The ESC/Java2 Calculi and Object Logics

Implications on Specification and Verification

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ESC/Java2

- ESC/Java2 is an *extended static checker*
  - based upon DEC/Compaq SRC ESC/Java
  - operates on JML-annotated Java code
  - behaves like a compiler
    - error messages similar to javac & gcc
    - completely automated
    - hides enormous complexity from user

What is Extended Static Checking?

annotated source → static checker → Error: ...

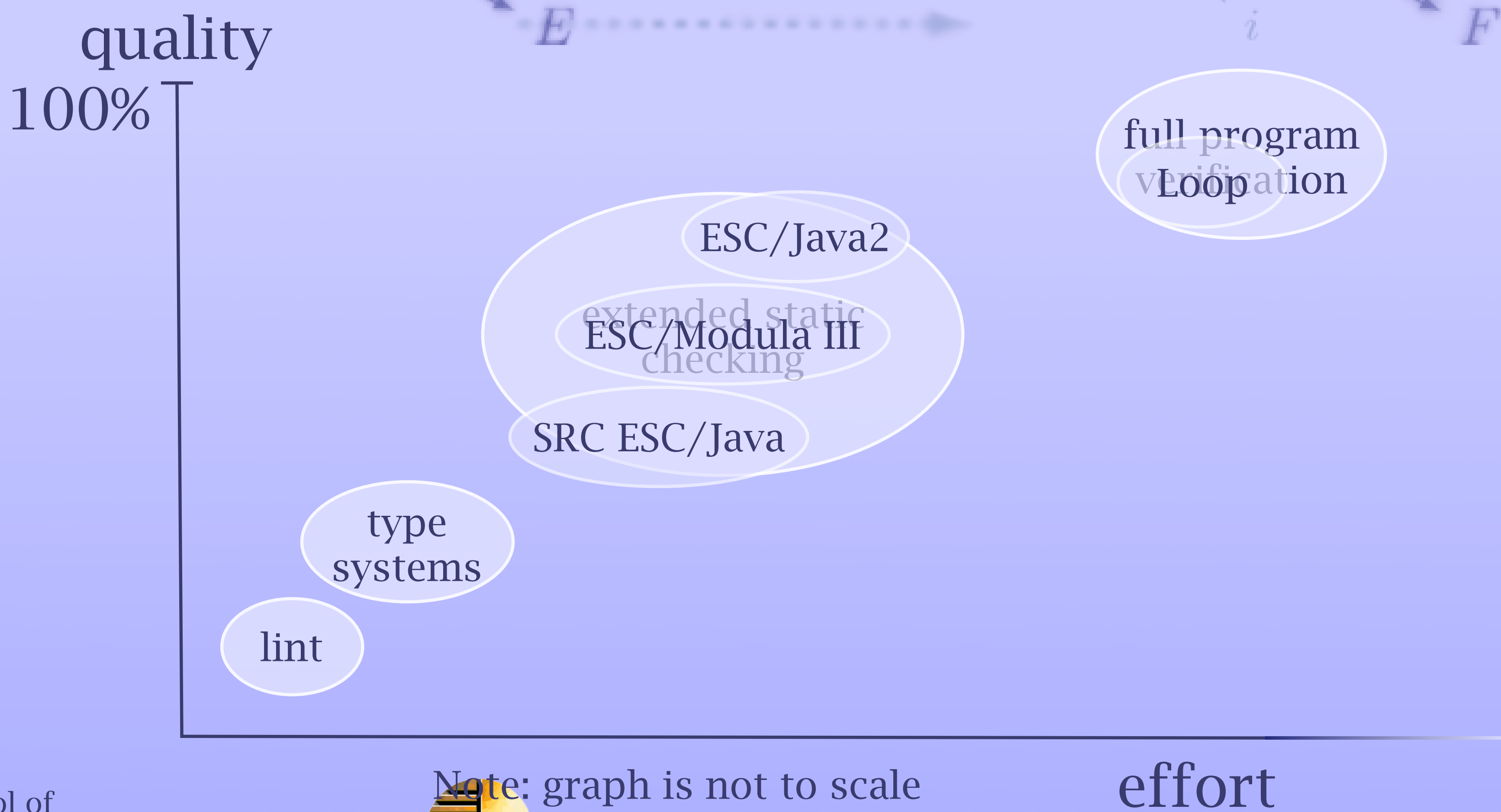
- type systems
  - Error: wrong number of arguments to call
- lint & modern compilers
  - Error: unreachable code
- full program verification
  - Error: qsort does not yield a sorted array

Why Not Just Test?

