The VerCors Tool Set

Verification of Parallel and Concurrent Software

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Outline

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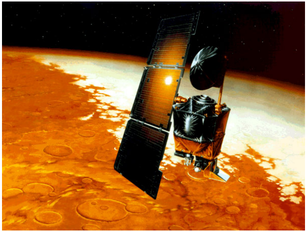
Concurrent programming is *error-prone*



Mars climate orbiter

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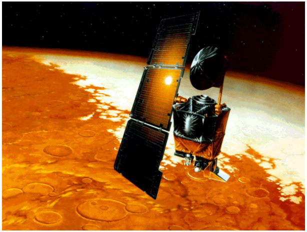
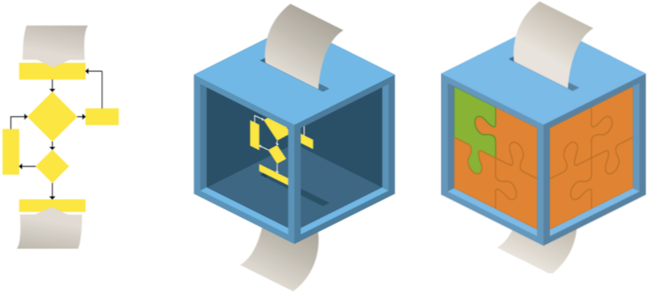


Mars climate orbiter

THERAC-25

Automated program verification



The VerCors Tool Set

Verifying Java programs: *example*

```
class Counter {
    int count;

    public void incr(int y) {
        this.count := this.count + y;
    }
}
```

Verifying Java programs: *example*

```
class Counter {
    int count;

    requires Perm(this.count, write);
    public void incr(int y) {
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}
```

Writing permission for *this.count* is required

Verifying Java programs: *example*

```
class Counter {
    int count;

    requires Perm(this.count, write);
    ensures Perm(this.count, write);
    public void incr(int y) {
        this.count := this.count + y;
    }
}
```

Writing permission for *this.count* is ensured

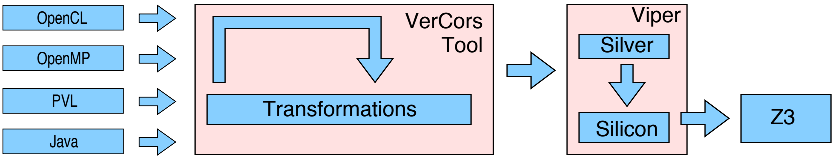
Verifying Java programs: *example*

```
class Counter {
    int count;

    requires Perm(this.count, write);
    ensures Perm(this.count, write);
    ensures this.count = old(this.count) + y;
    public void incr(int y) {
        this.count := this.count + y;
    }
}
```

this.count is conrrectly incremented

The VerCors Tool Set - *Overview*



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Deterministic parallel programming

Concurrency as optimisation

Sequential program annotated by *compiler directives*	*compiled into*	Multi-threaded programs or GPU kernels

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Compiler directives

Give hints to the compiler to know *where* and *how* to parallelise sequential code.

Deterministic parallel programming

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Give hints to the compiler to know *where* and *how* to parallelise sequential code. Some implementations are:

- OpenACC
- OpenMP
- PENCIL, etc.

Deterministic parallel programming

Concurrency as optimisation

Sequential program annotated by *compiler directives*	*compiled into*	Multi-threaded programs or GPU kernels

Compiler directives

Give hints to the compiler to know *where* and *how* to parallelise sequential code. Some implementations are:

- OpenACC
- OpenMP *(for C)*
- PENCIL, etc.

Verifying OpenMP programs - *NFM 2017*

for (**int** $i = 0$; $i < N$; i++) {
  $C[i] = A[i]$;
}

for (**int** $i = 0$; $i < N$; i++) {
  $D[i] = C[i+1] + B[i]$;
}

Verifying OpenMP programs - *NFM 2017*

```
for (int i = 0; i < N; i++) {
    C[i] = A[i];
}

for (int i = 0; i < N; i++) {
    D[i] = C[i + 1] + B[i];
}
```

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```

Verifying OpenMP programs - *NFM 2017*

```
#pragma omp parallel {
    #pragma omp for
    for (int i = 0; i < N; i++) {
        C[i] = A[i];
    }

    #pragma omp for
    for (int i = 0; i < N; i++) {
        D[i] = C[i + 1] + B[i];
    }
}
```

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for (int i = 0; i < N; i++) {
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        D[i] = C[i + 1] + B[i];
    }
}
```

