
Cours MALG & MOVEX

Vérification mécanisée de contrats (II) (The ANSI/ISO C Specification Language (ACSL))

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Année universitaire 2024-2025

① Programs as Predicate

Transformers

② Annotations

③ Contracts

Logic Specification

Gestion et utilisation des

étiquettes pré-définies

Validation des annotations

(type HOARE)

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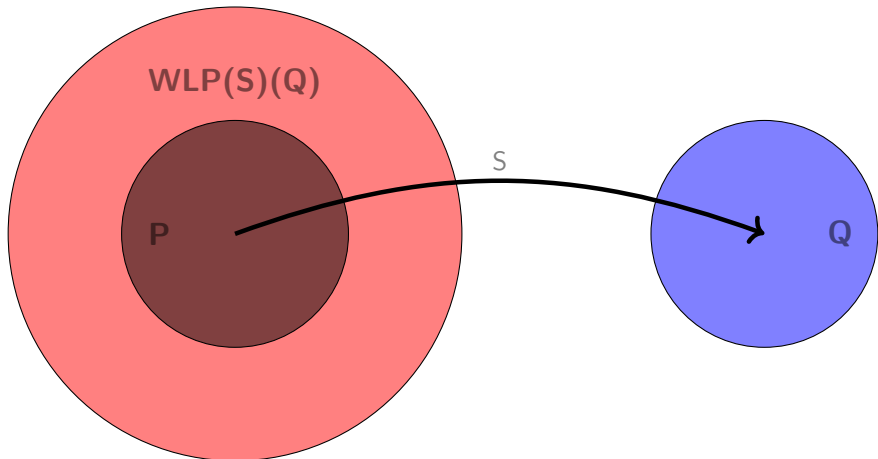
② Annotations

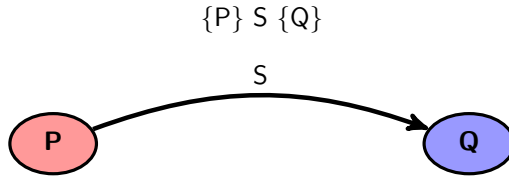
③ Contracts

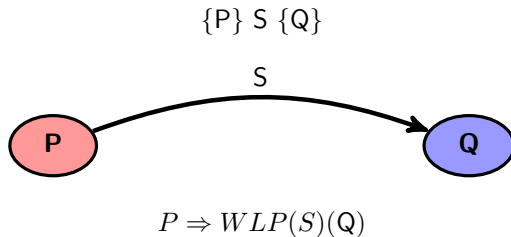
Logic Specification

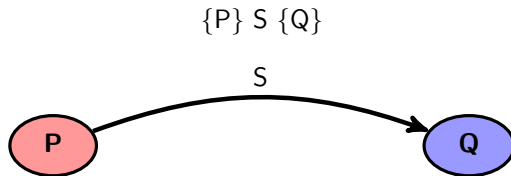
Gestion et utilisation des étiquettes pré-définies

Validation des annotations (type HOARE)









$$P \Rightarrow WLP(S)(Q)$$

Computing $WLP(S)(Q)$?

Writing a simple contract

variables x

requires $x \geq 0 \wedge x \leq 10$;

ensures $\begin{cases} x \% 2 = 0 \Rightarrow 2 \cdot \text{result} = x +; \\ x \% 2 \neq 0 \Rightarrow 2 \cdot \text{result} = x - 1; \end{cases}$

begin

int y ;

$y = x / 2$;

return(y);

end

► result is the value returned by the command *return*(y).

► *return*(y) is equivalent to $\text{result} := y$.

(Writing a simple contract.)

Listing 1 – project-divers/annotation.c

```
/*@ requires x <= 0 && x >= 10;
   @ assigns \nothing;
   @ ensures x % 2 == 0 ==> 2*\result == x;
   @ ensures x % 2 != 0 ==> 2*\result == x-1;
   @*/
int annotation(int x)
{
    int y;
    y = x / 2;
    return(y);
}
```

(Writing a simple contract.)