- testing is essential, but
  - expensive to write and *maintain*
  - finds errors *late*
  - *misses* many errors

- static checking and testing are *complementary techniques*

Comparison of Static Checkers



ESC/Java2 Use

JML-annotated program

⇩

ESC/Java2

⇩

"null-dereference error on line 486"

- Modularly checks for:
  - null-dereference errors
  - array bounds errors
  - type cast errors
  - specification violations
  - race conditions & deadlocks
  - ... dozens of other errors

Soundness and Completeness

- a sound and complete prover is non-automated, very complex, and expensive
  - modular checking
  - properties of arithmetic and floats
  - complex invariants and data structures
- instead, design and build an unsound and incomplete verification tool
  - trade soundness and completeness for automation and usability

JML: The Java Modeling Language

- a behavioral interface specification language
- syntax and semantics are very close to Java
- annotations written as comments in code
- JML is a very rich language
  - standard constructs include preconditions, postconditions, invariants, etc.
- one language used for documentation, runtime checking, and formal verification

A JML Example and ESC/Java2 Demo

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

  Bag(int[] input) {
    n = input.length;
    a = new int[n];
    System.arraycopy(input, 0,
                     a, 0, n);
  }

  boolean isEmpty() {
    return n == 0;
  }

  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;
  }
}
```

The Annotated Class

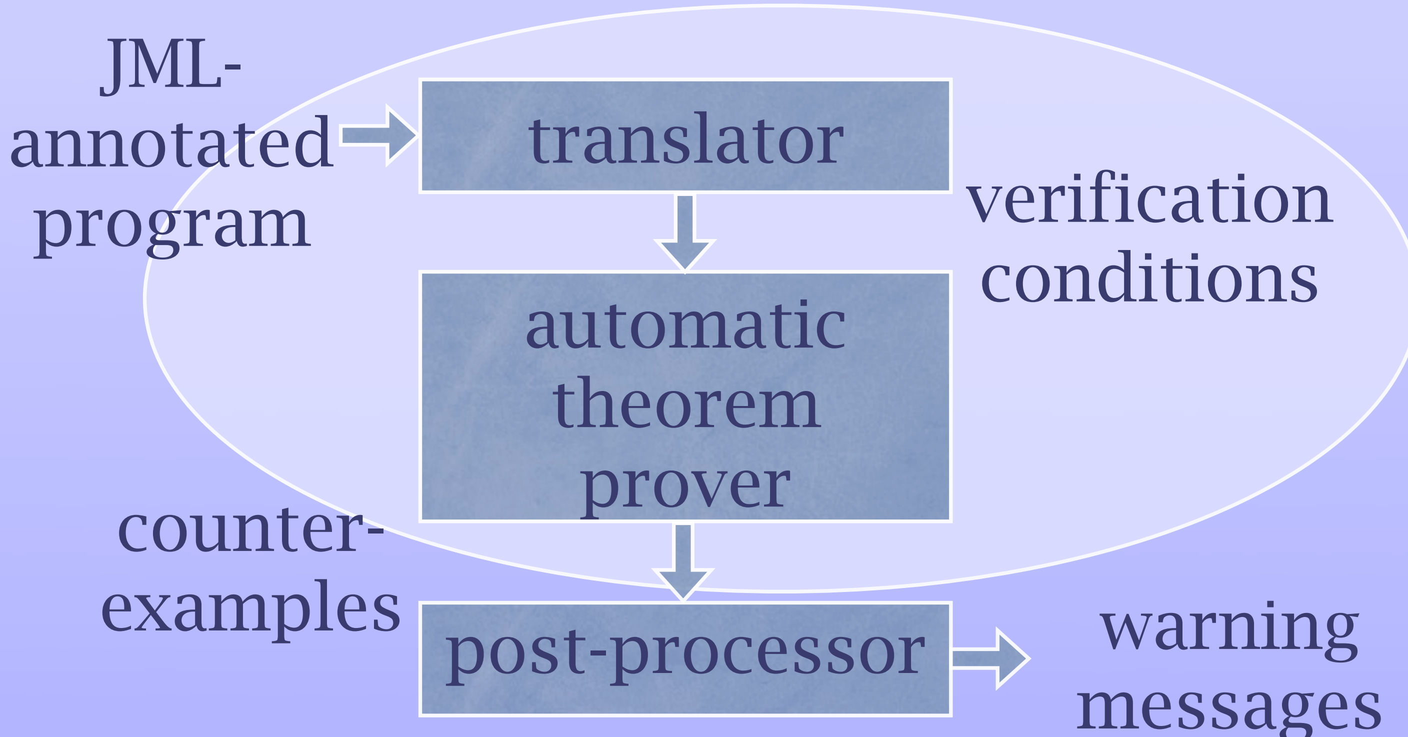
```
class Bag {
  /*@ non_null */ int[] a;
  int n;
  //@ invariant 0 <= n && n <= a.length;
  //@ ghost public boolean empty;
  //@ invariant empty == (n == 0);

