Konzepte objektorientierter Programmierung

– Lecture 12 –

Prof. Dr. Peter Müller

Software Component Technology

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ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Agenda for Today

12. Extended Static Checking

    12.1 Overview and Demo

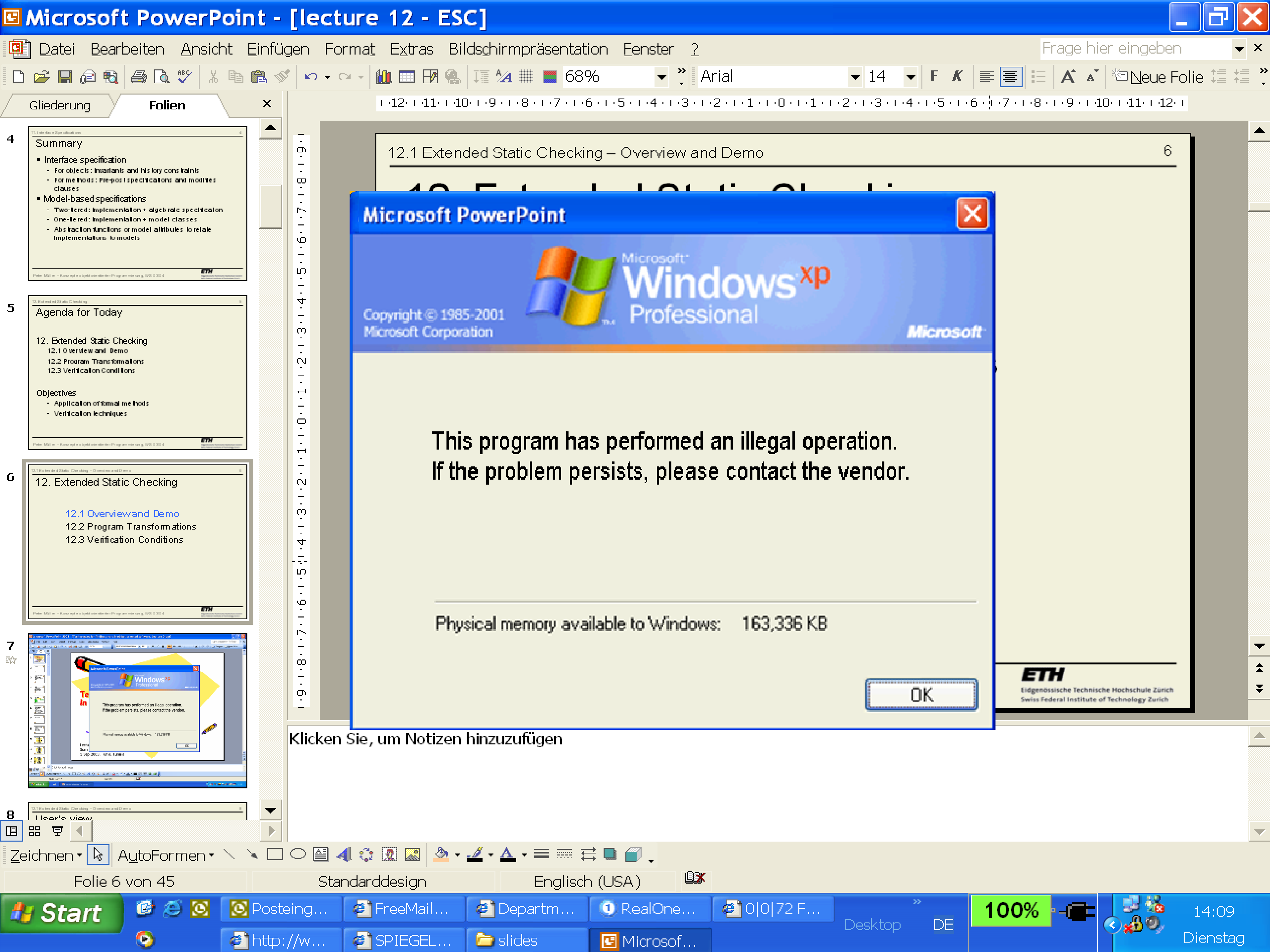
    12.2 Program Transformations

    12.3 Verification Conditions

Objectives

- Application of formal methods
- Verification techniques

[This lecture is partly based on Rustan Leino's lecture 0 at the *Summer school on Formal Models of Software.* Tunisia, 2002/2003]



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Summary

- Interface specification
  - For objects: Invariants and history constraints
  - For methods: Pre-/postspecifications and modifies clauses
- Model-based specifications
  - Two-tiered: Implementation + algebraic specification
  - One-tiered: Implementation + model classes
  - Abstraction functions or model attributes to relate implementations to models

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  12.2 Program Transformations
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Objectives
  - Application of formal methods
  - Verification techniques

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12.2 Program Transformations
12.3 Verification Conditions

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User's view

12.1 Extended Static Checking – Overview and Demo

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Microsoft

This program has performed an illegal operation.
If the problem persists, please contact the vendor.