```
#pragma omp parallel {
    #pragma omp for
        schedule(static) nowait
    for (int i = 0; i < N; i++) {
        C[i] = A[i];
    }

    #pragma omp for
        schedule(static) nowait
    for (int i = 0; i < N; i++) {
        D[i] = C[i] + B[i];
    }
}
```

Verifying OpenMP programs - *NFM 2017*

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Verifying loop parallelisations - *FASE 2015*

Specifying a contract for every loop iteration, capturing its resources

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$$\frac{}{\vdash\ \textbf{for}\,(\textbf{int}\ i = 0; i < N; i\,{+}{+})\{\ S_i\ \}}$$

Verifying loop parallelisations - *FASE 2015*

Specifying a contract for every loop iteration, capturing its resources

$$\frac{\vdash \{P_0\}\ S_0\ \{Q_0\} \qquad \cdots \qquad \vdash \{P_{N-1}\}\ S_{N-1}\ \{Q_{N-1}\}}{\vdash\ \textbf{for}\,(\textbf{int}\ i = 0; i < N; i{+}{+})\{\ S_i\ \}}$$

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Deterministic parallelism: *iteration contracts*

```
void clear(int A[], int len) {
    for (int i = 0; i < len; i++) {
        A[i] = 0;
    }
}
```

Deterministic parallelism: *iteration contracts*

$\textbf{requires}\ A \neq \texttt{null} \wedge \textbf{length}(A) = len;$

```
void clear(int A[], int len) {
    for (int i = 0; i < len; i++) {
        A[i] = 0;
    }
}
```

The input array A may not be `null`

Deterministic parallelism: *iteration contracts*

```
requires A ≠ null ∧ length(A) = len;
requires (forall* int k; 0 ≤ k < len; Perm(A[k], write));
void clear(int A[], int len) {
    for (int i = 0; i < len; i++) {
        A[i] = 0;
    }
}
```

Permission is required to write to every element of A

Deterministic parallelism: *iteration contracts*

$$
\begin{array}{l}
\textbf{requires } A \neq \texttt{null} \wedge \textbf{length}(A) = len; \\
\textbf{requires } (\textbf{forall}{*}\ \textbf{int } k;\ 0 \leq k < len;\ \text{Perm}(A[k], \text{write})); \\
\textbf{ensures } (\textbf{forall}{*}\ \textbf{int } k;\ 0 \leq k < len;\ \text{Perm}(A[k], \text{write})); \\
\textbf{ensures } (\textbf{forall int } k;\ 0 \leq k < len;\ A[k] = 0); \\
\textbf{void } \texttt{clear}(\textbf{int } A[\,], \textbf{int } len)\ \{ \\
\quad \textbf{for } (\textbf{int } i = 0;\ i < len;\ i{+}{+})\ \{ \\
\quad\quad A[i] = 0; \\
\quad \} \\
\}
\end{array}
$$

A "cleared" array is ensured

Deterministic parallelism: *iteration contracts*

$\textbf{requires}\ A \neq \texttt{null} \wedge \textbf{length}(A) = \mathit{len};$
$\textbf{requires}\ (\textbf{forall}{*}\ \textbf{int}\ k;\ 0 \leq k < \mathit{len};\ \text{Perm}(A[k], \text{write}));$
$\textbf{ensures}\ (\textbf{forall}{*}\ \textbf{int}\ k;\ 0 \leq k < \mathit{len};\ \text{Perm}(A[k], \text{write}));$
$\textbf{ensures}\ (\textbf{forall}\ \textbf{int}\ k;\ 0 \leq k < \mathit{len};\ A[k] = 0);$
$\textbf{void}\ \texttt{clear}(\textbf{int}\ A[\,],\ \textbf{int}\ \mathit{len})\ \{$
$\quad \textbf{for}\ (\textbf{int}\ i = 0;\ i < \mathit{len};\ i{+}{+})$
$\qquad \textbf{requires}\ \text{Perm}(A[i], \text{write})\quad \{$
$\qquad A[i] = 0;$
$\quad \}$
$\}$

Iteration i requires permission to write to $A[i]$

Deterministic parallelism: *iteration contracts*

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Iteration i ensures permission to write to $A[i]$

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\quad \}\\
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$$

Iteration i “cleared” $A[i]$

Deterministic parallelism: *verified examples*

1. **Histogram**: calculating the *histogram* of a matrix.
2. **Loop dependencies**: several examples with forward/backward *loop dependencies*.
3. **Reductions**: several examples with *reduction patterns* (e.g. summations).
4. **Loop vectorisation**: several examples with *loop vectorisations*.

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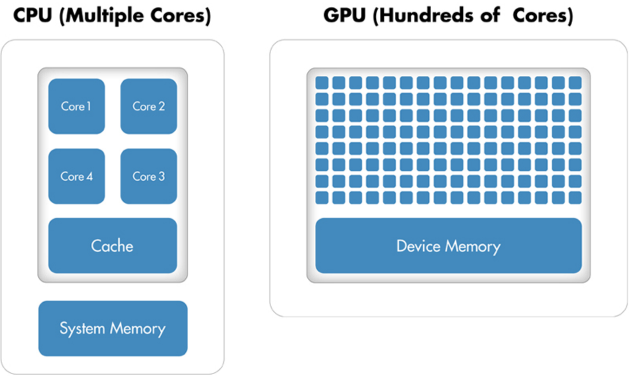
See our *FASE2015* and *NFM2017* papers for more details

Outline

GPU computing model



source https://www.mathworks.com

Single-Instruction-Multiple-Data *(SIMD)*