  //@ requires input != null;
  //@ ensures this.empty == (input.length == 0);
  public Bag(int[] input) {
    n = input.length;
    a = new int[n];
    System.arraycopy(input, 0, a, 0, n);
    //@ set empty = n == 0;
  }

  //@ ensures \result == empty;
  public boolean isEmpty() {
    return n == 0;
  }
```

```
  //@ requires !empty;
  //@ modifies empty;
  //@ modifies n, a[*];
  public 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--;
    //@ set empty = n == 0;
    //@ assert empty == (n == 0);
    a[mindex] = a[n];
    return m;
  }
}
```

ESC/Java2 Architecture



The ESC/Java2 Object Logic

- (very) partial semantics for Java and JML
- written in unsorted first-order logic
- highly tuned to current theorem prover's capabilities and quirks
  - Nelson's Simplify prover circa mid-80s
- originally consisted of 81 axioms
- extended by 20 axioms in ESC/Java2

Example Java Type Axioms

```
(DEFPRED (<: t0 t1))

(BG_PUSH (<: |T_java.lang.Object|
             |T_java.lang.Object|))

; <: reflexive
(BG_PUSH
  (FORALL (t)
    (<: t t)))


; <: transitive
(BG_PUSH
  (FORALL (t0 t1 t2)
    (IMPLIES (AND (<: t0 t1) (<: t1 t2))
      (<: t0 t2))))
```

```
;anti-symmetry
(BG_PUSH
 (FORALL
  (t0 t1)
  (IMPLIES (AND (<: t0 t1) (<: t1 t0))
           (EQ t0 t1))))


; primitive types are final
(BG_PUSH (FORALL (t)
        (IMPLIES (<: t |T_boolean|)
                 (EQ t |
T_boolean|))))
```

Examples Showing Java Incompleteness

```
(BG_PUSH (FORALL (x)
          (IFF (is x |T_char|) (AND (<= 0 x) (<= x 65535)))))
(BG_PUSH (FORALL (x)
          (IFF (is x |T_byte|) (AND (<= -128 x) (<= x 127)))))
(BG_PUSH (FORALL (x)
          (IFF (is x |T_short|) (AND (<= -32768 x) (<= x 32767)))))
(BG_PUSH (FORALL (x)
          (IFF (is x |T_int|) (AND (<= intFirst x) (<= x intLast)))))
(BG_PUSH (FORALL (x)
          (IFF (is x |T_long|) (AND (<= longFirst x) (<= x longLast)))))

(BG_PUSH (< longFirst intFirst))
(BG_PUSH (< intFirst -1000000))
(BG_PUSH (< 1000000 intLast))
(BG_PUSH (< intLast longLast))
```

Examples of Java & JML Semantics

```
(DEFPRED (is x t))

(BG_PUSH (FORALL (x t)
                 (is (cast x t) t)))

(BG_PUSH (FORALL (x t)
                 (IMPLIES (is x t) (EQ (cast x t) x))))

(BG_PUSH
 (FORALL (e a i)
         (is (select (select (asElems e) a) i)
             (elemtype (typeof a)))))

(DEFPRED (nonnullelements x e)
   (AND (NEQ x null)
        (FORALL (i)
                (IMPLIES (AND (<= 0 i) (< i (arrayLength x)))
                         (NEQ (select (select e x) i) null)))))
```

ESC/Java2 Calculi

- used for verification condition generation in Dijkstra wp/wlp style
- easy for small/research languages
- much harder for “real world” languages
  - typed concurrent object-oriented language
  - dynamic memory allocation and GC
  - exceptions
  - aliasing

VC Generation for Java

annotated source

↓

guarded commands

↓

verification condition