Physical memory available to Windows: 163,336 KB

OK

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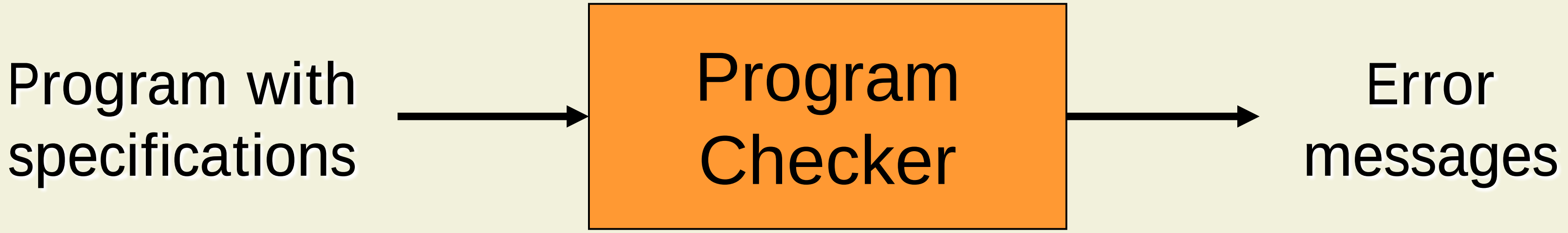
User's view


Program with specifications

Program Checker

Error messages

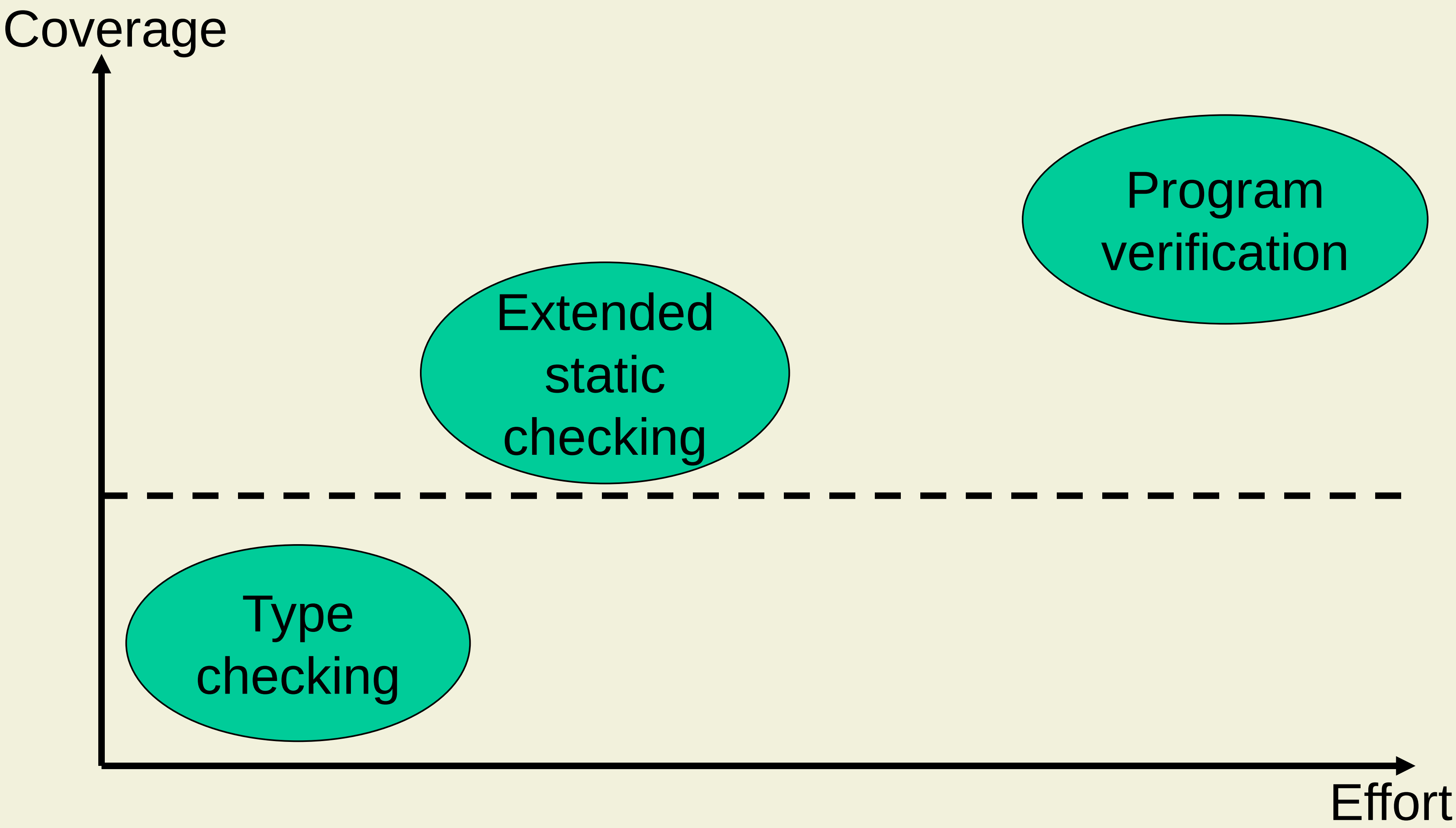
```
public class Bag {
   private /*@non_null*/ int[ ] a;
   private int n;

   //@ invariant 0 <= n && n <= a.length;

   public Bag( /*@non_null*/ int[ ] initial )
    { … }
  …
  …
}
```