```
__kernel void add1(__global int A[]) {
    // get thread identifier
    int tid = get_global_id(0);

    // increase entry by one
    A[tid] = A[tid] + 1;
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}
```

Single-Instruction-Multiple-Data *(SIMD)*

$tid = 0$	$tid = 1$	$tid = 2$	$tid = 3$	$tid = 4$
$tid = 5$	$tid = 6$	$tid = 7$	$tid = 8$	$tid = 9$
$tid = 10$	$tid = 11$	$tid = 12$	$tid = 13$	$tid = 14$
$tid = 15$	$tid = 16$	$tid = 17$	$tid = 18$	$tid = 19$

Single-Instruction-Multiple-Data *(SIMD)*

$A[0] = A[0] + 1$	$A[1] = A[1] + 1$	$A[2] = A[2] + 1$	$A[3] = A[3] + 1$	$A[4] = A[4] + 1$
$A[5] = A[5] + 1$	$A[6] = A[6] + 1$	$A[7] = A[7] + 1$	$A[8] = A[8] + 1$	$A[9] = A[9] + 1$
$A[10] = A[10] + 1$	$A[11] = A[11] + 1$	$A[12] = A[12] + 1$	$A[13] = A[13] + 1$	$A[14] = A[14] + 1$
$A[15] = A[15] + 1$	$A[16] = A[16] + 1$	$A[17] = A[17] + 1$	$A[18] = A[18] + 1$	$A[19] = A[19] + 1$

Thread specifications

```
__kernel void add1(__global int A[]) {
    // get thread identifier
    int tid = get_global_id(0);

    // increase entry by one
    A[tid] = A[tid] + 1;
}
```

Thread specifications

```
requires A ≠ null;
__kernel void add1(__global int A[]) {
    // get thread identifier
    int tid = get_global_id(0);

    // increase entry by one
    A[tid] = A[tid] + 1;
}
```

The input array may not be `null`

Thread specifications

```
requires A ≠ null;
requires Perm(A[get_global_id(0)], write);
__kernel void add1(__global int A[]) {
    // get thread identifier
    int tid = get_global_id(0);

    // increase entry by one
    A[tid] = A[tid] + 1;
}
```

Thread with ID i requires *write permission* for $A[i]$

Thread specifications

```
requires A ≠ null;
requires Perm(A[get_global_id(0)], write);
ensures Perm(A[get_global_id(0)], write);
__kernel void add1(__global int A[]) {
    // get thread identifier
    int tid = get_global_id(0);

    // increase entry by one
    A[tid] = A[tid] + 1;
}
```

Thread with ID *i* ensures *write permission* for *A*[*i*]

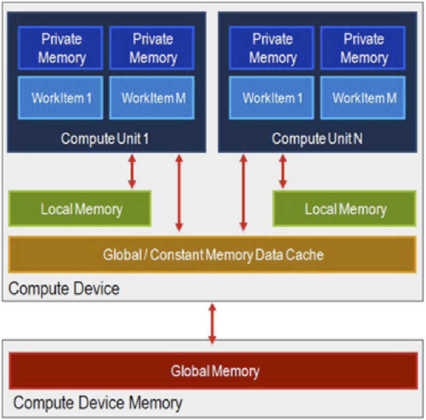
Thread specifications

requires $A \neq$ `null`;
requires Perm(A[`get_global_id(0)`], write);
ensures Perm(A[`get_global_id(0)`], write);
ensures A[`get_global_id(0)`] $=$ **old**(A[`get_global_id(0)`]) $+ 1$;
__**kernel** **void** `add1`(__**global** **int** A[ ]) {
    // get thread identifier
    int *tid* = `get_global_id(0)`;

    // increase entry by one
    $A[tid] = A[tid] + 1$;
}

Thread with ID i has incremented $A[i]$

GPU architecture: *threads & workgroups*



Barrier specifications

