# Type-State Analysis

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CIS 700 – Fall 2017

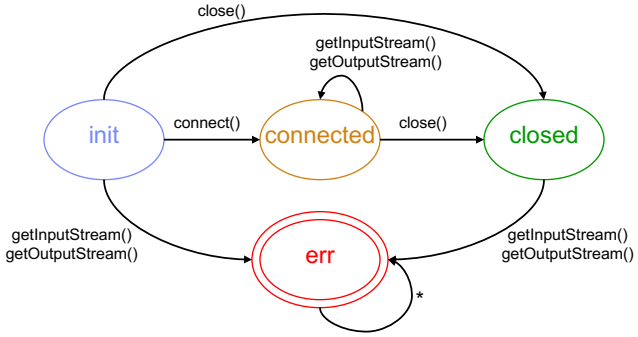
## Motivation

| Phase | Defect Removal Cost Multiplier |
|---|---|
| Requirements | 1 |
| Design | 3 |
| Code,Unit Test | 5 |
| Function/System Test | 12 |
| User Acceptance Test | 32 |
| Production | 95 |

# Typestate

- Application Trends
  - Increasing number of libraries and APIs
  - Non-trivial restrictions on permitted sequences of operations
- **Typestate:** Temporal safety properties, encoded as DFAs
- Apply to many libraries and APIs

  **e.g. "Don't use a Socket unless it is connected"**







# Goal

- **Typestate Verification: statically ensure that no execution of a Java program can transition to err**
  - Sound* (excluding concurrency)
  - Precise enough (reasonable number of false alarms)
  - Scalable
    - Handle programs of realistic size
    - Handle all Java features

* In the real world, some other caveats apply.

## Challenge: Aliasing

```
void foo(Socket s, Socket t) {
  s.connect();
  t.getInputStream(); // potential error?
}
```

- **Strong Updates may be required**
  - Rules out solely flow-insensitive analysis

```
void foo(Socket s, Socket t) {
  s.connect();        // s MUST point to connected
  t = s;              // t MUST point to connected
  t.getInputStream();
}
```




## Difficulties

```
class SocketHolder {  Socket s;  }
Socket makeSocket() { return new Socket(); // A }
open(Socket l) {
   l.connect();
}
talk(Socket s) {
  s.getOutputStream()).write("hello");
}
dispose(Socket s) { h.s.close(); }
main() {
  Set<SocketHolder> set = new HashSet<SocketHolder>();
  while(…) {
     SocketHolder h = new SocketHolder();
     h.s = makeSocket();
     set.add(h)
  } ;
  for (Iterator<SocketHolder> it = set.iterator(); …) {
     Socket g = it.next().s;
     open(g);
     talk(g);
     dispose(g);
  }
}
```

- **Flow-Sensitivity**
- **Interprocedural flow**
- **Context-Sensitivity**
- **Non-trivial Aliasing**
  - Destructive updates
- Path Sensitivity (ESP)
- Full Java Language
  - Exceptions, Reflection, ….
- Big programs

## Our Approach

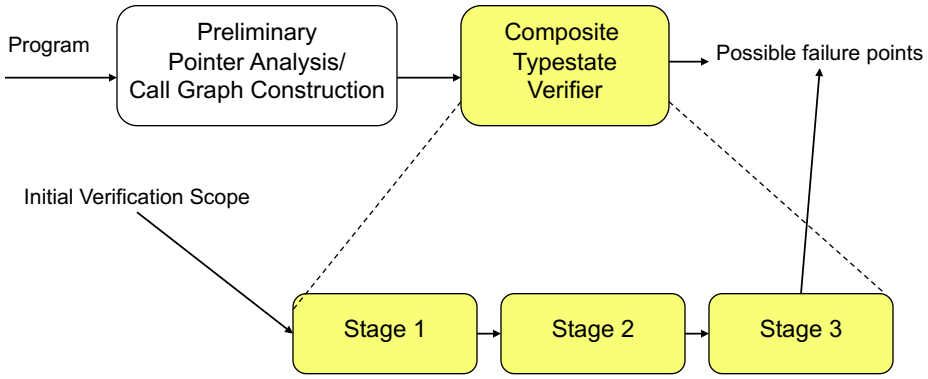
- **Flow-sensitive, context-sensitive abstract interpretation**
  - Abstract domains combine typestate and points-to
  - Techniques for inexpensive strong updates
    - *Uniqueness*
    - *Focus*
- **Staging**
  - Family of abstractions of varying cost/precision
  - Early stages reduce work for latter stages




## Why this is cool

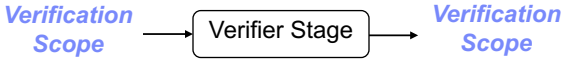
- **Nifty abstractions**
  - Combined domain
    - More precise than 2-stage approach
    - Concentrate expensive effort where it matters
  - Parameterized hierarchy of abstractions
  - Relatively inexpensive techniques that allow precise aliasing
    - Much cheaper than shape analysis
    - More precise than usual “scalable” analyses
- **It works pretty well**
  - Techniques are complementary
  - Flow-sensitive functional IPA with sophisticated alias analysis on ~100KLOC in 20 mins.
    - Overapproximate inexpensive facts (distributive)
    - Underapproximate expensive facts (non-distributive)
  - <5% false warnings

