Verification of a Java Compiler in Isabelle

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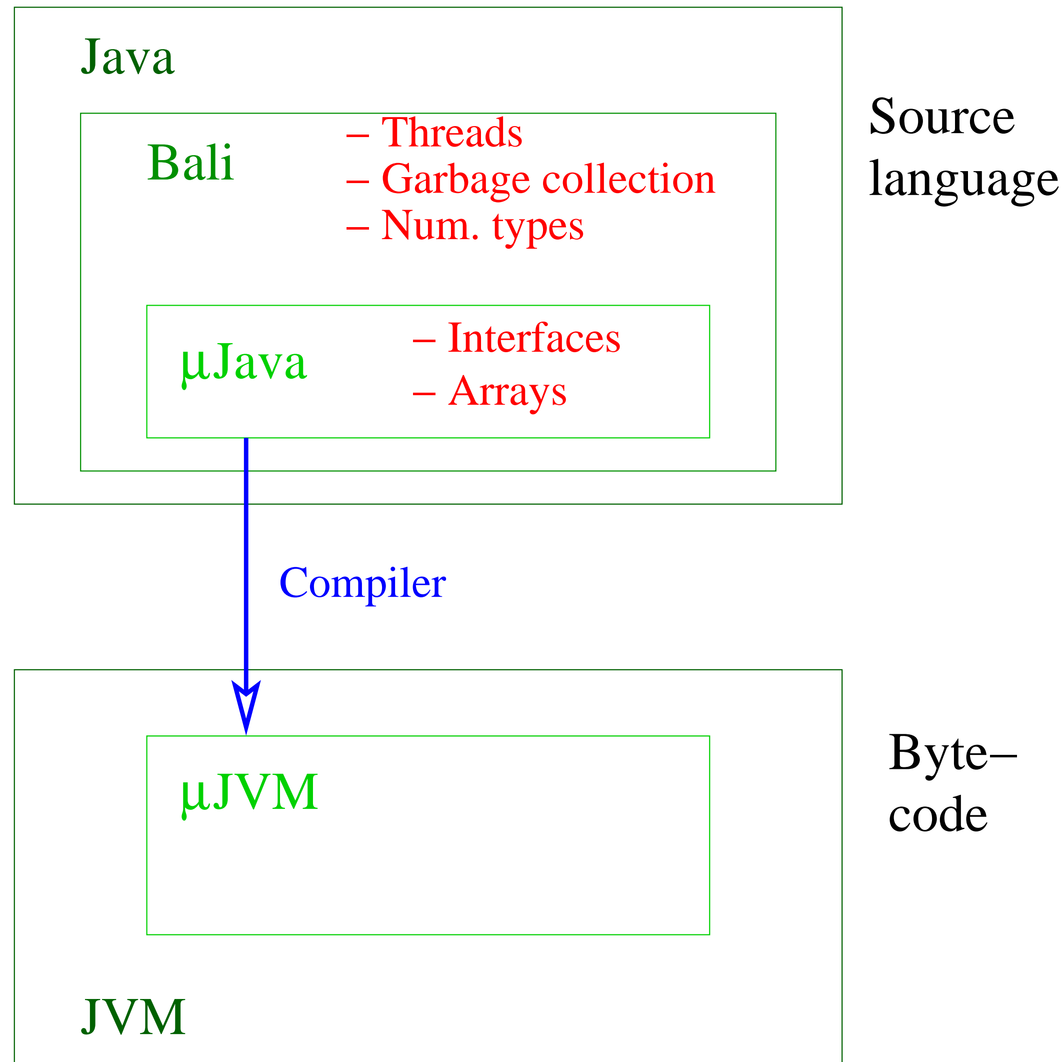
- Java:
  - Types, values, terms, ...
  - Typing and operational semantics
- JVM
- Compiler
  - Definition
  - Proof Techniques
- Compilation and Bytecode Verification

Java and Isabelle-Java



Java: Types, Values, Terms (1)

… defined as inductive data types:

Types:

datatype `prim_ty = Void | Boolean | Integer`

datatype *ref_ty* = `NullT | ClassT` *cname*

datatype *ty* = `PrimT` *prim_ty* | `RefT` *ref_ty*

Values:

datatype *val* = `Unit | Bool` *bool* | `Intg` *int* | `Null | Addr` *loc*

- No interfaces / arrays
- Only numeric type: `Integer`

Java: Types, Values, Terms (2)

Terms:

```
datatype expr = ...
        | NewC cname
        | vname ::= expr
        | {cname} expr . vname ::= expr
        | BinOp binop expr expr
        | {cname} expr . mname {(ty) list} (expr) list

datatype stmt = ...
        | Expr expr
        | If (expr) stmt Else stmt
        | Throw expr
```

Method Call: Annotation

$a_2 . m(a_3, c) \Longrightarrow \{A_2\}\ a_2 . m(\{[A_1, C]\}\ [a_3, c])$

Java: Methods, Classes, Programs

	Class name			
	Superclass name			
fdecl	vname	ty		
	...	...		
	...	...		
mdecl	mname	ty list	ty	java_mb
	...	...	...	...

java_mb $=$

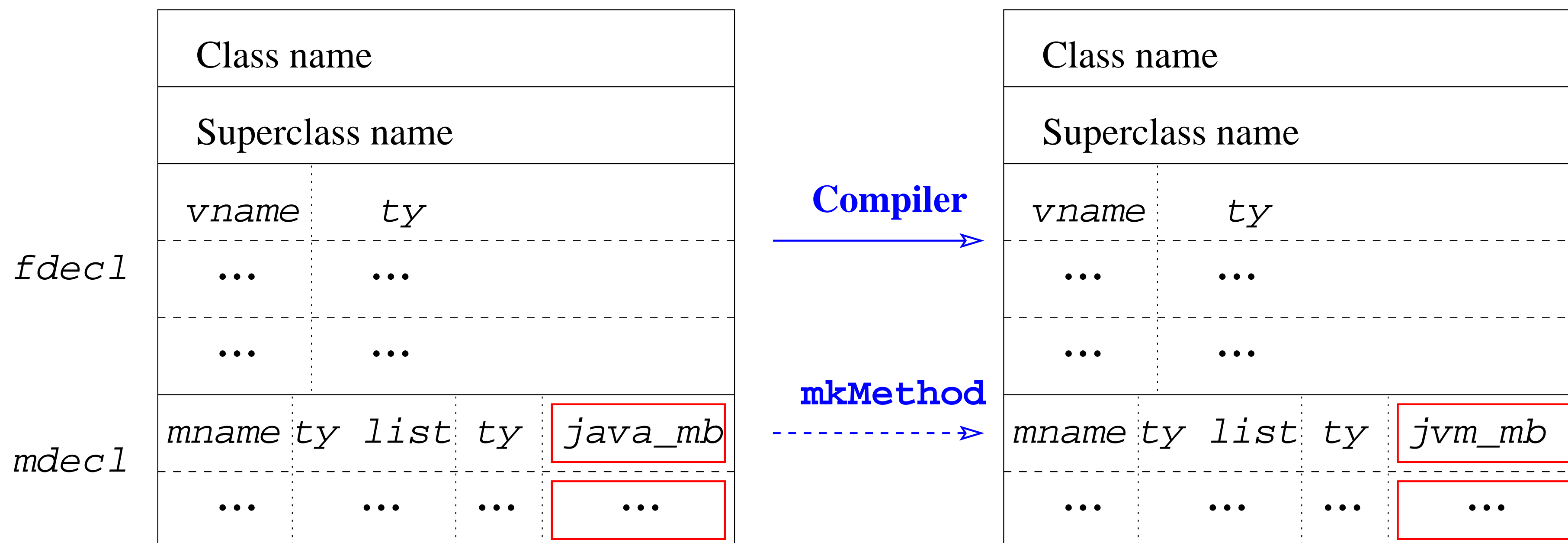
vname list $\times$ *(vname* $\times$ *ty) list*