```
__kernel void addcomplex(__global int A[]) {
    // get thread identifier
    int tid = get_global_id(0);

    // perform the updates
    A[tid] = A[tid] + 1;
    if (tid > 0) {
        A[tid − 1] = 2 ∗ A[tid − 1];
    }
}
```

Barrier specifications

```
__kernel void addcomplex(__global int A[]) {
    // get thread identifier
    int tid = get_global_id(0);

    // perform the updates
    A[tid] = A[tid] + 1;

    barrier(global);

    if (tid > 0) {
        A[tid - 1] = 2 * A[tid - 1];
    }
}
```

A barrier is required here for correctness!

Barrier specifications

```
requires Perm(A[get_global_id(0)], write);
__kernel void addcomplex(__global int A[]) {
    // get thread identifier
    int tid = get_global_id(0);

    // perform the updates
    A[tid] = A[tid] + 1;

    barrier(global);

    if (tid > 0) {
        A[tid − 1] = 2 ∗ A[tid − 1];
    }
}
```

Thread with ID i can *write* to $A[i]$ and *read* from $B[i]$

Barrier specifications

```
requires Perm(A[get_global_id(0)], write);
__kernel void addcomplex(__global int A[]) {
    // get thread identifier
    int tid = get_global_id(0);

    // perform the updates
    A[tid] = A[tid] + 1;

    barrier(global) {
        requires Perm(A[tid], write);
        ensures tid > 0 ⇒ Perm(A[tid − 1], write);
    };

    if (tid > 0) {
        A[tid − 1] = 2 ∗ A[tid − 1];
    }
}
```

The barrier *consumes* all read permissions

Barrier specifications

```
requires Perm(A[get_global_id(0)], write);
__kernel void addcomplex(__global int A[]) {
  // get thread identifier
  int tid = get_global_id(0);

  // perform the updates
  A[tid] = A[tid] + 1;

  barrier(global) {
    requires Perm(A[tid], write);
    ensures tid > 0 ⇒ Perm(A[tid − 1], write);
  };

  if (tid > 0) {
    A[tid − 1] = 2 ∗ A[tid − 1];
  }
}
```

The barrier *redistributes* all consumed permissions

GPU kernels: *verified examples*

1. **Parallel prefix sum**: data-race freedom of a *paralell prefix sum* algorithm.
2. **Summations**: kernels with *atomic*, *barriers*, and *reductions*.
3. **Floats**: support for *floating point* arithmetics.

GPU kernels: *verified examples*

1. **Parallel prefix sum**: data-race freedom of a *paralell prefix sum* algorithm.
2. **Summations**: kernels with *atomic*, *barriers*, and *reductions*.
3. **Floats**: support for *floating point* arithmetics.

Outline

Static verification: *deductive verification*

```
requires P1 * P2;
ensures Q1 * Q2;
void main(args) {
    S1 || S2;
}
```

$$\dfrac{\dfrac{\dfrac{\cdots}{\vdash \{P_1\}\, S_1\, \{Q_1\}} \qquad \dfrac{\cdots}{\vdash \{P_2\}\, S_2\, \{Q_2\}}}{\vdash \{P_1 * P_2\}\, S_1 \parallel S_2\, \{Q_1 * Q_2\}}}{\vdash \{P_1 * P_2\}\, \mathtt{main}(args)\, \{Q_1 * Q_2\}}$$

Static verification: *deductive verification*

```
requires P1 * P2;
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void main(args) {
    S1 || S2;
}
```

$$\dfrac{\dfrac{\dfrac{\cdots}{\vdash \{P_1\}\, S_1\, \{Q_1\}} \qquad \dfrac{\cdots}{\vdash \{P_2\}\, S_2\, \{Q_2\}}}{\vdash \{P_1 * P_2\}\, S_1 \parallel S_2\, \{Q_1 * Q_2\}}}{\vdash \{P_1 * P_2\}\, \texttt{main}(args)\, \{Q_1 * Q_2\}}$$

Strong correctness guarantees

Static verification: *deductive verification*

requires $P_1 * P_2$;
ensures $Q_1 * Q_2$;
void `main`$(args)$ {
    $S_1 \parallel S_2$;
}

$$\dfrac{\dfrac{\dfrac{\cdots}{\vdash \{P_1\}\, S_1\, \{Q_1\}} \qquad \dfrac{\cdots}{\vdash \{P_2\}\, S_2\, \{Q_2\}}}{\vdash \{P_1 * P_2\}\, S_1 \parallel S_2\, \{Q_1 * Q_2\}}}{\vdash \{P_1 * P_2\}\, \texttt{main}(args)\, \{Q_1 * Q_2\}}$$

Hard to construct a proof

Static verification: *model checking*

