Checking contracts in Event-B Reporting the introduction and the use of automated tools for verifying software-based systems in higher education

Dominique Méry
Telecom Nancy,Université de Lorraine
dominique.mery@loria.fr

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Summary

Current Summary

Objectives

modelling, verifying, validating

Lectures on *modelling, designing, verifying and validating software-based systems* taught in the MsC *Computer Science* at Faculty of Science of the University of Lorraine and in the Computer Engineering Master of the School *Telecom Nancy* of the University of Lorraine.

- The epistemological concepts were given using the classical blackboard and chalk and progressively we have moved to integrate automated verification techniques and tools.
- Group of 50 students in +4 for regular students from a highly competive selection ...
- Group of 20 students in +4 for apprentice students (two months at school and two months at company)

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Idea

To introduce progressively the concepts of verification using the Floyd-Hoare principle and to show how students can develop a tool for their pet programming language.

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First steps in FMTea...academic year 1983/1984

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- Main tools are pen and paper !

Teaching Verification Techniques in 1983/1984

Third Year University Degree (List of courses)

RAPPEL DE L'ORGANISATION DES ENSEIGNEMENTS DE LA LICENCE SMI.

Matière	U.V.	Cours		T.D.	
Programmation PASCAL (semaine bloquée)	0	15	Perrin	25	de Bary
Architecture des Ordinateurs et langage d'assemblage	1/2	26	Perrin	34,5	Perrin
Algorithmique des Tables Arbres et Graphes	1/2	26	Cousot	34,5	Kaced
Informatique de Gestion	1/2	24	de Bary	32	de Bary
Bases de Données	1/2	24	de Bary	32	de Bary
2c Système d'Exploitation des Ordinateurs	1/2	24	Cousot	32	Mery
Analyse Numérique	1/2	19,5	Schmitt	39	Ginie d'Arnaud
Analyse	1	37,5	Rhin	75	Idt

Total 196 + 304 = 500 heures annu

Teaching Verification Techniques in 1983/1984

Fourth Year University Degree (List of courses)

ANNEXE 3. : ORGANISATION DES ENSEIGNEMENTS DE LA MAITRISE SMI. - 2/

Matière	U.V.	Cours		T.D.	
Logique Mathématique	1/2	26	Chauvin	34,5	Tyvaert
Sémantique et Logique des programmes	1/2	26	Cousot	34,5	Mery
Langages de Program-mation et Compilation	1/2	26	Cousot	39	Kaced
Mathématiques du contrôle	1/2	24	Sec	37,5	Sallet
Contrôle de Processus en temps réel	1/2	24	Perrin	32	Perrin
Téléinformatique	1/2	24	Cousot	32	Mery
Probabilités et Statis-tiques.	1	38	Rhin et Nasi	76	Sertour
		188	+	285,5	473,5 heures annuelles plus stage industrie

Teaching Verification Techniques in 1983/1984

Course Semantics and Logics for Programs

SEMANTIQUE ET LOGIQUE DES PROGRAMMES

- Sémantique opérationnelle des langages de programmation,
- Méthode de Floyd de preuve de propriétés d'invariance (correction partielle, absence d'erreur à l'exécution) des programmes impératifs séquentiels,
- Méthode axiomatique de Hoare,
- Preuves de terminaison utilisant un ordre bien fondé,
- Méthode des assertions intermittentes de Burstall pour démontrer la correction totale des programmes impératifs séquentiels,
- Correction et complétude des méthodes de preuve relatives à une sémantique opérationnelle,
- Démonstration de la correction de programmes applicatifs par induction

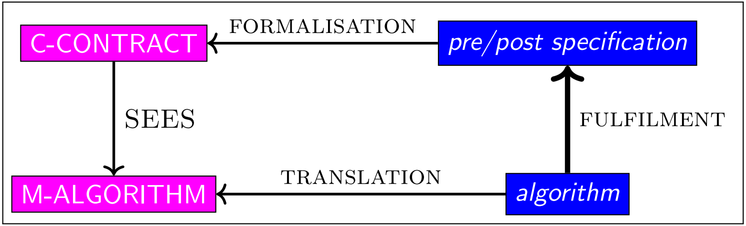
From PAP (Pen And Paper) to FIDE (Formal IDE)

- (1983-1993) Fruitful period for proof tools as Coq, Isabelle, ...
- The temporal framework and model checking techniques
- The B proposal and the use of proof assistants
- Experiment with techniques and tools
  - TLA tools
  - Rodin, Atelier-B
  - PAT
  - PRISM
  - Z3, CVC, ...
  - Frama-c
  - DAFNY

Sketch

The main steps of our method:

- FORMALISATION Expression of the contract as assertions defined in an Event-Bcontext.
- TRANSLATION Translation of annotations as elements of the invariant and of the basic computation steps between two successive labels as events.