Listing 2 – project-divers/annotationwp.c

```
/*@ requires 0 <= x && x <= 10;
   @ assigns \nothing;
   @ ensures x % 2 == 0 ==> 2*\result == x;
   @ ensures x % 2 != 0 ==> 2*\result == x-1;
   @*/
int annotation(int x)
{
  /*@ assert x % 2 == 0 ==> 2* (x / 2) == x; */
  /*@ assert x % 2 != 0 ==> 2* (x / 2) == x-1; */
  int y;
  /*@ assert x % 2 == 0 ==> 2* (x / 2) == x; */
  /*@ assert x % 2 != 0 ==> 2* (x / 2) == x-1; */
  y = x / 2;
  /*@ assert x % 2 == 0 ==> 2*y == x; */
  /*@ assert x % 2 != 0 ==> 2*y == x-1; */
  return(y);
  /*@ assert x % 2 == 0 ==> 2*y == x; */
  /*@ assert x % 2 != 0 ==> 2*y == x-1; */
}
```

Property to check

$$x \geq 0 \wedge x \leq 10 \Rightarrow \begin{cases} x \% 2 \neq 0 \Rightarrow 2 \cdot (x/2) = x-1 \\ x \% 2 = 0 \Rightarrow 2 \cdot (x/2) = x \end{cases}$$

(Checking the precondition.)

Listing 3 – project-divers/annotation0.c

```
g/*@ requires x >= 0 && x < 0;  
  @ assigns \nothing;  
  @ ensures \result == 0;  
  @*/  
int annotation(int x)  
{  
    int y;  
    y = y / (x-x);  
    return(y);  
}
```

(Checking the precondition.)

Listing 4 – project-divers/annotation0wp.c

```
/*@ requires x >= 0 && x < 0;  
  @ assigns \nothing;  
  @ ensures \result == 0;  
  @*/  
int annotation(int x)  
{  
  /*@ assert y / (x-x) == 0; */  
  int y;  
  /*@ assert y / (x-x) == 0; */  
  y = y / (x-x);  
  /*@ assert y == 0; */  
  return(y);  
  /*@ assert y == 0; */  
}
```

Property to check

$$x \geq 0 \wedge x < 0 \Rightarrow y / (x - x) = 0$$

```
//@ assert  $P(v0, v)$  :  
 $S1; S2$   
//@ assert  $Q(v0, v)$  :
```

- ▶ Applying the property :
 $wp(S1; S2)(A) =$
 $wp(S1)(wp(S2)(A))$

```
//@ assert  $P(v0, v)$  :  
 $S1$ ;  
//@ assert  $wp(S2)(Q(v0, v))$  :  
 $S2$ ;  
//@ assert  $Q(v0, v)$  :
```

```
//@ assert  $P(v0, v)$  :  
//@ assert  $xp(S1)(wp(S2)(Q(v0, v)))$  :  
 $S1$ ;  
//@ assert  $wp(S2)(Q(v0, v))$  :  
 $S2$ ;  
//@ assert  $Q(v0, v)$  :
```

```
//@ assert  $P(v0, v)$  :  
IF  $B$  THEN  
   $S1$   
ELSE  
   $S2$   
FI  
//@ assert  $Q(v0, v)$  :
```

- Applying the property :
 $wp(if(B, S1, S2))(A) =$
 $b \wedge wp(S1)(A) \vee \neg b \wedge$
 $wp(S2)(A).$

```
//@ assert  $P(v0, v)$  :  
IF  $B$  THEN  
   $S1$   
ELSE  
   $S2$   
FI  
//@ assert  $Q(v0, v)$  :
```

```
//@ assert  $P(v0, v)$  :  
IF  $B$  THEN  
   $S1$   
  //@ assert  $Q(v0, v)$  :  
ELSE  
   $S2$   
  //@ assert  $Q(v0, v)$  :  
FI  
//@ assert  $Q(v0, v)$  :
```

Transformations of annotated programs (2)

```
//@ assert  $P(v0, v)$  :  
IF  $B$  THEN  
   $S1$   
//@ assert  $Q(v0, v)$  :  
ELSE  
   $S2$   
//@ assert  $Q(v0, v)$  :  
FI  
//@ assert  $Q(v0, v)$  :
```