```
void main(args) {
    S1 || S2;
}
```

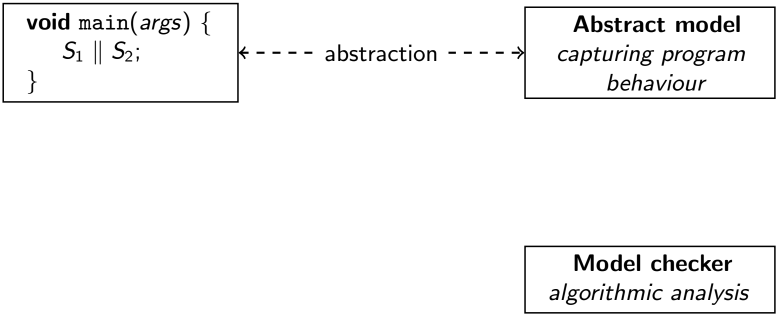
Static verification: *model checking*

```
void main(args) {
    S1 || S2;
}
```

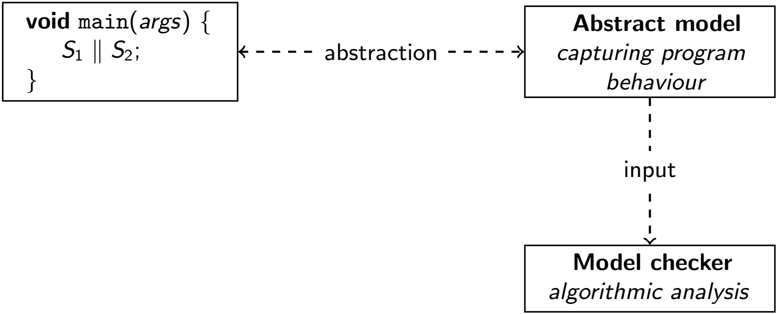
Abstract model
capturing program behaviour

Static verification: *model checking*

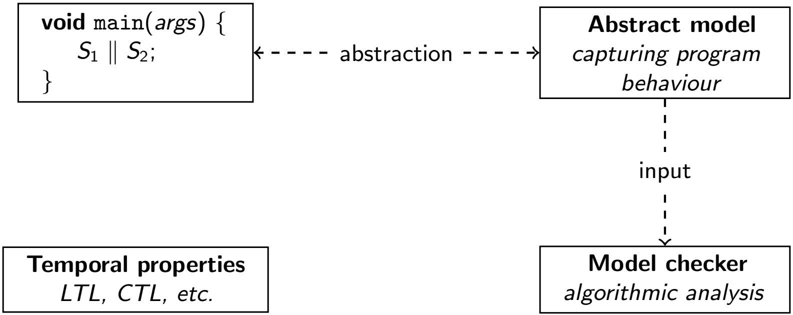
Static verification: *model checking*



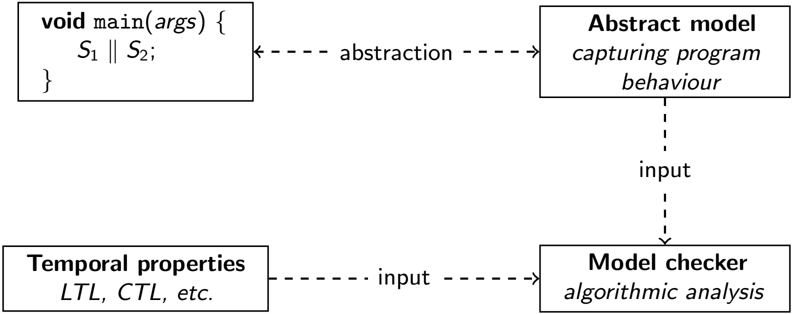
Static verification: *model checking*



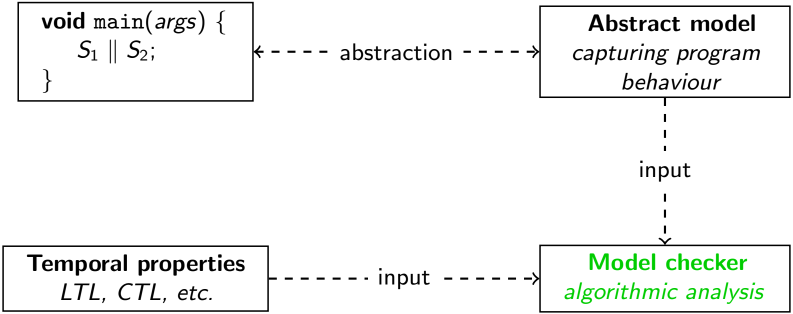
Static verification: *model checking*