Current Summary

Current Summary

Detecting overflows of computations

Listing 1: Function average

```
#include <stdio.h>
#include <limits.h>
int average(int a,int b)
{
  return((a+b)/2);
}

int main()
{
  int x,y;
  x=INT_MAX;y=INT_MAX;
  printf("Average for %d and %d is %d\n",x,y,
         average(x,y));
  return 0;
}
```

Execution

Execution produces a result

```
Average  for 2147483647 and 2147483647 is -1
```

Execution

Execution produces a result

```
Average  for 2147483647 and 2147483647 is -1
```

Using frama-c produces a required annotation

```
int average(int a, int b)
{
  int __retres;
  /*@ assert rte: signed_overflow: -2147483648 <= a + b; */
  /*@ assert rte: signed_overflow: a + b <= 2147483647; */
  __retres = (a + b) / 2;
  return __retres;
}
```

Annotated Example 1

Listing 2: Function average.....

```
#include <stdio.h>
#include <limits.h>
/*@  requires  0 <= a;
     requires a <= INT_MAX ;
     requires  0 <= b;
     requires b <= INT_MAX ;
     requires  0 <= a+b;
     requires a+b <= INT_MAX ;
     ensures \result <= INT_MAX;
*/
int average(int a,int b)
{
  return((a+b)/2);
}

int main()
{
  int x,y;
  x=INT_MAX / 2;y=INT_MAX / 2;
  //  printf("Average  for %d and %d is %d\n",x,y,
  //      );
  return average(x,y);
}
```

Current Summary

Nose Gear Velocity

- Estimated ground velocity of the aircraft should be available only if it is within 3 $\mathtt{km/hr}$ of the true velocity at some moment within past 3 seconds

Characterization of a System (I)

- NG velocity system:
  - **Hardware**:
    - *Electro-mechanical sensor*: detects rotations
    - *Two 16-bit counters*: Rotation counter, Milliseconds counter
    - *Interrupt service routine*: updates rotation counter and stores current time.
  - **Software**:
    - *Real-time operating system*: invokes update function every `500 ms`
    - *16-bit global variable*: for recording rotation counter update time
    - *An update function*: estimates ground velocity of the aircraft.
- Input data available to the system:
  - *time*: in `milliseconds`
  - *distance*: in `inches`
  - *rotation angle*: in `degrees`
- Specified system performs velocity estimations in *imperial* unit system
- Note: expressed functional requirement is in *SI* unit system (km/hr).

Characterization of a System (II) cont.

What are the main properties to consider for formalization?

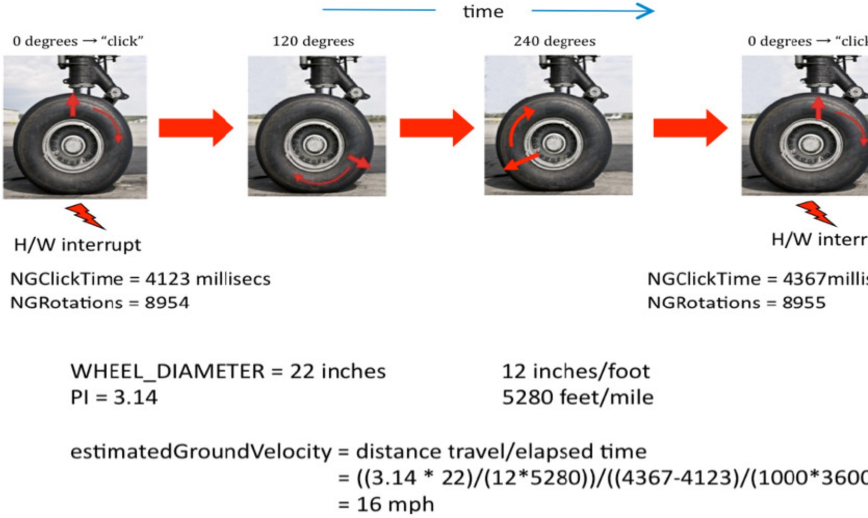
- Two different types of data:
  - counters with modulo semantics
  - non-negative values for time, distance, and velocity
- Two dimensions: *distance* and *time*
- Many units: distance (`inches`, `kilometers`, `miles`), time (`milliseconds`, `hours`), velocity (`kph`, `mph`)
- And interaction among components

How should we model?