Bag.java:18: Array index possibly too large

Extended Static Checking



ESC/Java

- ESC/Java checks programs for coding errors …
    - Null-dereferences
    - Array bounds errors
    - Illegal casts
    - Race conditions, deadlocks
- … and specification violations
    - Simple pre-post specifications
    - Simple invariants

Program Checker Design Tradeoffs

- Objectives
  - Fully automated reasoning
  - As little annotation overhead as possible
  - Performance
- ESC/Java is not sound
  - Errors may be missed
- ESC/Java is not complete
  - Warnings do not always report errors (false alarms)

ESC/Java Demo

```
class Bag {
  int[ ] a;
  int n;


  int extractMin( ) {
    int m = Integer.MAX_VALUE;
    int mindex = 0;
    for ( int i = 1; i <= n; i++ )
      if ( a[ i ] < m )
        { mindex =i; m = a[ i ]; }
    n--;
    a[ mindex ] = a[ n ];
    return m;
}
```

ESC/Java Demo

```
class Bag {
  int[ ] a;       //@ invariant a != null;
  int n;


  int extractMin( ) {
    int m = Integer.MAX_VALUE;
    int mindex = 0;
    for ( int i = 1; i <= n; i++ )
      if ( a[ i ] < m )
        { mindex =i; m = a[ i ]; }
    n--;
    a[ mindex ] = a[ n ];
    return m;
}
```

Warning:
Possible null deference.
Plus other warnings

ESC/Java Demo

```
class Bag {
  int[ ] a;         //@ invariant a != null;
  int n;            //@ invariant 0 <= n && n <= a.length;


  int extractMin( ) {
    int m = Integer.MAX_VALUE;
    int mindex = 0;
    for ( int i = 1; i <= n; i++ )
      if ( a[ i ] < m )
        { mindex =i; m = a[ i ]; }
    n--;
    a[ mindex ] = a[ n ];
    return m;
}
```

Warning:
Array index possibly too large

ESC/Java Demo

```
class Bag {
  int[ ] a;        //@ invariant a != null;
  int n;           //@ invariant 0 <= n && n <= a.length;


  int extractMin( ) {
    int m = Integer.MAX_VALUE;
    int mindex = 0;
    for ( int i = 0; i < n; i++ )
      if ( a[ i ] < m )
        { mindex =i; m = a[ i ]; }
    n--;
    a[ mindex ] = a[ n ];
    return m;
}
```

Warning:
Array index possibly too large

ESC/Java Demo

```
class Bag {
  int[ ] a;        //@ invariant a != null;
  int n;           //@ invariant 0 <= n && n <= a.length;

  //@ requires n > 0;
  int extractMin( ) {
    int m = Integer.MAX_VALUE;
    int mindex = 0;
    for ( int i = 0; i < n; i++ )
      if ( a[ i ] < m )
        { mindex =i; m = a[ i ]; }
    n--;
    a[ mindex ] = a[ n ];
    return m;
}
```

Warning:
Possible negative array index

Interface Specifications

- Annotation language is tailored towards ESC
  - No method invocations in specifications
  - No data abstraction (no models)
- Simple annotations (non_null)
- Method annotations
  - pre-post specifications
  - modifies clauses
- Object invariants

Assume Annotation

- Assume a condition **without checking**

```
//@ assume E;
```

- Useful to avoid full verification
- Assume is a source of unsoundness

```
int prime( int n ) { … }
void m( ) {
  int p = prime( 5 );
  //@ assume (\forall int i,j; i*j==p && i>0 && j>0 ==> i==1 ¦¦ j==1);
  … // code works only if p is prime
}
```