Transformations of annotated programs (2)

```
//@ assert  $P(v0, v)$  :  
IF  $B$  THEN  
   $S1$   
//@ assert  $Q(v0, v)$  :  
ELSE  
   $S2$   
//@ assert  $Q(v0, v)$  :  
FI  
//@ assert  $Q(v0, v)$  :
```

```
//@ assert  $P(v0, v)$  :  
IF  $B$  THEN  
//@ assert  $B \wedge wp(S2)(Q(v0, v))$  :  
   $S1$   
//@ assert  $Q(v0, v)$  :  
ELSE  
//@ assert  $\neg B \wedge wp(S2)(Q(v0, v))$  :  
   $S2$   
//@ assert  $Q(v0, v)$  :
```


Transformations of annotated programs (2)

```
//@ assert  $P(v0, v)$  :  
IF  $B$  THEN  
   $S1$   
  //@ assert  $Q(v0, v)$  :  
ELSE  
   $S2$   
  //@ assert  $Q(v0, v)$  :  
FI  
//@ assert  $Q(v0, v)$  :
```

```
//@ assert  $P(v0, v)$  :  
IF  $B$  THEN  
  //@ assert  $B \wedge wp(S2)(Q(v0, v))$  :  
   $S1$   
  //@ assert  $Q(v0, v)$  :  
ELSE  
  //@ assert  $\neg B \wedge wp(S2)(Q(v0, v))$  :  
   $S2$   
  //@ assert  $Q(v0, v)$  :
```

```
//@ assert  $P(v0, v)$  :  
IF  $B$  THEN  
  //@ assert  $b \wedge wp(S1)(Q(v0, v))$  :  
   $S1$   
  //@ assert  $Q(v0, v)$  :  
ELSE  
  //@ assert  $\neg b \wedge wp(S2)(Q(v0, v))$  :  
   $S2$   
  //@ assert  $Q(v0, v)$  :  
FI  
//@ assert  $Q(v0, v)$  :
```

Transformations of annotated programs (2)

```
//@ assert  $P(v0, v)$  :  
IF  $B$  THEN  
   $S1$   
  //@ assert  $Q(v0, v)$  :  
ELSE  
   $S2$   
  //@ assert  $Q(v0, v)$  :  
FI  
//@ assert  $Q(v0, v)$  :
```

```
//@ assert  $P(v0, v)$  :  
IF  $B$  THEN  
  //@ assert  $B \wedge wp(S2)(Q(v0, v))$  :  
   $S1$   
  //@ assert  $Q(v0, v)$  :  
ELSE  
  //@ assert  $\neg B \wedge wp(S2)(Q(v0, v))$  :  
   $S2$   
  //@ assert  $Q(v0, v)$  :
```

```
//@ assert  $P(v0, v)$  :  
IF  $B$  THEN  
  //@ assert  $b \wedge wp(S1)(Q(v0, v))$  :  
   $S1$   
  //@ assert  $Q(v0, v)$  :  
ELSE  
  //@ assert  $\neg b \wedge wp(S2)(Q(v0, v))$  :  
   $S2$   
  //@ assert  $Q(v0, v)$  :  
FI  
//@ assert  $Q(v0, v)$  :
```

- ▶ $b \wedge P(v0, v) \Rightarrow b \wedge wp(S1)(Q(v0, v))$
- ▶ $\neg b \wedge P(v0, v) \Rightarrow \neg b \wedge wp(S2)(Q(v0, v))$

```
//@ assert  $P(v0, v)$  :  
//@ loop invariant  $I(v0, v)$  :  
WHILE  $B$  THEN  
   $S$   
OD  
//@ assert  $Q(v0, v)$  :
```

- ▶ Applying the iteration rule of Hoare Logic :

```
//@ assert  $P(v0, v)$  :  
//@ loop invariant  $I(v0, v)$  :  
WHILE  $B$  THEN  
   $S$   
OD  
//@ assert  $Q(v0, v)$  :
```

```
//@ assert  $P(v0, v)$  :  
//@ loop invariant  $I(v0, v)$  :  
//@ assert  $I(v0, v)$  :  
WHILE  $B$  THEN  
  //@ assert  $b \wedge I(v0, v)$  :  
   $S$   
  //@ assert  $I(v0, v)$  :  
OD  
//@ assert  $Q(v0, v)$  :
```