Static verification: *model checking*

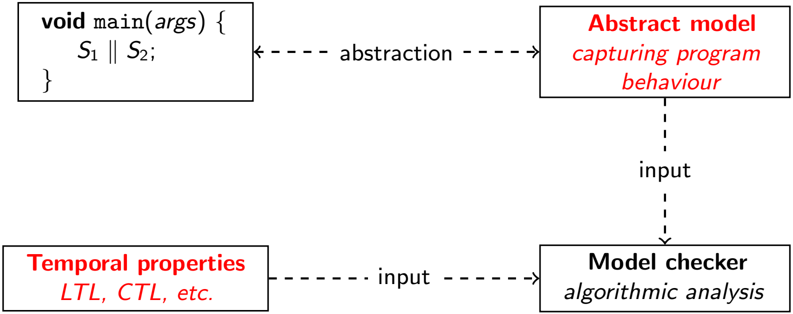


Static verification: *model checking*



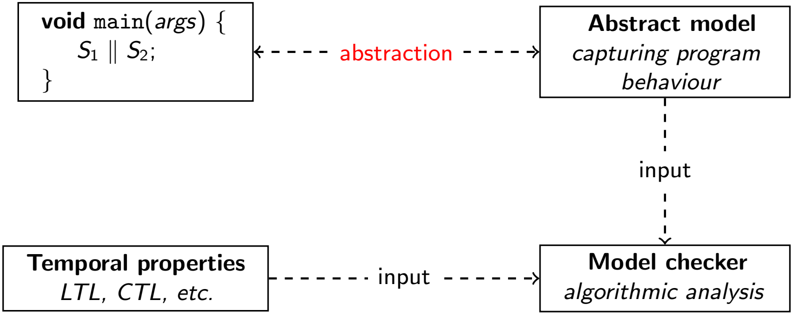
Good automation

Static verification: *model checking*



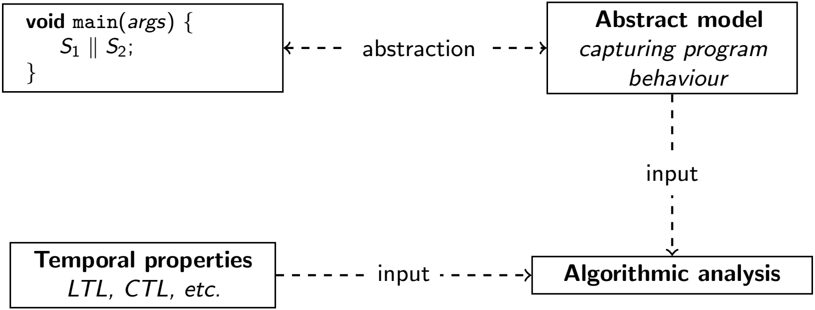
State-space explosion problems

Static verification: *model checking*

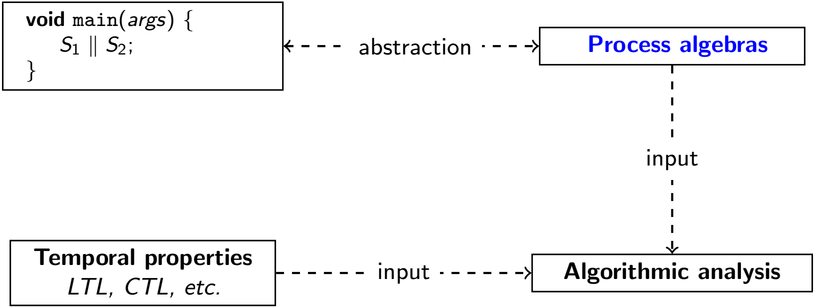


Is the program abstraction correct?

Our approach: *deductive + algorithmic verification*

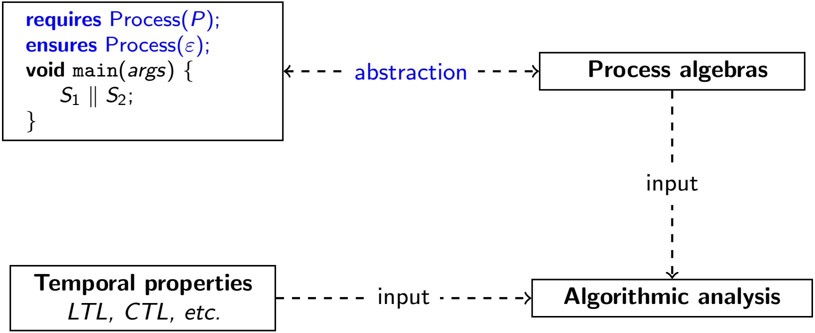


Our approach: *deductive + algorithmic verification*