$\times$ *stmt* $\times$ *expr*

mdecl $=$

mname $\times$ *ty list* $\times$ *ty* $\times$ *java_mb*

Java / JVM: Methods, Classes, Programs



$java_mb =$
$vname\ list \times (vname \times ty)\ list \times stmt \times expr$

$jvm_mb =$
$nat \times nat \times bytecode$

$'c\ mdecl = mname \times ty\ list \times ty \times\ 'c$
$'c\ cdecl = cname \times cname \times fdecl\ list \times\ 'c\ mdecl\ list$

Java: Typing

Inductively defined judgements

- Expressions: $E \vdash e ::_E T$
- Statements: $E \vdash s ::_S \sqrt{}$

with environment E: *java_mb env* $=$ *java_mb prog* $\times$ *lenv*

Java: Operational Semantics

State

σ : *xstate* $=$ *xcpt option* $\times$ *heap* $\times$ *locals*

Evaluation

- of expressions: $\Gamma \vdash (\sigma, e) \longrightarrow_E (v, \sigma')$

- of statements: $\Gamma \vdash (\sigma, s) \longrightarrow_S \sigma'$

with program Γ: *java_mb prog*

$\Longrightarrow$ big step ("natural") semantics

Type Safety

Evaluation transforms state σ *conforming* to E to state σ' again conforming to E.

JVM: Instructions

```
datatype instr
        = Load nat                  | Store nat
        | LitPush val               | New cname
        | Getfield vname cname      | Putfield vname cname
        | Checkcast cname
        | Invoke cname mname (ty list)
        | Return
        | Pop
        | Dup      | Dup_x1      | Dup_x2      | Swap
        | IAdd
        | Goto int     | Ifcmpeq int

bytecode = instr list
```

JVM: State and Operational Semantics

State

datatype $\mathit{jvm_state} = \mathit{xcpt\ option} \times \mathit{heap} \times \mathit{frame\ list}$
$\mathit{frame} = \mathit{opstack} \times \mathit{locvars} \times \mathit{cname} \times \mathit{sig} \times \mathit{nat}$

Operational Semantics

- One-step execution relation:

```
exec_instr (Load idx) G hp stk vars Cl sig pc frs =
      (None, hp, ((vars ! idx) # stk, vars, Cl, sig, pc+1)#frs)
```

- Execution `exec_all` as transitive closure

Compiler: Definition (1)

```
mkExpr  :: java_mb => expr => bytecode
mkStmt  :: java_mb => stmt => bytecode

mkExpr jmb (vn::=e) = mkExpr jmb e @ [Dup , Store (index jmb vn)]

mkExpr jmb ({cn}e1.mn {Ts}(ps)) =
      mkExpr jmb e1 @ mkExprs jmb ps @ [Invoke cn mn Ts]

mkStmt jmb (c1;; c2) = (mkStmt jmb c1) @ (mkStmt jmb c2)
```

Compiler: Definition (2)