- Applying the iteration rule of Hoare Logic :

```
//@ assert  $P(v0, v)$  :  
//@ loop invariant  $I(v0, v)$  :  
WHILE  $B$  THEN  
   $S$   
OD  
//@ assert  $Q(v0, v)$  :
```

- ▶ Applying the iteration rule of Hoare Logic :

```
//@ assert  $P(v0, v)$  :  
//@ loop invariant  $I(v0, v)$  :  
//@ assert  $I(v0, v)$  :  
WHILE  $B$  THEN  
  //@ assert  $b \wedge I(v0, v)$  :  
   $S$   
  //@ assert  $I(v0, v)$  :  
OD  
//@ assert  $Q(v0, v)$  :
```

- ▶ $b \wedge I(v0, v) \Rightarrow wp(S)(I(v0, v))$
- ▶ $P(v0, v) \Rightarrow I(v0, v)$
- ▶ $\neg b \wedge I(v0, v) \Rightarrow Q(v0, v)$

- (The ANSI/ISO C Specification Language (ACSL)) (25 février 2025) (Dominique Méry)

- ▶ Assertions at a control point of the program

```
/*@  assert pred; */
```

```
//@  assert pred;
```

- ▶ Assertions at a control point of the program components.

```
/*@  for id1,id2, ..., idn: assert pred; */
```

(Incrementing a number)

Listing 5 – project-divers/compwp0.c

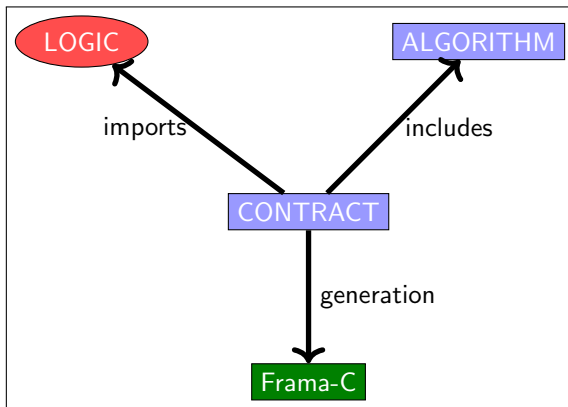
```
#define x0 5
/*@ assigns \nothing; */
int exemple() {
    int x=x0;
    //@ assert x == x0;
    x = x + 1;
    //@ assert x == x0+1;
    return x;
}
```

(Incrementing a number)

Listing 6 – project-divers/compwp0wp.c

```
#define x0 5
/*@ assigns \nothing; */
int exemple() {
    //@ assert x0 == x0;
    //@ assert x0+1 == x0+1;
    int x=x0;
    //@ assert x == x0;
    //@ assert x+1 == x0+1;
    x = x + 1;
    //@ assert x == x0+1;
    return x;
}
```


- ▶ requires
- ▶ assigns
- ▶ ensures
- ▶ decreases
- ▶ predicate
- ▶ logic
- ▶ lemma



▶ predicate

(Definition of function odd/even)

Listing 7 – project-divers/predicate4.c

```
//@ predicate pair(integer x) = (x/2)*2==x;
//@ predicate impair(integer x) = (x/2)*2!=x;
//@ lemma ex: \forall integer a,b; a < b ==> 2*a < 2*b;

/*@ inductive is_gcd(integer a, integer b, integer c) {
  case zero: \forall integer n; is_gcd(n,0,n);
  case un: \forall integer u,v,w; u >= v ==> is_gcd(u-v,v,w);
  case deux: \forall integer u,v,w; u < v ==> is_gcd(u,v-u,w);
}
*/
```

(Predicate)

Listing 8 – project-divers/predicate1.c

```
/*@ predicate is_positive(integer x) = x > 0; */  
/*@ logic integer get_sign(real x) = @ x > 0.0 ? 1 : (x < 0.0 ? -1 : 0);  
*/  
/*@ logic integer max(int x, int y) = x > y ? x : y;  
*/
```