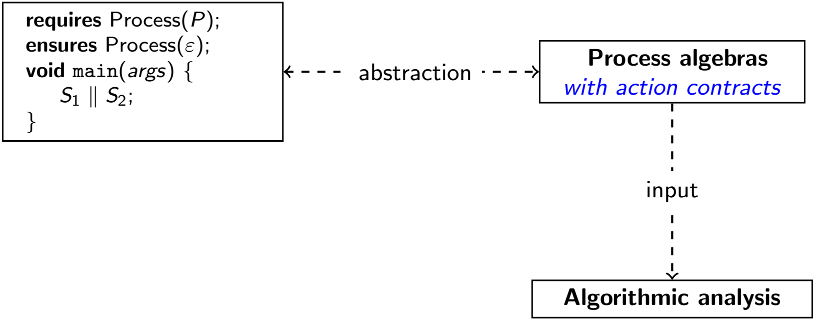
Abstract models are *process algebra terms*

Our approach: *deductive + algorithmic verification*



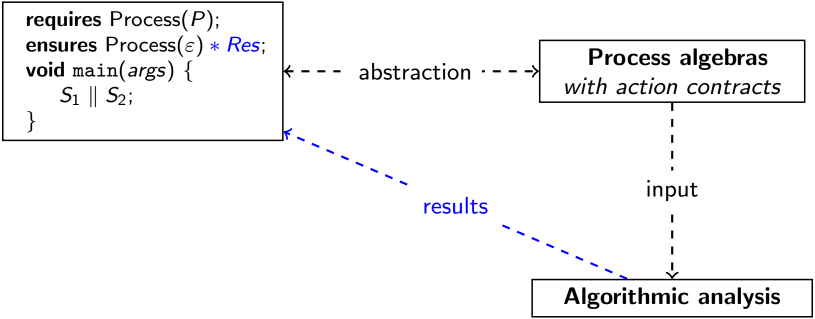
Deductively verifying *correctness* of the abstraction

Our approach: *deductive + algorithmic verification*



The properties are encoded as *process/action contracts*

Our approach: *deductive + algorithmic verification*



Applying model checking result *in the program logic*

Example program: *concurrent counting*

Concrete program