Assert Annotation

- Assert can be used to write specifications inside method bodies

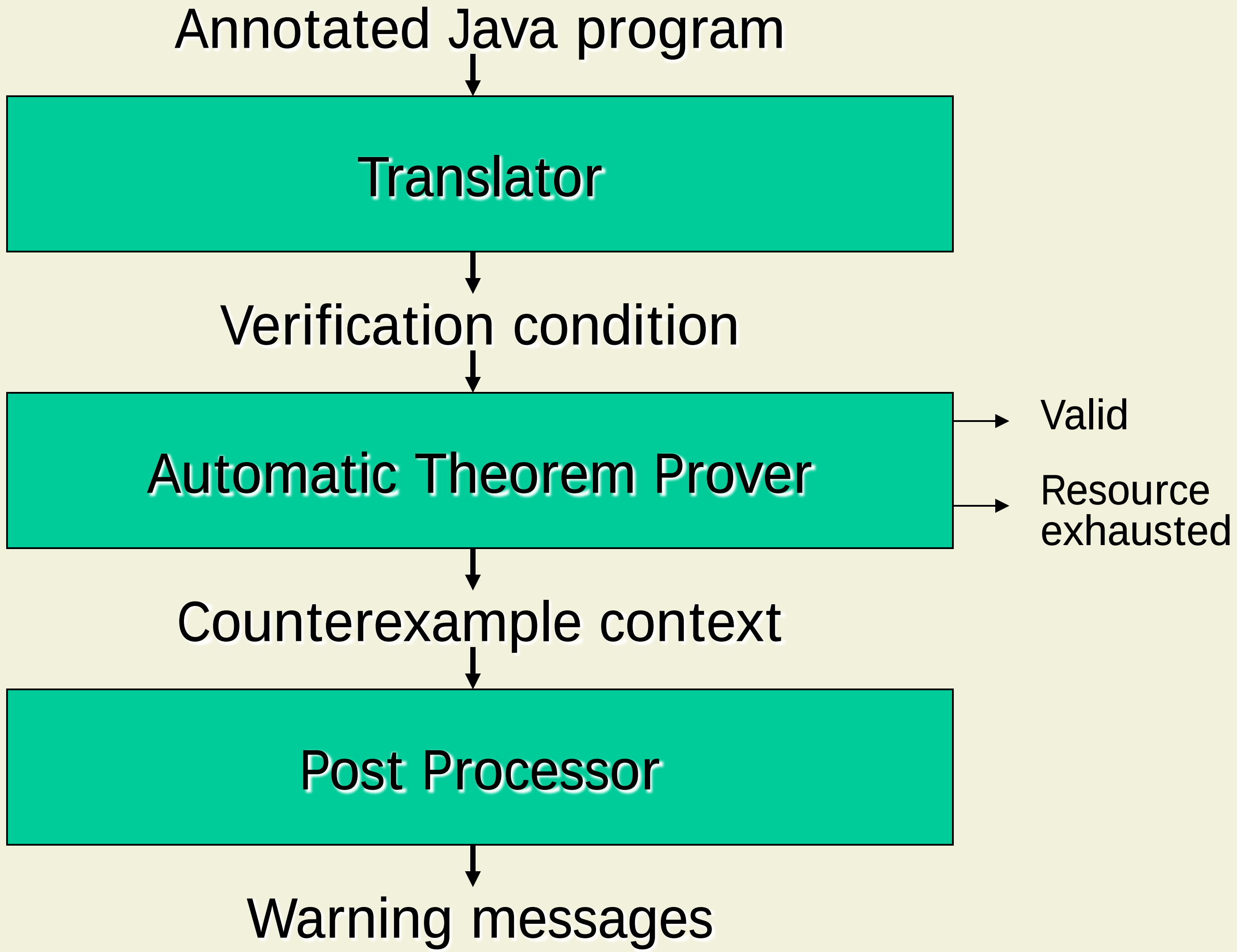
```
//@ assert E;
```

- Semantics:
  - Evaluate E
  - If E then skip else abort

```
void m1( ) {
  int a = 5 ;
  int b = a - 5 ;
  //@ assume b != 0;
  int c = a / b;
}
```

```
void m2( ) {
  int a = 5 ;
  int b = a - 5 ;
  //@ assert b != 0;
  int c = a / b;
}
```