- Designer needs to consider units and conversions between them to manipulate the model
- One approach: Model units as *sets*, and conversions as constructed types – *projections*.
- Example:

1 $estimateVelocity \in \mathtt{MILES} \times \mathtt{HOURS} \rightarrow \mathtt{MPH}$
2 $mphTokph \in \mathtt{MPH} \rightarrowtail\!\!\!\!\twoheadrightarrow \mathtt{KPH}$

Sample Velocity Estimation



Safety Property Run Time Error (RTE)

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Safety Property

- Storing the number of `NGClick` in a n-bit variable VNGClick
- Integers are denoted by the set *Int* and is simply defined by the interval *Int*$\hat{=}INT\_MIN..INT\_MAX$.
- Safety requirement:
  The value of ***`VNGClick`*** *is always in the range of implementation Int*
  or equivalently $VNGClick \in Int$

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  or equivalently $VNGClick \in Int$

- $Length = \pi * diameter * VNGClick$ (**mathematical property**)
- $Length \leq 6000$ (**domain property**)
- $\pi * diameter * VNGClick \leq 6000$
- $VNGClick \leq 6000/(\pi * diameter)$
  - if n=8, then $2^7 - 1 = 127$ and $6000/(\pi * [22, inch]) = 6000/(\pi * 55, 88) = 6000/(3, 24 * [55, 88, cm]) = 6000/(3, 24 * 0.5588) \approx 3419$ and the condition of safety can not be satisfied in any situation.
  - if n=16, then $2^{15} - 1 = 65535$ and $6000/(\pi * [22, inch]) \approx 3419$ and the condition of safety can be satisfied in any situation since $3419 \leq= 65535$.

Safety Property Run Time Error (RTE)

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- Integers are denoted by the set *Int* and is simply defined by the interval *Int*$\hat{=} INT\_MIN..INT\_MAX$.
- Safety requirement:
  The value of ***`VNGClick`*** *is always in the range of implementation Int* or equivalently $VNGClick \in Int$

$$RTE\_VNGClick : 0 \leq vNGClick \leq INT\_MAX \qquad (1)$$

- The current value of VNGClick is always bounded by the two values 0 and INT_MAX.

Current Summary

bug0.c

Listing 3: Bug bug0

```
#include <stdio.h>
#include <stdlib.h>
#include <time.h>

int main() {
    int x, y;
    // Seed the random number generator with the current time
    srand(time(NULL));
    // Generate a random number between 1 and 100
    x = rand() % 100 + 1;
    // Perform some calculations
    y = x / (100 - x);
    printf("Result: %d\n", y);
    return 0;
}
```

bug00.c

Listing 4: Bug bug00

```
// Heisenbug
#include <stdio.h>
#include <stdlib.h>
#include <time.h>



int main() {
  int x, y,i=0;

    for (i = 0; i <= 100000; i++) {
    // Seed the random number generator with the current time
    srand(time(NULL));

    // Generate a random number between 1 and 100
    x = rand() % 100 + 1;
        printf("Result: x= %d\n",x);
    // Perform some calculations
    y = x / (100 - x);

    printf("Result: i=%d  %d\n",i, y);
    }

    return 0;
}
```

bug000.c

Listing 5: Bug bug000

```
// Heisenbug
#include <stdio.h>
#include <stdlib.h>
#include <time.h>



int main() {
  int x, y,i=0;

    for (i = 0; i <= 100; i++) {
    // Seed the random number generator with the current time
    srand(time(NULL)+i);

    // Generate a random number between 1 and 100
    x = rand() % 100 + 1;
         printf("Result: x= %d\n",x);
    // Perform some calculations
    y = x / (100 - x);

    printf("Result: i=%d  %d\n",i, y);
    }

    return 0;
}
```

Current Summary

Verifying program correctness

A program P *satisfies* a (pre,post) contract:

- P transforms a variable v from initial values v_0 and produces a final value v_f: $v_0 \xrightarrow{\mathsf{P}} v_f$
- v_0 satisfies pre: $\mathsf{pre}(v_0)$ and v_f satisfies post : $\mathsf{post}(v_0, v_f)$
- $\mathsf{pre}(v_0) \wedge v_0 \xrightarrow{\mathsf{P}} v_f \Rightarrow \mathsf{post}(v_0, v_f)$
- $\mathbb{D}$ est le domaine RTE de V