```
class Counter {
  public int val;

  static void add2(Counter c) {
    parallel {
      atomic-add(c.val, 1);
    } and {
      atomic-add(c.val, 1);
    }
  }
}
```

Program abstraction

Example program: *concurrent counting*

Concrete program

```
class Counter {
    public int val;

  ensures c.val = old(c.val) + 2;
    static void add2(Counter c) {
      parallel {
        atomic-add(c.val, 1);
      } and {
        atomic-add(c.val, 1);
      }
    }
}
```

Program abstraction

How to verify this property?

Example program: *concurrent counting*

Concrete program

```
class Counter {
    public int val;

    static void add2(Counter c) {
       parallel {
           atomic-add(c.val, 1);
        } and {
           atomic-add(c.val, 1);
        }
    }
}
```

Program abstraction

```
action incr;
```

The incr action *abstracts* the atomic-add's.

Example program: *concurrent counting*

Concrete program

```
class Counter {
    public int val;

    static void add2(Counter c) {
        parallel {
            atomic-add(c.val, 1);
        } and {
            atomic-add(c.val, 1);
        }
    }
}
```

Program abstraction

```
action incr;

process parincr() := incr || incr;
```

The parincr process *abstracts* the add2 program.

Example program: *concurrent counting*

Concrete program

```
class Counter {
    public int val;

    static void add2(Counter c) {
      parallel {
         atomic-add(c.val, 1);
       } and {
         atomic-add(c.val, 1);
       }
    }
}
```

Program abstraction

```
guard true;
effect x = old(x) + 1;
action incr;

process parincr() := incr || incr;
```

Contracts are used to encode the *properties of interest*.

Example program: *concurrent counting*

Concrete program	Program abstraction

Concrete program

```
class Counter {
    public int val;

    static void add2(Counter c) {
       parallel {
          atomic-add(c.val, 1);
       } and {
          atomic-add(c.val, 1);
       }
    }
}
```

Program abstraction

guard true;
effect $\mathtt{x} = \mathbf{old}(\mathtt{x}) + 1$;
action incr;

requires true;
ensures $\mathtt{x} = \mathbf{old}(\mathtt{x}) + 2$;
process $\mathtt{parincr}() := \mathtt{incr} \parallel \mathtt{incr}$;

Contracts are used to encode the *properties of interest*.

Example program: *concurrent counting*

Concrete program

```
class Counter {
    public int val;

   requires Process(parincr);
   requires c.val ~ x;
    static void add2(Counter c) {
       parallel {
          atomic-add(c.val, 1);
       } and {
          atomic-add(c.val, 1);
       }
    }
}
```

Program abstraction

```
guard true;
effect x = old(x) + 1;
action incr;

requires true;
ensures x = old(x) + 2;
process parincr() := incr || incr;
```

Linking concrete program to abstract model.

Example program: *concurrent counting*

Concrete program	Program abstraction
class Counter {	
public int *val*;	
requires Process(`parincr`);	**guard** true;
requires *c*.*val* ∼ `x`;	**effect** `x` = **old**(`x`) + 1;
static void add2(Counter *c*) {	**action** `incr`;
parallel {	
act `incr` **do** `atomic-add`(*c*.*val*, 1);	**requires** true;
} **and** {	**ensures** `x` = **old**(`x`) + 2;
act `incr` **do** `atomic-add`(*c*.*val*, 1);	**process** `parincr`() := `incr` ∥ `incr`;
}	
}	
}	

Linking abstract actions to concrete implementation.

Example program: *concurrent counting*

Concrete program

```
class Counter {
    public int val;

   requires Process(parincr);
   requires c.val ~ x;
   ensures Process(ε);
    static void add2(Counter c) {
       parallel {
          act incr do atomic-add(c.val, 1);
       } and {
          act incr do atomic-add(c.val, 1);
       }
    }
}
```

Program abstraction

```
guard true;
effect x = old(x) + 1;
action incr;

requires true;
ensures x = old(x) + 2;
process parincr() := incr || incr;
```

Linking concrete program to abstract model.

Example program: *concurrent counting*

Concrete program

```
class Counter {
    public int val;

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   requires c.val ~ x;
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   ensures c.val = old(c.val) + 2;
    static void add2(Counter c) {
       parallel {
          act incr do atomic-add(c.val, 1);
       } and {
          act incr do atomic-add(c.val, 1);
       }
    }
}
```

Program abstraction

```
guard true;
effect x = old(x) + 1;
action incr;

requires true;
ensures x = old(x) + 2;
process parincr() := incr || incr;
```

Using the result from analyzing all traces of `parincr`.

Model abstractions: *underlying theory*

Formalised using the Coq proof assistant

Model abstractions: *verified examples*

1. **Concurrent counting**: verifying that a concurrent counter computes the correct result.
2. **No-send-after-read**: verifying that confidential data can not be send after being received.
3. **Parallel GCD**: verifying that a parallel GCD algorithm computes the correct result.
4. **Locking protocol**: verifying that a lock implementation adheres to the intended locking protocol.

Model abstractions: *verified examples*

1. **Concurrent counting**: verifying that a concurrent counter computes the correct result.
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Model abstractions: *verified examples*

1. **Concurrent counting**: verifying that a concurrent counter computes the correct result.
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3. **Parallel GCD**: verifying that a parallel GCD algorithm computes the correct result.
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See our *VSTTE2017* paper for more details

Outline

Conclusion

Future directions

1. Verifying *distributed software*.
2. Automatic generation of *annotations*.
3. Generating *meaningful* error messages.

Conclusion

Future directions

1. Verifying *distributed software*.
2. Automatic generation of *annotations*.
3. Generating *meaningful* error messages.

VerCors Verification Tool Set

- Automated verification of parallel and concurrent software.
- More information: http://utwente.nl/vercors.
- Download & try online: https://github.com/utwente-fmt/vercors.