Tool Architecture



Annotated Java program

Translator

Verification condition

Automatic Theorem Prover

Valid

Resource exhausted

Counterexample context

Post Processor

Warning messages

12. Extended Static Checking

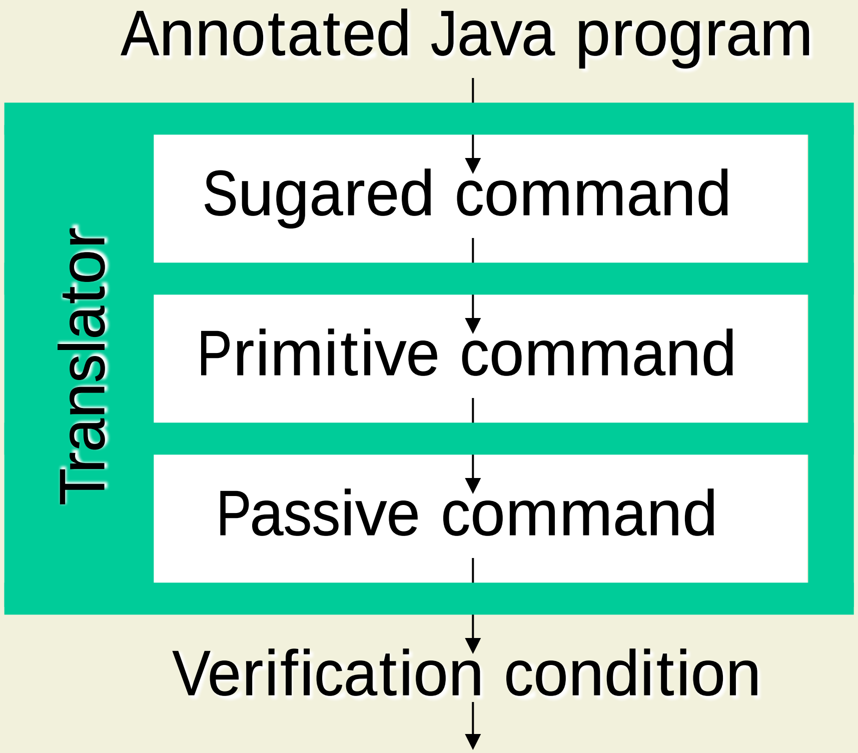
12.1 Overview and Demo

12.2 Program Transformations

12.3 Verification Conditions

Translator

- Java programs are difficult to handle
  - Many different statements and expressions
- Approach
  - **Translate** source program **to guarded command language**
  - **Make simplifications** to facilitate extended static checking



Sugared Commands

- Assume and assert are treated as statements
- If- and switch-statements are replaced by **nondeterministic choice []**
- Only one **loop statement** (with loop invariant)

```
S,T  ::=assert E
   |   assume E
   |   x = E
   |   S ; T
   |   S [] T
   |   loop {inv E} S → T end
   |   call x =  t.m(E)
   |   …
```

Sugared Commands: Example

```
x =  t.f.g;
if (x < 0) x = -x;
/*@ assert x >= 0; */
```

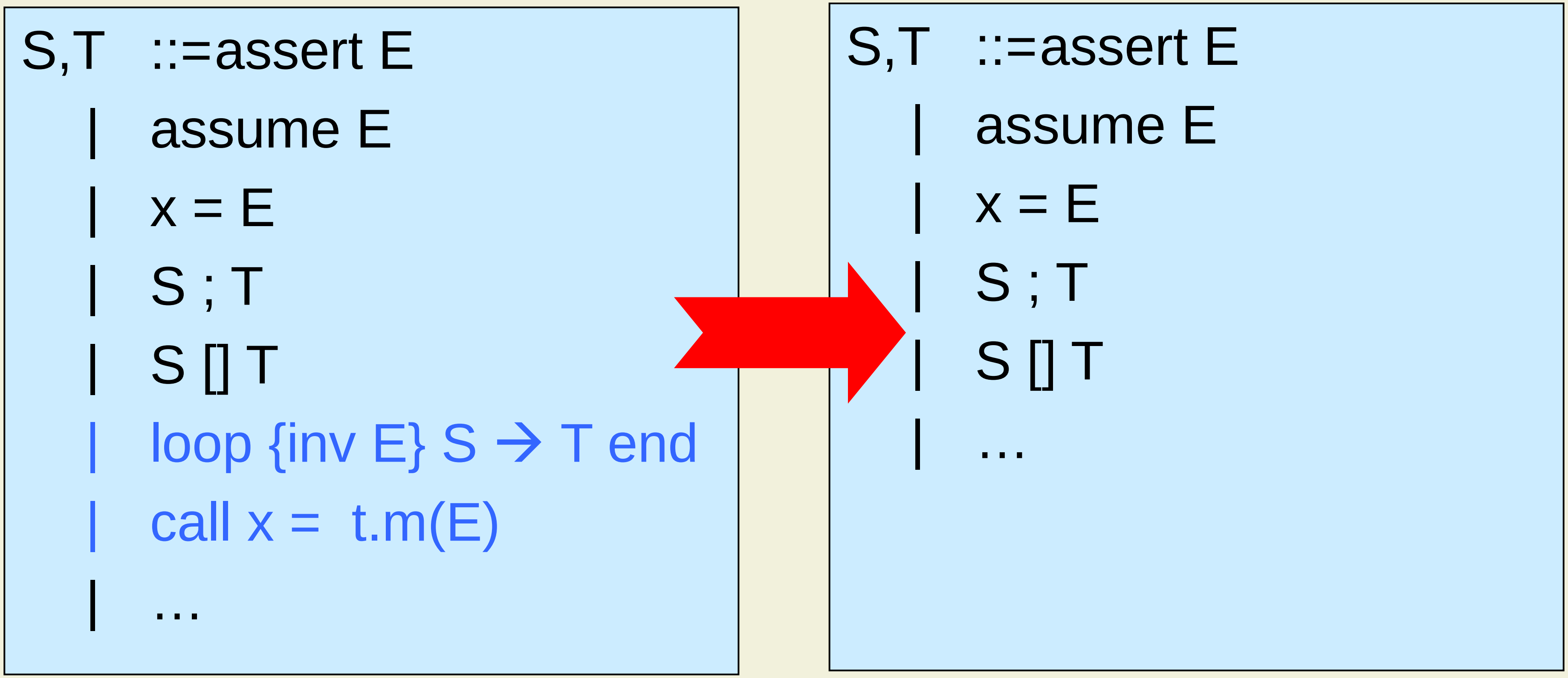
```
tmp = t.f;
x = tmp.g;
if (x < 0)
  x = -x;
else
  ;
/*@ assert x >= 0; */
```

```
assert t ≠ null;
tmp =  select( f,t );
assert tmp ≠ null;
x = select( g,tmp )

(
  assume x < 0;
  x = -x
[]
  assume ¬(x < 0)
);

assert x >= 0
```