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- P transforms a variable v from initial values v_0 and produces a final value v_f: $v_0 \xrightarrow{\text{P}} v_f$
- v_0 satisfies pre: pre(v_0) and v_f satisfies post : post(v_0, v_f)
- pre$(v_0) \wedge v_0 \xrightarrow{\text{P}} v_f \Rightarrow$ post(v_0, v_f)
- $\mathbb{D}$ est le domaine RTE de V

requires $pre(v_0)$
ensures $post(v_0, v_f)$
variables X

begin
$0 : P_0(v_0, v)$
$\mathtt{instruction}_0$
$\ldots$
$i : P_i(v_0, v)$
$\ldots$
$\mathtt{instruction}_{f-1}$
$f : P_f(v_0, v)$
end

- $pre(v_0) \wedge v = v_0 \Rightarrow P_0(v_0, v)$
- $pre(v_0) \wedge P_f(v_0, v) \Rightarrow post(v_0, v)$
- For any pair of labelsℓ, ℓ' such that $\ell \longrightarrow \ell'$, one verifies that, pour any values $v, v' \in \textsc{Memory}$

$$\left(\begin{array}{l} \left(\begin{array}{l} pre(v_0) \wedge P_\ell(v_0, v)) \\ \wedge cond_{\ell,\ell'}(v) \wedge v' = f_{\ell,\ell'}(v) \end{array} \right) \\ \Rightarrow P_{\ell'}(v_0, v') \end{array} \right),$$

Contracts - Verification Conditions

contract P
variables v
requires $pre(v_0)$
ensures $post(v_0, v_f)$

begin
$0 : P_0(v_0, v)$
$\mathtt{S}_0$
$\ldots$
$i : P_i(v_0, v)$
$\ldots$
$\mathtt{S}_{f-1}$
$f : P_f(v_0, v)$
end

Contracts - Verification Conditions

```
contract P
variables v
requires pre(v0)
ensures post(v0, vf)
    begin
    0 : P0(v0, v)
    S0
    ...
    i : Pi(v0, v)
    ...
    Sf-1
    f : Pf(v0, v)
    end
```

Verification conditions are listed as follows:

- (initialisation)
  $pre(v_0) \wedge v = v_0 \Rightarrow P_0(v_0, v)$
- (finalisation)
  $pre(v_0) \wedge P_f(v_0, v) \Rightarrow post(v_0, v)$
- (induction)
  For each labels pair ℓ, ℓ'
  such that $\ell \longrightarrow \ell'$, one checks that,
  for any value $v, v' \in \textsc{Memory}$
  $$\left(\begin{array}{l} \left(\begin{array}{l} pre(v_0) \wedge P_\ell(v_0, v)) \\ \wedge cond_{\ell,\ell'}(v) \wedge v' = f_{\ell,\ell'}(v) \end{array} \right) \\ \Rightarrow P_{\ell'}(v_0, v') \end{array} \right),$$

Three kinds of verification conditions should be checked and we justify the method in the full version..

From PAP to Rodin . . .

From PAP to Rodin . . .

MACHINE M
SEES $C0$
VARIABLES
v, pc
INVARIANTS
typing : $v \in D$
control : $pc \in L$
$\ldots$
atℓ : $pc = \ell \Rightarrow P_{\ell}(v0, v)$
$\ldots$
$th1 : pre(v_0) \wedge v = v_0 \Rightarrow P_0(v_0, v)$
$th2 : pre(v_0) \wedge P_f(v_0, v)$
$\Rightarrow post(v_0, v)$
$\ldots$
END
$\ldots$
END

From PAP to Rodin ...

MACHINE M
SEES $C0$
VARIABLES
v, pc
INVARIANTS
typing : $v \in D$
control : $pc \in L$
$\ldots$
atℓ : $pc = \ell \Rightarrow P_\ell(v0, v)$
$\ldots$
$th1 : pre(v_0) \wedge v = v_0 \Rightarrow P_0(v_0, v)$
$th2 : pre(v_0) \wedge P_f(v_0, v) \Rightarrow post(v_0, v)$
$\ldots$
END
$\ldots$
END