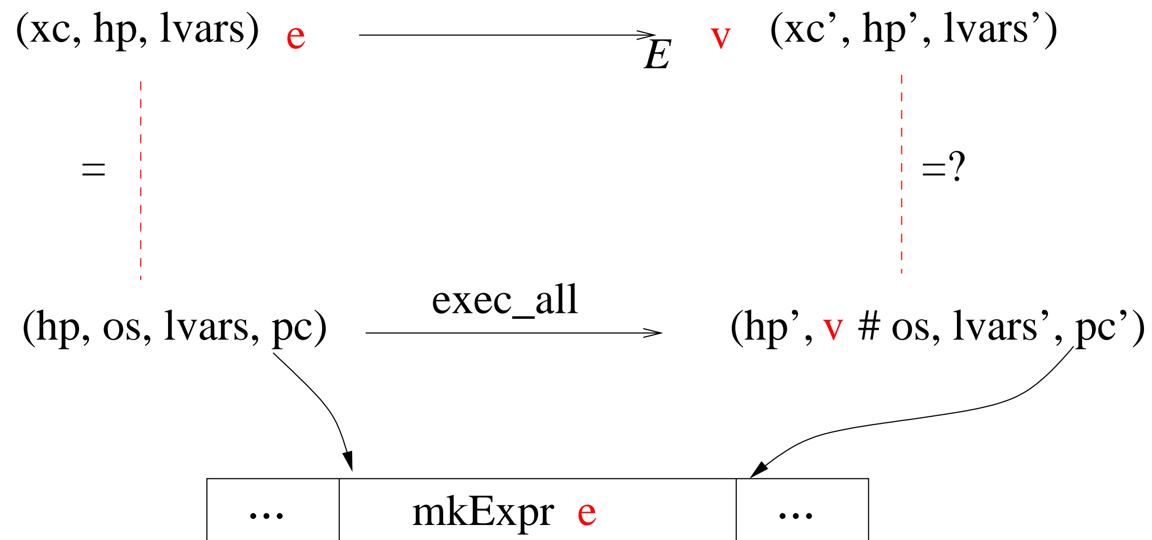
```
mkMethod :: java_mb => nat * nat * bytecode

mkMethod jmb == let (params,locals,blk,res) = jmb
                in (max_ssize jmb blk res,
                    length locals,
                    concat (map (mkInit jmb) locals) @
                    mkStmt jmb blk @ mkExpr jmb res @ [Return])
```

Compiler: Correctness Statement

Assumption (preliminary): No exceptions during evaluation

Correctness (for expressions):



Statements: similar

Verification: Preconditions

Remember: *Current environment* (Γ, Λ) given by:

- Current program Γ
- locals Λ of current method (identified by class C and signature S)

Preconditions:

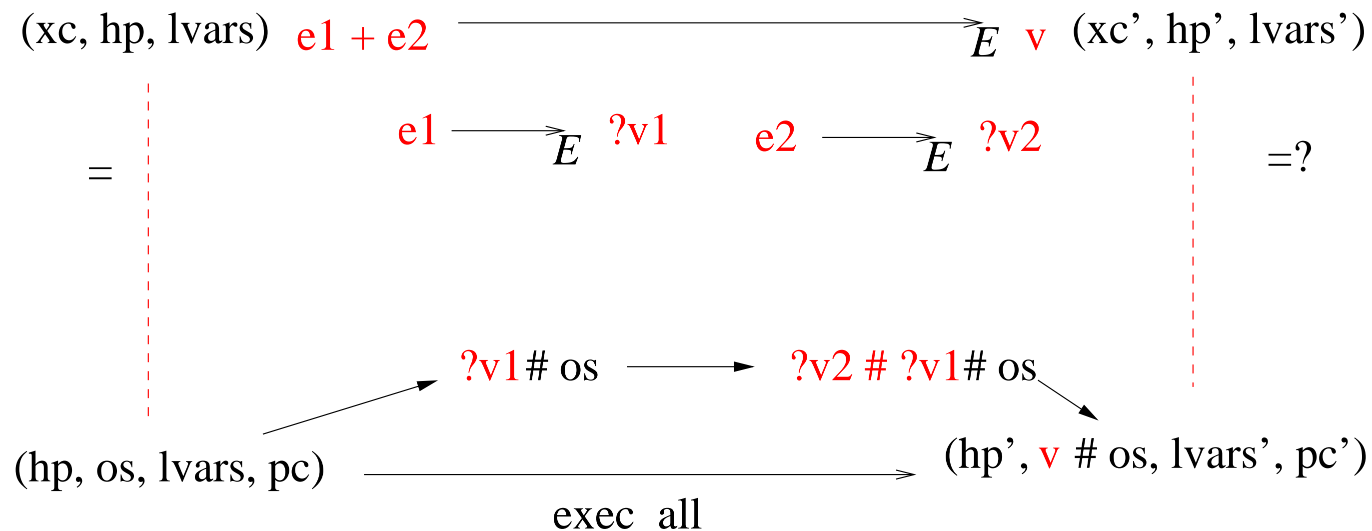
- Γ is well-formed
- C and S are defined in Γ
- State $(xc, hp, lvars)$ conforms to environment (Γ, Λ)
- Expression e is well-typed: $\exists T.(\Gamma, \Lambda) \vdash e ::_E T$