From Sugared to Primitive Commands



S,T ::=assert E
| assume E
| x = E
| S ; T
| S [] T
| loop {inv E} S → T end
| call x = t.m(E)
| …

S,T ::=assert E
| assume E
| x = E
| S ; T
| S [] T
| …

Treatment of Loops

- Reasoning about loops is difficult
- Approach in ESC/Java: Consider **only first iteration** of the loop plus evaluation of condition after first iteration

```
while( n > 0 ) {
  res = res * n;
  n = n - 1;
}
```

```
if (n > 0) {
  res = res * n;
  n = n - 1;
  if (n > 0)
    assume false;
}
```

```
( assume n > 0;
  res = res * n;
  n = n – 1
  ( assume n > 0;
    assume false;
  []
    assume ¬(n > 0)  )
[]
  assume ¬(n > 0)  );
```

Treatment of Loops: Problems

```
int n = 1;
while( true ) {
  int r = 5 / n;
  n = n - 1;
}
```

```
n = 1;
if ( true ) {
  int r = 5 / n;
  n = n - 1;
  if ( true )
    assume false;
}
```

```
n = 1;
(
  assume true;
  int r = 5 / n;
  n = n - 1;
  (
    assume true;
    assume false;
  []
    assume ¬ true  )
[]
  assume ¬true
);
```

Treatment of Loops is Unsound

- **Problems** might occur **in later iterations**
- **Practical experience** shows that most errors are caught in first iteration
- loopSafe option for **sound treatment** of loops
  - Based on specification of **loop invariant**

Treatment of Method Calls

- Method calls are handled by referring to the **specification of the called method**
  - Preconditions have to be **established** (assert)
  - Postconditions can be **assumed** to hold (assume)

```
//@ requires P;
//@ ensures Q;
int m( T t ) { … }
```

```
call x = m( E );
```

- Using specifications enables **modular checking**
  - One method at a time
  - Dynamic method binding is handled by **behavioral subtyping**

Treatment of Method Calls: Example

```
//@ requires P;
//@ ensures Q;
int m( T t ) { … }
```

```
call x = m( E );
```

Pattern

```
var t,\result in
  t = E;
  assert P;
  // execution of m skipped
  assume Q;
  x = \result;
end
```

```
//@ requires d > 0;
//@ ensures \result == ( n / d );
int div( int n, int d ) { … }
```

```
call x = div( 5,3 );
assert x <= 5;
```

Example

```
var n,d,\result in
  n = 5; d = 3;
  assert d > 0;
 // execution of m skipped
  assume \result == ( n / d );
  x = \result;
end;
assert x <= 5
```

Side-Effects and Modifies Clauses

```
//@ requires d > 0;
//@ modifies this.attr;
//@ ensures \result == ( n / d );
int div( int n, int d ) { … }
```

```
this.attr = 5;

call x = div( 5,3 );
assert x <= 5;

assert this.attr == 5;
```

```
this.attr = 5;

var n,d,\result in
  n = 5; d = 3;
  assert d > 0;
  // execution of m skipped
  assume \result == ( n / d );
  x = \result;
end;
assert x <= 5

assert this.attr == 5;
```

Playing Havoc

```
//@ requires d > 0;
//@ modifies this.attr;
//@ ensures \result == ( n / d );
int div( int n, int d ) { … }
```

```
this.attr = 5;

call x = div( 5,3 );
assert x <= 5;

assert this.attr == 5;
```

```
this.attr = 5;

var n,d,\result in
  n = 5; d = 3;
  assert d > 0;
  var attr0 in
    attr0 = this.attr;
    havoc this.attr;
    assume \result == ( n / d );
    x = \result;
  end;
end;
assert x <= 5

assert this.attr == 5;
```

- **havoc** assigns an **arbitrary value** to a variable

From Sugared to Primitive Commands

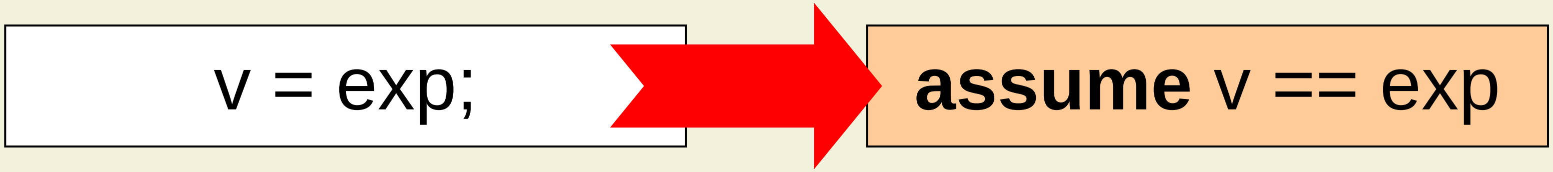
From Primitive to Passive Commands

```
S,T  ::=assert E
  |   assume E
  |   x = E
  |   S ; T
  |   S [] T
  |   …
```

```
S,T  ::=assert E
  |   assume E
  |   S ; T
  |   S [] T
  |   …
```