```
x = a[ i++ ];

assume preconditions
assume invariants
...
i0 = i;
i = i + 1;
assert (LABEL null@218: a != null);
assert (LABEL IndexNeg@218: 0 <= i0);
assert (LABEL IndexTooBig@218: i0 < a.length);
x = elems[a][i0];
...
assert postconditions
assert invariants
```

$$\forall i_0.(i_0 = i \implies \ldots)$$

Verification Condition

- formula in unsorted, first-order predicate calculus
  - equality and function symbols
  - quantifiers
  - arithmetic operators
  - select and store operations
  - e.g., $\forall x. \forall y. \exists z. (x > y \implies z \times 2 == \ldots$

Example Verification Condition

- verification condition large & unstructured

```
(EXPLIES (LBLNEG |vc.Bag.isEmpty.11.2| (IMPLIES (AND (EQ |n@pre:3.6| |n:
3.6|) (EQ |n:3.6| (asField |n:3.6| T_int)) (EQ |a@pre:2.8| |a:2.8|) (EQ |a:
2.8| (asField |a:2.8| (array T_int))) (< (fClosedTime |a:2.8|) alloc) (EQ |
MAX_VALUE@pre:10..| |MAX_VALUE:10..|) (EQ |@true| (is |MAX_VALUE:10..|
T_int)) (EQ |length@pre:unknown| |length:unknown|) (EQ |length:unknown|
(asField |length:unknown| T_int)) (EQ |elems@pre| elems) (EQ elems (asElems
elems)) (< (eClosedTime elems) alloc) (EQ LS (asLockSet LS)) (EQ |
alloc@pre| alloc) (EQ |state@pre| state)) (NOT (AND (EQ |@true| (is this
T_Bag)) (EQ |@true| (isAllocated this alloc)) (NEQ this null) (EQ RES
(integralEQ (select |n:3.6| this) 0)) (LBLPOS |trace.Return^0,12.4| (EQ |
@true| |@true|)) (NOT (LBLNEG |Exception@13.2| (EQ |ecReturn| |
ecReturn|))))))) (AND (DISTINCT |ecReturn|) (< 1000000 pos2147483647)))
```

Problems with Current Logic

- unsorted
  - no mental model, no type checking
- tightly coupled to Simplify prover
  - unmaintained, two generations old
- very incomplete
  - want to verify new properties and some functional specifications
- never checked for soundness

A New ESC/Java2 Logic

- partial semantics for Java and JML
- written in *sorted* first-order logic
- independent of any particular prover
- written in PVS and translated to SMT-LIB
  - supported by many new provers

PVS Theories

- new explicit memory model

```
escjava2_references_and_objects : THEORY
  BEGIN
    ReferenceType, Reference : TYPE+
    Object : TYPE+
  END escjava2_references_and_objects

Heap : DATATYPE
  BEGIN
  IMPORTING escjava2_references_and_objects
    empty : empty?
    heap(h : Heap, r : Reference, o : Object) : heap?
  END Heap
```

Heap Theory

```
escjava2_memory : THEORY
  BEGIN
  IMPORTING Heap

    Time : TYPE FROM int
    BooleanField, DiscreteNumberField, ContinuousNumberField, ReferenceField : TYPE+

    ERROR_OBJECT : Object

    size(h : Heap) : RECURSIVE nat
    memGet(h : Heap, r : Reference) : RECURSIVE Object
    memSet(h : Heap, r : Reference, object : Object) : Heap

    ...etc...
```

Allocation

```
escjava2_memory_allocation : THEORY
  BEGIN
  IMPORTING escjava2_memory, functions[Reference, Time]

    allocation_time(r : Reference) : Time

    % allocation times start at 0
    allocation_time_is_non_negative : AXIOM
      FORALL(r : Reference) : 0 <= allocation_time(r)

    % the allocation time of two different references must be different
    allocation_time_is_injective : AXIOM
      injective?(allocation_time)