(Lemma)

Listing 9 – project-divers/lemma1.c

```
/*@ lemma div_mul_identity:  
@ \forall real x, real y; y != 0.0 => y*(x/y) == x; @*/  
  
/*@ lemma div_qr:  
@ \forall int a, int b; a >= 0 && b > 0 =>  
\exists int q, int r; a == b*q + r && 0 <= r && r < b; @*/
```

(Definition of fibonacci function)

Listing 10 – project-divers/predicate2.c

```
/*@ axiomatic mathfibonacci{  
  @ logic integer mathfib(integer n);  
  @ axiom mathfib0: mathfib(0) == 1;  
  @ axiom mathfib1: mathfib(1) == 1;  
  @ axiom mathfibrec: \forall integer n; n > 1  
  ==> mathfib(n) == mathfib(n-1)+mathfib(n-2);  
  @ } */
```

(Definition of gcd)

Listing 11 – project-divers/predicate3.c

```
/*@ inductive is_gcd(integer a, integer b, integer d) {  
  @ case gcd_zero:  
  @ \forall integer n; is_gcd(n,0,n);  
  @ case gcd_succ:  
  @ \forall integer a,b,d; is_gcd(b, a % b, d) ==> is_gcd(a,b,d); @}  
  @ */
```

- ▶ $\backslash old(x)$ désigne la valeur de la variable x au moment de l'appel de la fonction.
- ▶ Cette expression est utilisable uniquement dans la postcondition *ensures*

(Valeur initiale x0)

Listing 12 – project-divers/old1.c

```
/*@ requires \valid(a) && \valid(b);  
  @ assigns *a,*b;  
  @ ensures *b == \old(*b)+\old(*a)+2;  
  @ ensures *a == \old(*a)+2;  
  @ ensures \result == 0;  
*/  
int old(int *a, int *b) {  
    int x,y;  
    x = *a;  
    y = *b;  
    x = x + 1;  
    x = x + 1;  
    y = y + x;  
    *a = x;  
    *b = y;  
    return 0 ;  
}
```

- ▶ $\backslash at(e, id)$ désigne la valeur de e au point de contrôle id .
- ▶ id doit être rencontré avant $\backslash at(e, id)$
- ▶ id est une expression parmi Pre, Here, Old, Post, LoopEntry, LoopCurrent, Init
- ▶ $\backslash old(e)$ est équivalent à $\backslash at(e, Old)$

(label Pre)

Listing 13 – project-divers/at1.c

```
/*@
  requires \valid(a) && \valid(b);
  assigns *a,*b;
  ensures  *a == \old(*a)+2;
  ensures  *b == \old(*b)+\old(*a)+2;
*/
int at1(int *a, int *b) {
  //@ assert *a == \at(*a, Pre);
  *a = *a + 1;
  //@ assert *a == \at(*a, Pre)+1;
  *a = *a + 1;
  //@ assert *a == \at(*a, Pre)+2;
  *b = *b + *a;
  //@ assert *a == \at(*a, Pre)+2 && *b == \at(*b, Pre)+\at(*a, Pre)+2;
  return 0;
}
```


(autre label)

Listing 14 – project-divers/at2.c

```
void f (int n) {  
  for (int i = 0; i < n; i++) {  
    /*@ assert \at(i, LoopEntry) == 0; */  
    int j=0;  
    while (j++ < i) {  
      /*@ assert \at(j, LoopEntry) == 0; */  
      /*@ assert \at(j, LoopCurrent) + 1 == j; */  
    }  
  }  
}
```

- ▶ requires
- ▶ assigns
- ▶ ensures
- ▶ decreases
- ▶ predicate
- ▶ logic
- ▶ lemma

(Contrat invalide)

Listing 15 – project-divers/anno0.c

```
int main(void){
    signed long int x,y,z;
    x = 1;
    /*@ assert x == 1; */
    y = 2;
    /*@ assert x == 1 && y == 2; */
    z = x * y;
    /*@ assert x == 1 && y == 1 && z==2; */
    return 0;
}
```

(Contrat valide)