Eliminating Assignments

- Since **we do not execute** the translated program, we do **not** have to **actually modify the variables**
- It is sufficient for the checker to know that after the assignment `v = exp;` the condition `v == exp` holds
- Approach: **Replace assignments by assumptions**



Eliminating Assignments (cont'd)

- **Problem:** v appears on right-hand side

v = v + 1;

assume v == v + 1

- **Solution:** New variable v_n for each assignment

(**assume** x < 0;
x = -x

[]
assume ¬(x < 0)
);
assert x >= 0

(**assume** $x_0 < 0$;
$x_1 = -x_0$;
$x_2 = x_1$
[]
assume ¬($x_0 < 0$);
$x_2 = x_0$);
assert $x_2 >= 0$

(**assume** $x_0 < 0$;
assume $x_1 == -x_0$;
assume $x_2 == x_1$
[]
assume ¬($x_0 < 0$);
assume $x_2 == x_0$);
assert $x_2 >= 0$

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Weakest Preconditions

- A **Hoare triple**

  { P } S { Q }

  says that if command **S** is started in a state satisfying **P**, then **S** terminates **without error** in a state satisfying **Q**

- The **weakest precondition** of a command **S** with respect to a postcondition **Q**, written wp(**S**, **Q**), is the weakest **P** such that

  { P } S { Q }

wp for Passive Commands

wp(**assert** E,Q) = E && Q

wp(**assume** E, Q) = E ==> Q

wp(S;T, Q) = wp(S, wp(T,Q))

wp(S [] T, Q) = wp(S,Q) && wp(T,Q)

wp Calculation

wp(S;T, Q) = wp(S, wp(T,Q))
wp(S [] T, Q) = wp(S,Q) && wp(T,Q)

wp(
assert w == 1;
(**assume** i == 5;
[] **assume** w == 1);
, i==5) =

wp(**assert** w == 1; , wp(
(**assume** i == 5;
[] **assume** w == 1);
, i==5)) =

wp(**assert** w == 1; , wp(**assume** i == 5 , i==5) &&
wp(**assume** w == 1 , i==5)) =

wp Calculation (cont'd)

wp(**assert** E,Q) = E && Q
wp(**assume** E, Q)= E ==> Q

wp(**assert** w == 1; , wp(**assume** i == 5 , i==5) &&
wp(**assume** w == 1 , i==5)) =

wp(**assert** w == 1; ,
(i==5 ==> i==5) && (w==1 ==> i==5)) =

w==1 && (i==5 ==> i==5) && (w==1 ==> i==5)

Verification Conditions

- The **verification condition** VC_m for a method m is

$$Pre_m \Longrightarrow wp(\ body_m, Post_m\ )$$

- **Modifies clauses** are **used** to reason about calls, **but not checked**
  - Another source of unsoundness

Verification Conditions (cont'd)

- **Universal background predicate** BP_{Univ} specifies properties of the programming language
  - Example: $(\forall t: \ t <: \ t)$
- **Type-specific background predicate** specifies properties of the program
  - Bag <: java.lang.Object
- The verification condition passed to the theorem prover is

