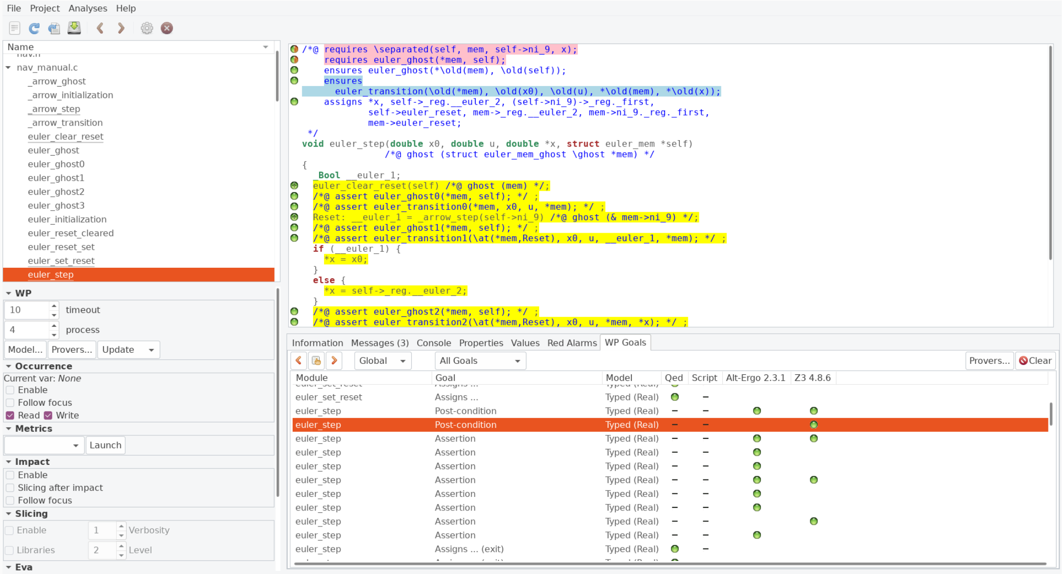
Exemple avec Spécification

```
/*@ ghost struct euler_mem_ghost {
          _Bool euler_reset;
          struct euler_reg _reg;
          struct _arrow_mem_ghost ni_9;
   };
*/
/*@ predicate euler_ghost0(struct euler_mem_ghost mem, struct euler_mem *self) =
      mem.euler_reset == self->euler_reset && mem.euler_reset == \false;
*/
/*@ predicate euler_ghost1(struct euler_mem_ghost mem, struct euler_mem *self) =
      euler_ghost0(mem, self)
      && _arrow_ghost(mem.ni_9, self->ni_9);
*/
/*@ predicate euler_ghost2(struct euler_mem_ghost mem, struct euler_mem *self) =
      euler_ghost1(mem, self);
*/
/*@ predicate euler_ghost3(struct euler_mem_ghost mem, struct euler_mem *self) =
      euler_ghost2(mem, self)
      && (!_arrow_initialization(mem.ni_9) ==> mem._reg.__euler_2 == self->_reg.__euler_2);
*/
/*@ predicate euler_ghost(struct euler_mem_ghost mem, struct euler_mem *self) =
      mem.euler_reset ? (mem.euler_reset == self->euler_reset) : (euler_ghost3(mem, self));
*/
```

Exemple avec Spécification

```
/*@ predicate euler_transition0(struct euler_mem_ghost mem_in,
                                double x0, double u,
                                struct euler_mem_ghost mem_out) =
      \true;
*/
/*@ predicate euler_transition1(struct euler_mem_ghost mem_in,
                                double x0, double u, _Bool __euler_1,
                                struct euler_mem_ghost mem_out) =
      euler_transition0(mem_in, x0, u, mem_out)
      && _arrow_transition(mem_in.ni_9, mem_out.ni_9, __euler_1);
*/
/*@ predicate euler_transition2(struct euler_mem_ghost mem_in,
                                double x0, double u,
                                struct euler_mem_ghost mem_out, double x) =
      \exists _Bool __euler_1;
        euler_transition1(mem_in, x0, u, __euler_1, mem_out)
        && (__euler_1 ? (x == x0) : (x == mem_in._reg.__euler_2));
*/
/*@ predicate euler_transition3(struct euler_mem_ghost mem_in,
                                double x0, double u,
                                struct euler_mem_ghost mem_out, double x) =
      euler_transition2(mem_in, x0, u, mem_out, x)
      && mem_out._reg.__euler_2 == (x + 0.1 * u);
*/
/*@ predicate euler_transition(struct euler_mem_ghost mem_in,
                               double x0, double u,
                               struct euler_mem_ghost mem_out, double x) =
      \exists struct euler_mem_ghost mem_reset;
        euler_reset_cleared(mem_in, mem_reset)
        && euler_transition3(mem_reset, x0, u, mem_out, x);
*/
```

Frama-C



File Project Analyses Help
Name
nav_manual.c
_arrow_ghost
_arrow_initialization
_arrow_step
_arrow_transition
euler_clear_reset
euler_ghost
euler_ghost0
euler_ghost1
euler_ghost2
euler_ghost3
euler_initialization
euler_reset_cleared
euler_reset_set
euler_set_reset
euler_step
WP
10 timeout
4 process
Model... Provers... Update
Occurrence
Current var: None
Enable
Follow focus
Read Write
Metrics
Launch
Impact
Enable
Slicing after impact
Follow focus
Slicing
Enable 1 Verbosity
Libraries 2 Level
Eva
/*@ requires \separated(self, mem, self->ni_9, x);
requires euler_ghost(*mem, self);
ensures euler_ghost(*\old(mem), \old(self));
ensures
euler_transition(\old(*mem), \old(x0), \old(u), *\old(mem), *\old(x));
assigns *x, self->_reg.__euler_2, (self->ni_9)->_reg._first,
self->euler_reset, mem->_reg.__euler_2, mem->ni_9._reg._first,
mem->euler_reset;
*/
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) */;
/*@ assert euler_ghost0(*mem, self); */ ;
/*@ assert euler_transition0(*mem, x0, u, *mem); */ ;
Reset: __euler_1 = _arrow_step(self->ni_9) /*@ ghost (& mem->ni_9) */;
/*@ assert euler_ghost1(*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_ghost2(*mem, self); */ ;
/*@ assert euler_transition2(\at(*mem,Reset), x0, u, *mem, *x); */ ;
Information Messages (3) Console Properties Values Red Alarms WP Goals
Global All Goals Provers... Clear
Module Goal Model Qed Script Alt-Ergo 2.3.1 Z3 4.8.6
euler_set_reset Assigns ... Typed (Real)
euler_step Post-condition Typed (Real)
euler_step Post-condition Typed (Real)
euler_step Assertion Typed (Real)
euler_step Assigns ... (exit) Typed (Real)

Conclusion

Résumé

- Un compilateur certifiant Lustre vers C / Frama-C
- Une compilation différente du *reset*
- Un raisonnement basé sur des simulations

Futur

- Prototype
- *reset* monolithique ?
- Optimisations
- Réels
- SPARK / Ada
- Transport de spécifications
- Comparaison avec la sortie SMT

Références I

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