MACHINE M
EVENTS
INITIALISATION
BEGIN
$(pc, v) :| \left(\begin{array}{l} pc' = l0 \wedge v' = v0 \\ \wedge pre(v0) \end{array} \right)$
END
$\ldots$
$e(\ell, \ell')$
WHEN
$pc = \ell$
$cond_{\ell,\ell'}(v)$
THEN
$pc := \ell'$
$v := f_{\ell,\ell'}(v)$
END
$\ldots$
END

Technical problems for students

(Induction Principle (I))

A property $S(z0, z)$ is a safety for an annotated program P if, and only if, there exists a property $I(z0, z)$ satisfying:

1. $\forall z0, z \in \mathsf{L} \times \mathsf{D}.init(z0) \wedge z = z0 \Rightarrow I(z0, z)$
2. $\forall z0, z, z' \in \mathsf{L} \times \mathsf{D}.init(z0) \wedge I(z0, z) \wedge (z \underset{P}{\longrightarrow} z') \Rightarrow I(z0, z')$
3. $\forall z0, z \in \mathsf{L} \times \mathsf{D}.init(z0) \wedge I(z0, z) \Rightarrow S(z0, z)$

(Induction Principle (II))

A property $S(\ell 0, x0, \ell, x)$ is a safety property for an annotated program P if, and only if, there exists a property $I(\ell 0, x0, \ell, x)$ satisfying:

1. $\forall \ell 0, \in \mathsf{L}, x0 \in \mathsf{D}.\ell 0 \in \mathsf{L0} \wedge pre(x0) \wedge x = x0 \wedge pc = \ell 0 \Rightarrow J(\ell 0, x0, \ell, x)$
2. $\forall \ell, \ell' \in \mathsf{L}, x, x0 \in \mathsf{D}.\ell 0 \in \mathsf{L0} \wedge pre(x0) \wedge J(\ell 0, x0, \ell, x) \wedge$ $BA(e(\ell, \ell'),)(\ell, x, \ell', x') \Rightarrow J(\ell 0, x0, \ell', x')$
3. $\forall \ell 0, \ell \in \mathsf{L}, x0, x \in \mathsf{D}.pre(x0) \wedge \ell 0 \in$ $\mathsf{L0} \wedge J(\ell 0, x0, \ell, x) \Rightarrow S(\ell 0, x0, \ell, x)$

Technical problems for students

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A property $S(\ell 0, x0, \ell, x)$ is a safety property for an annotated program P if, and only if, there exists a property $I(\ell 0, x0, \ell, x)$ satisfying:

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2. $\forall \ell, \ell' \in \mathsf{L}, x, x0 \in \mathsf{D}. \ell 0 \in \mathsf{L0} \wedge pre(x0) \wedge J(\ell 0, x0, \ell, x) \wedge BA(e(\ell, \ell'),)(\ell, x, \ell', x') \Rightarrow J(\ell 0, x0, \ell', x')$
3. $\forall \ell 0, \ell \in \mathsf{L}, x0, x \in \mathsf{D}. pre(x0) \wedge \ell 0 \in \mathsf{L0} \wedge J(\ell 0, x0, \ell, x) \Rightarrow S(\ell 0, x0, \ell, x)$

(Induction Principle (III))

A property $S(x0, \ell, x)$ is a safety for an annotated program P with one entry point if, and only if, there exists a property $I(x0, \ell, x)$ satisfying:

1. $\forall x0 \in \mathsf{D}. pre(x0) \wedge x = x0 \wedge \ell = \ell 0 \Rightarrow J(x0, \ell, x)$
2. $\forall \ell, \ell' \in \mathsf{L}, x, x0 \in \mathsf{D}. pre(x0) \wedge J(x0, \ell, x) \wedge BA(e(\ell, \ell'),)(\ell, x, \ell', x') \Rightarrow J(x0, \ell', x')$
3. $\forall \ell \in \mathsf{L}, x0, x \in \mathsf{D}. pre(x0) \wedge J(x0, \ell, x) \Rightarrow S(x0, \ell, x)$

Soundness of the translation

(Soundness of the method)

If the initialisation init, the generalisation gen and the step induction are proved to be correct by the Rodin platform, the property $S(x0, \ell, x)$ is a correct safety property for the program P. In particular, one can handle the partial correctness and the run time error safety properties.