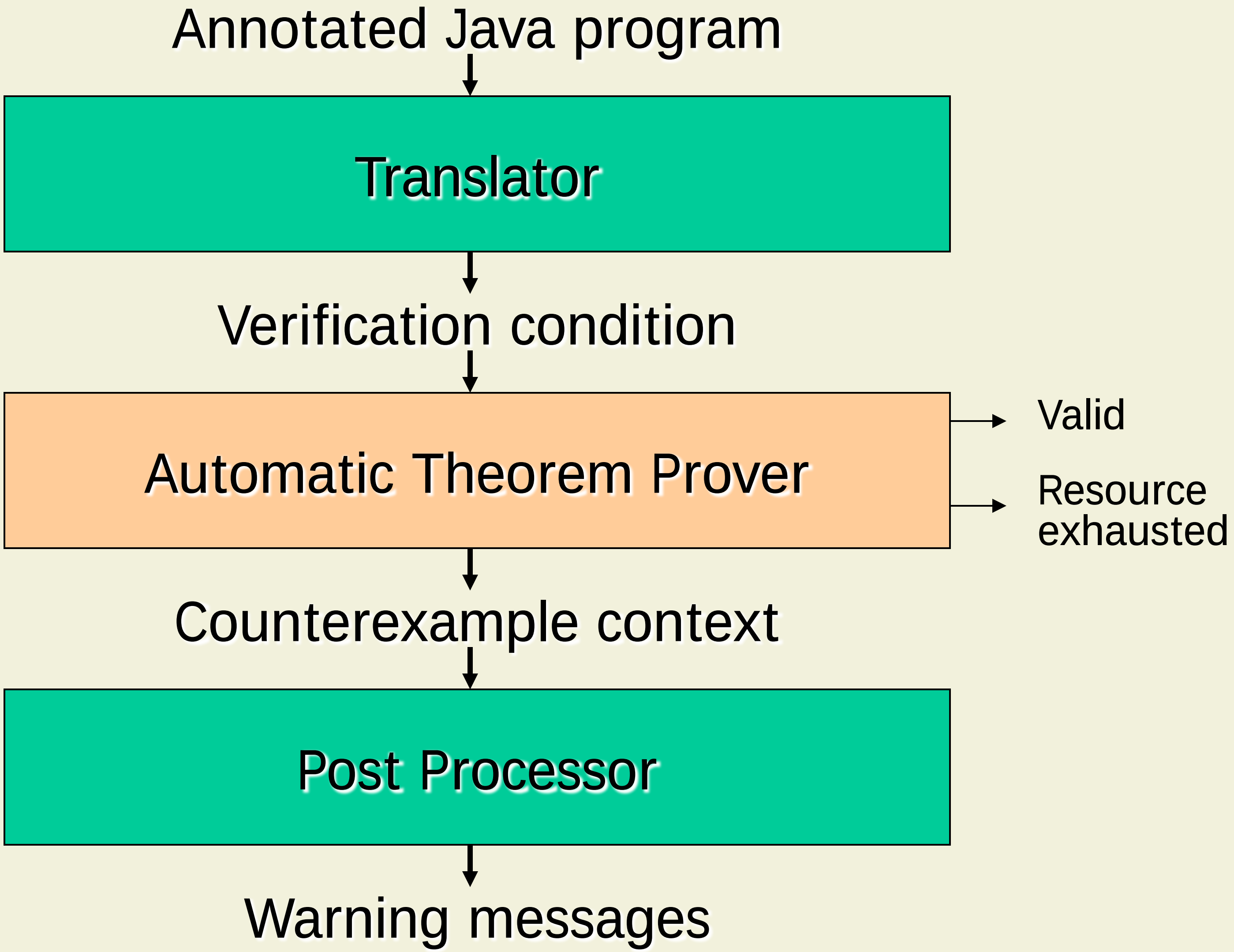
$$\boxed{BP_{Univ} \ \&\& \ BP_T \ ==> \ VC_m}$$

Verification Condition Example

```
   (AND
    (<: T_T |T_java.lang.Object|)
    (EQ T_T (asChild T_T |T_java.lang.Object|))
    (DISTINCT arrayType |T_boolean| |T_char| |T_byte| |T_short| |T_int|
               |T_long| |T_float| |T_double| |T_.TYPE|
               T_T |T_java.lang.Object|)))
 (EXPLIES
  (LBLNEG |vc.T
   (IMPLIES
    (AND
     (EQ |elems@
     (EQ elems (
     (< (eClosed
     (EQ LS (asL
     (EQ |alloc@
    (NOT
     (AND
      (EQ |@true
      (OR
       (AND
        (OR
         (AND
          (< |x:2.21| 0)
          (LBLPOS |trace.Then^0,3.15| (EQ |@true| |@true|))
          (EQ |x:3.17| (- 0 |x:2.21|))
```

```
class T {
  static int abs( int x ) {
    if ( x < 0 ) { x = -x; }
    //@ assert x >= 0;
  }
}
```

Tool Architecture



Annotated Java program

Translator

Verification condition

Automatic Theorem Prover

Valid

Resource exhausted

Counterexample context

Post Processor

Warning messages

Theorem Prover: “Simplify”

- Automatic: **No user interaction**
- **Refutation based**: To prove φ it will attempt to satisfy ¬φ
  - If this is possible, a counterexample is found, and we know a reason why φ is invalid
  - If it fails to satisfy ¬φ then φ is considered to be valid

Time Limits

- Logic used in Simplify is **semi-decidable**
  - Each procedure that proves all valid formulas loops forever on some invalid ones
- Simplify works with a **time limit**
  - When time limit is reached, counterexample is returned
  - Longer computation might turn out that returned counterexample is inconsistent
- Time limits are a source of **incompleteness**
  - Spurious counterexamples lead to spurious warnings

Experience: Annotations

- Capture common design decisions
- Suggested immediately by warnings
- Overhead: 4-10% of source code
- ~1 annotation per field or parameter
- Most common annotations:
  - non_null
  - Container element types

Experience: Performance

- 50% of all methods: < 0.5 s
- 80% of all methods: < 1 s
- Time limit: 300 s

- Total time for Javafe (~40kloc): 65 min

References

- Cormac Flanagan, K. Rustan M. Leino, Mark Lillibridge, Greg Nelson, James B. Saxe, and Raymie Stata: *Extended static checking for Java*. PLDI, ACM Press, 2002.
  Available from course web site

- Download ESC/Java (tool, documentation, sources):
  http://research.compaq.com/SRC/esc