$\leadsto$ Correctness statement for "reasonable" programs only

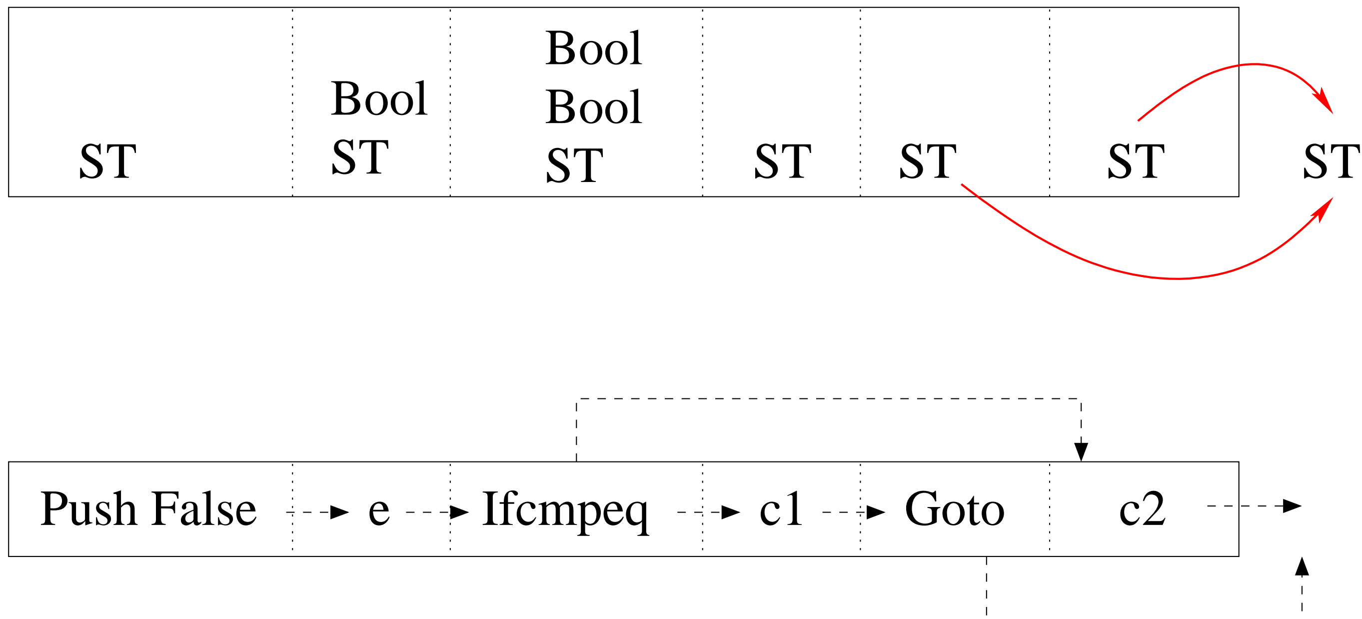
Proof Techniques

Proof: Induction over evaluation relation:

- Propagate assumptions, e.g.: conformance (requires Type Safety)
- Apply induction hypotheses
- Evaluate symbolically



Compilation and Bytecode Verification




```
mkStTpStmt  :: java_mb => stmt => statetype list
mkStmt      :: java_mb => stmt => bytecode
```

Summary

Formalization

- Contains most essentials, some details missing
- Few Isabelle specifics $\leadsto$ transferable to other environments

Compiler

- Translation of method bodies; no data refinements, no optimizations (which?)
- Object-orientation of minor importance
- Executable (extraction of ML code), easy to produce “real” class files
- Big step semantics leads to concise correctness statement

To do

- Integrate exceptions
- Compilation and bytecode verification
- Streamline proofs
- Tackle larger language fragments