    ...etc...
```

Java Typesystem

```
escjava2_java_typesystem : THEORY
  BEGIN
    IMPORTING escjava2_memory

    Boolean : Type+ FROM boolean
    DiscreteNumber : TYPE+ FROM int
    ContinuousNumber : TYPE+ FROM real
    BigIntNumber : TYPE+ FROM int
    RealNumber : TYPE+ FROM real
    JavaNumber : TYPE = [DiscreteNumber + ContinuousNumber]
    JMLNumber : TYPE = [JavaNumber + BigIntNumber + RealNumber]
    Number : TYPE = JMLNumber
    java_lang_Object : ReferenceType

    java_lang_Boolean_TRUE : Boolean
    java_lang_Boolean_FALSE : Boolean

    NULL : Reference
```

Object Model

```
escjava2_object_fields_base[fieldType : TYPE, valueType : TYPE] : THEORY
  BEGIN
    IMPORTING escjava2_memory, escjava2_java_typesystem

    select(field : fieldType, object : Object) : valueType
    store(field : fieldType, object : Object, value : valueType) : Object
  END escjava2_object_fields_base

escjava2_object_fields : THEORY
  BEGIN
    IMPORTING escjava2_memory, escjava2_java_typesystem,
              escjava2_object_fields_base[BooleanField, Boolean],
              escjava2_object_fields_base[DiscreteNumberField, DiscreteNumber],
              escjava2_object_fields_base[ContinuousNumberField, ContinuousNumber],
              escjava2_object_fields_base[ReferenceField, Reference]

    is_field_of(f : ReferenceField, r : Reference) : boolean =
      FORALL(h : Heap) :
        memGet(h, r) /= ERROR_OBJECT AND select(f, memGet(h, r))
```

SMT-LIB Theories

- ~100 axioms thus far
- SMT-LIB has no parameterisation, operator overloading, or subsorts
  - SMT-LIB theory sees no size reduction
- we are working with SMT-LIB prover authors to embed **all** core ESC/Java2 theories into **all** SMT-LIB provers
  - thus, no prelude with new provers

Sorts of New Logic

```
:sorts ( # sort that represents *values* of Java's boolean base type
         Boolean
         # sort that represents *values* of all Java's base types
         # but for Boolean
         Number
         # sort that represents all Java non-base types
         ReferenceType
         # ... represents object references
         Reference
         # ... represents object values
         Object
         # Boolean, Number, Object fields
         BooleanField
         NumberField
         ReferenceField
         # ... represents the heap
         Memory )
```

Example Axioms

```
# <: is anti-symmetric
(forall ?x ReferenceType
   (forall ?y ReferenceType
     (implies (and (<: ?x ?y) (<: ?y ?x))
              (= (?x ?y)))))

# java.lang.Object is top of subtype hierarchy
(forall ?x ReferenceType (<: ?x java.lang.Object))

# subtype rules for arrays
(forall ?x ReferenceType
   (forall ?y ReferenceType
     (implies (<: ?x ?y)
              (<: (array ?x) (array ?y)))))
```

Theory Refinement

- develop logic in PVS
  - refine the logic, reduce set of axioms as much as possible, check obvious lemmas
  - translate simple VCs from ESC/Java2 into PVS syntax to double-check theory and refine the rewrite set and strategies
  - develop translator from PVS to SMT-LIB and maintain logic in higher-order prover
  - foundation for merging Loop and ESC/Java2

Benefits of New Logic

- ESC/Java2 will support multiple provers
  - use multiple provers concurrently
  - choose prover(s) based upon context
- proof(s) of soundness
  - new logic also being encoded in Isabelle (by Chalin) and Coq (by Schubert)

Benefits to ESC/Java2

- increase ESC/Java2 soundness, completeness, and performance
  - able to verify larger, more complex programs than ever before
- explicit warnings and explanations in ESC/Java2 about soundness and completeness issues

Current Work

- initial version of new logic sketched out
  - found several type errors in original logic
  - dramatically more understandable
- beginning to use new provers
  - starting with *Sammy* from Tinelli and *haRVey* from Ranise
- incorporate new provers into ESC/Java2
  - increase independence of tool from Simplify prover

Open Questions

- how to "factor out" calculus and logic from implementation of ESC/Java2
- would like to prove that the new logic subsumes the old logic
- how to integrate with other logics
  - of particular interest is how to integrate with full verification Loop
  - how to perform proof reuse when moving from first-order to higher-order semantics

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