Listing 16 – project-divers/anno00.c

```
int main(void){
    signed long int x,y,z; //    int x,y,z;
    x = 1;
    /*@ assert x == 1; */
    y = 2;
    /*@ assert x == 1 && y == 2; */
    z = x * y;
    /*@ assert x == 1 && y == 2 && z == 2; */
    return 0;
}
```

```
...  
/*@ loop invariant I;  
   @ loop assigns L;  
*/  
...
```

(Invariant de boucle)

Listing 17 – project-divers/anno5.c

```
/*@ requires a >= 0 && b >= 0;  
   ensures 0 <= \result;  
   ensures \result < b;  
   ensures \exists integer k; a == k * b + \result;  
*/  
int rem(int a, int b) {  
    int r = a;  
    /*@  
       loop invariant  
       (\exists integer i; a == i * b + r) &&  
       r >= 0;  
       loop assigns r;  
    */  
    while (r >= b) { r = r - b; };  
    return r;  
}
```

(Invariant de boucle)

Listing 18 – project-divers/anno6.c

```
/*@ requires a >= 0 && b >= 0;  
    ensures 0 <= \result;  
    ensures \result < b;  
    ensures \exists integer k; a == k * b + \result;  
*/  
int rem(int a, int b) {  
    int r = a;  
    /*@  
        loop invariant  
        (\exists integer i; a == i * b + r) &&  
        r >= 0;  
        loop assigns r;  
    */  
    while (r >= b) { r = r - b; }  
    return r;  
}
```

Echec de la preuve

L'invariant est insuffisamment informatif pour être prouvé et il faut ajouter une information sur y.

```
frama-c -wp anno6.c
[kernel] Parsing anno6.c (with preprocessing)
[wp] Warning: Missing RTE guards
[wp] anno6.c:8: Warning: Missing assigns clause (assigns 'everything' i
[wp] 2 goals scheduled
[wp] [Alt-Ergo 2.3.3] Goal typed_f_loop_invariant_preserved : Timeout (
[wp] [Cache] found:1
[wp] Proved goals:      1 / 2
    Qed:                1 (0.57ms)
    Alt-Ergo 2.3.3:      0 (interrupted: 1) (cached: 1)
[wp:pedantic-assigns] anno6.c:1: Warning:
    No 'assigns' specification for function 'f'.
    Callers assumptions might be imprecise.
```


Analyse avec succès

L'invariant est plus précis et donne des conditions liant x et y .

(Invariant de boucle)

Listing 19 – project-divers/anno7.c

```
int f() {  
  int x = 0;  
  int y = 10;  
  /*@  
    loop invariant  
    0 <= x < 11 && x+y == 10;  
  */  
  while (y > 0) {  
    x++;  
    y--;  
  }  
  return 0;  
}
```

```
frama-c -wp anno7.c
[kernel] Parsing anno7.c (with preprocessing)
[wp] Warning: Missing RTE guards
[wp] anno7.c:8: Warning: Missing assigns clause (assigns 'everything' i
[wp] 2 goals scheduled
[wp] [Cache] found:1
[wp] Proved goals:      2 / 2
    Qed:                  1 (0.32ms-3ms)
    Alt-Ergo 2.3.3:      1 (6ms) (8) (cached: 1)
[wp:pedantic-assigns] anno7.c:1: Warning:
    No 'assigns' specification for function 'f'.
    Callers assumptions might be imprecise.
```

- ▶ Un variant est une quantité qui décroît au cours de la boucle.
- ▶ Deux possibilités d'analyse sont possibles :
 - Terminaison d'une boucle (`variant`)
 - Terminaison de l'appel d'une fonction récursive (`decreawse`)

(Variant)

Listing 20 – project-divers/variant2.c

```
//@ loop variant e;
```

```
//@ decreases e;
```

- ▶ La terminaison est assurée en montrant que chaque boucle termine.
- ▶ Une boucle est caractérisée par une expression `expvariant(x)` appelée `variant` qui doit décroître à chaque exécution du corps de la boucle `S` où x_1 et x_2 sont les valeurs de X respectivement au début de la boucle `S` et à la fin de `S` :

$$\forall x_1, x_2. b(x_1) \wedge x_1 \xrightarrow{S} x_2 \Rightarrow \text{expvariant}(x_1) > \text{expvariant}(x_2)$$