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- Contract and verification conditions are translated into Event-B and are discharged by Rodin and its provers.
- Verification conditions are derived from Floyd's method.
- Annotation as assertion

A short example

contract SIMPLE
variables x
requires $x_0 \in \mathbb{N}$
ensures $x_f = 0$
begin
$\ell_0 : \{0 \leq x \leq x_0 \wedge x_0 \in \mathbb{N}\}$
while $0 <$ x $\mathbf{do}$
  $\ell_1 : \{0 < x \wedge x \leq x_0 \wedge x_0 \in \mathbb{N}\}$
  x := x $- 1$;
od
$\ell_2 : \{x = 0\}$end

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INVARIANTS
$inv1 : x \in \mathbb{N}$
$inv2 : l \in L$
$inv3 : l = l0 \Rightarrow$
$0 \leq x \wedge x \leq x0 \wedge x0 \in \mathbb{N}$
$inv4 : l = l1 \Rightarrow$
$0 < x \wedge x \leq x0 \wedge x0 \in \mathbb{N}$
$inv5 : l = l2 \Rightarrow x = 0$
$requires : x0 \in \mathbb{N} \wedge x = x0$
$\Rightarrow x = x0 \wedge x0 \in \mathbb{N}$
$ensures : x = 0 \wedge x = x0$
$\Rightarrow x = 0$

Event $Init$
then
  $act1 : x := x0$
  $act2 : l := l0$

Event $el0l1$
when
  $grd1 : l = l0$
  $grd2 : 0 < x$
then
  $act1 : l := l1$

Event $el0l2$
when
  $grd1 : l = l0$
  $grd2 : \neg(0 < x)$
then
  $act1 : l := l2$

Event $el1l0$
when
  $grd1 : l = l1$
then
  $act1 : l := l0$
  $act2 : x := x - 1$

Current Summary

From Floyd to Hoare

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- $\forall x_f, x_0.\mathsf{pre}(x_0) \wedge x_0 \xrightarrow{\mathsf{P}} x_f \Rightarrow \mathsf{post}(x_0, x_f)$

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- Questions of termination require the wp calculus . . .

Current Summary

Concluding Remarks

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- Learn Event-B language and set notation for the next year.
- Deepening of notations related to algorithms (endurant variables and perdurant variables) for preparing specific features of Frama-c.
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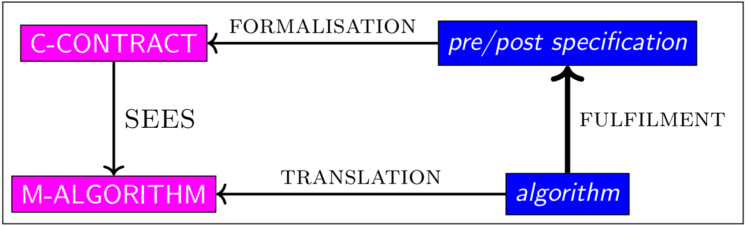
- One teacher or more teachers

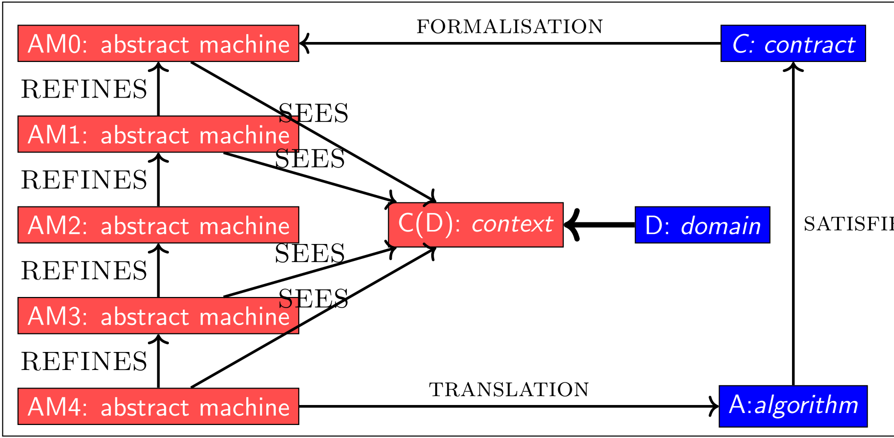
Sketch

The main steps of our method:

- FORMALISATION Expression of the contract as assertions defined in an Event-Bcontext.
- TRANSLATION Translation of annotations as elements of the invariant and of the basic computation steps between two successive labels as events.



Next year . . .



FORMALISATION
AM0: abstract machine
C: contract
REFINES
SEES
AM1: abstract machine
SEES
REFINES
AM2: abstract machine
C(D): context
D: domain
SATISFI
REFINES
SEES
AM3: abstract machine
SEES
REFINES
TRANSLATION
AM4: abstract machine
A:algorithm

Summary of concepts