(Variant)

Listing 21 – project-divers/variant1.c

```
/*@ requires n > 0;
    ensures \result == 0;
*/
int code(int n) {
    int x = n;
    /*@ loop invariant x >= 0 && x <= n;
        loop assigns x;
        loop variant x;
    */
    while (x != 0) {
        x = x - 1;
    };
    return x;
}
```

(Variant)

Listing 22 – project-divers/variant3.c

```
int f() {  
  int x = 0;  
  int y = 10;  
  /*@  
    loop invariant  
    0 <= x < 11 && x+y == 10;  
    loop variant y;  
  */  
  while (y > 0) {  
    x++;  
    y—;  
  }  
  return 0;  
}
```

(Variant)

Listing 23 – project-divers/variant4.c

```
g/*@ requires n <= 12;  
  @ decreases n;  
  @*/  
int fact(int n){  
  if (n <= 1) return 1;  
  return n*fact(n-1);  
}
```

- ▶ Pas de gestion de la mémoire comme les pointeurs
- ▶ Affectation à chaque variable une variable logique
- ▶ $x++$ avec x de type `int` et la C-variable est affectée à deux L-variables $x2 = x1 + 1$.

(Variant)

Listing 24 – project-divers/wp2.c

```
/*@CONSOLE
#include <LIMITS.h>
int q1() {
    int x=10,y=30,z=20;
    //@ assert x== 10 && y == z+x && z==2*x;
    y= z+x;
    //@ assert x== 10 && y == x+2*10;
    x = x+1;
    //@ assert x-1== 10 && y == x-1+2*10;
    return (0);
}
```

(Variant)

Listing 25 – project-divers/wp3.c

```
int q1() {
    int c = 2 ;
    /*@ assert c == 2; */
    int x;
    /*@ assert c == 2; */
    x = 3 * c ;
    /*@ assert x == 6; */
    return (0);
}
```


(Variant)

Listing 26 – project-divers/wp4.c

```
int main()
{
    int a = 42; int b = 37;
    int c = a+b; // i:1
    //@assert b == 37 ;
    a -= c; // i:2
    b += a; // i:3
    //@assert b == 0 && c == 79;
    return (0);
}
```

(Variant)

Listing 27 – project-divers/wp5.c

```
int main()
{
    int z; // instruction 8
    int a = 4; // instruction 7
    //@assert a == 4 ;
    int b = 3; // instruction 6
    //@assert b == 3 && a == 4;
    int c = a+b; // instruction 4
    /*@ assert b == 3 && c == 7 && a == 4 ; */
    a += c; // instruction 3
    b += a; // instruction 2
    //@ assert a == 11 && b == 14 && c == 7 ;
    //@ assert a + b == 25 ;
    z = a*b; // instruction 1
    //@assert a == 11 && b == 14 && c == 7 && z == 154;
    return (0);
}
```

(Variant)

Listing 28 – project-divers/wp6.c

```
int main()
{
    int a = 4;
    int b = 3;
    int c = a+b; // i:1
    a += c; // i:2
    b += a; // i:3
    //@assert a == 11 && b == 14 && c == 7 ;
    return (0);
}
```

Listing 29 – project-divers/wp7.c

```

/*@ ensures x == a;
   ensures y == b;
   */
void swap1(int a, int b) {
    int x = a;
    int y = b;
    //@ assert x == a && y == b;
    int tmp;
    tmp = x;
    x = y;
    y = tmp;
    //@ assert x == a && y == a;
}

void swap2(int a, int b) {
    int x = a;
    int y = b;
    //@ assert x == a && y == b;
    x = x + y;
    y = x - y;
    x = x - y;
    //@ assert x == b && y == a;
}

/*@ requires \valid(a);
   requires \valid(b);
   ensures *a == \old(*b);
   ensures *b == \old(*a);
   */
void swap3(int *a, int *b) {
    int tmp;
    tmp = *a;
    *a = *b;
    *b = tmp;
}

```