## Analysis Overview










- Sound, abstract representation of program state
- Flow-sensitive propagation of abstract state
- Context-sensitive: *functional approach to interprocedural analysis* [Sharir-Pneuli 82]
  - Tabulation Solver [Reps-Horwitz-Sagiv 95]
- ***Hierarchy of abstractions***

Base Abstraction

***AS := { < Abstract Object, TypeState> }***

- **Two-Stage Approach**
  - First alias analysis, then typestate analysis
- ***Abstract Object*** := heap partition from preliminary pointer analysis
  - e.g. allocation site
- **Transfer functions**
  - Straightforward from instrumented concrete semantics
  - Rely on preliminary pointer analysis to determine typestate transitions
  - **No Strong Updates**
    - ***{< I, T>} → { <I, T>, <I, δ(T)> }***
- **Works sometimes (75%)**




Base Abstraction

"Don't write to a closed PrintWriter"

*It works in some cases:*
- Simple abstraction
- Flow-sensitive, context-sensitive solver

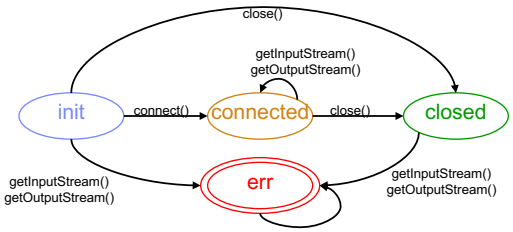

```
writeTo(PrintWriter w) { w.write(…); }
```
<P, open>, <Q,open>, <Q, closed>, <Q, ERR>
<P, open>, <Q,open>, <Q, closed>, ~~<Q, ERR>~~ ✓

```
main() {
  PrintWriter p = new PrintWriter(…); // P
  PrintWriter q = new PrintWriter(..); // Q
  q.close();
  writeTo(q);
  writeTo(p);
  if (?) {
    p.close();
  else {
    writeTo(p);
    p.close();
  }
}
```
<P, open>
<P, open>, <Q,open>
<P, open>, <Q,open>, <Q, closed>
<P, open>, <Q,open>, <Q, closed>, <Q, ERR>
<P, open>, <Q,open>, <Q, closed>, <Q, ERR>
<P, open>, <P,closed>, <Q, closed>, <Q,open>, <Q, ERR>
<P, open>, <Q,open>, <Q, closed>, <Q, ERR> ✓
<P, open>, <P, closed>, <Q,open>, <Q, closed>, <Q, ERR>

Base Abstraction

*Useless* for ***properties which require strong updates***

**"Don't use a Socket unless it is connected"**




```
open(Socket s) { s.connect();}
talk(Socket s) {
  s.getOutputStream()).write("hello"); }
dispose(Socket s) { s.close(); }
main() {
  Socket s = new Socket(); //S
  open(s);
  talk(s);
  dispose(s);
}
```

*<S, init>*

*<S, init> , <S, connected>*

*<S, init> , <S, connected>, <S, err>* ✗



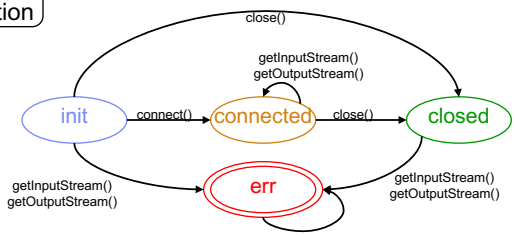

Unique Abstraction

***AS := { < Abstract Object, TypeState, Unique> }***

- **Transfer functions: Base Abstraction +**
  - **Unique := true (U)** when *creating* factoid at allocation site
  - **Unique := false (¬U)** when *propagating* factoid *through* an allocation site
- **Intuition: "Unique" ≈ "∃ exactly one concrete instance of abstract object"**
- **Strong Updates allowed for *e.op()* when**
  - Unique
  - *e* may point to exactly one abstract object
- **Works sometimes (80%)**

Unique Abstraction

***Strong updates***




```
open(Socket s) { s.connect();}
talk(Socket s) { s.getOutputStream()).write("hello"); }
dispose(Socket s) { s.close(); }
main() {
  Socket s = new Socket(); //S
  open(s);
  talk(s);
  dispose(s);
}
```

*<S, init, U>*

*<S, connected, U>*

*<S, connected, U>* ✓




Unique Abstraction

***More than just singletons?***

```
open(Socket s) { s.connect();}
talk(Socket s) { s.getOutputStream()).write("hello"); }
dispose(Socket s) { s.close(); }
main() {
  while (…) {
    Socket s = new Socket(); //S
    open(s);
    talk(s);
    dispose(s);
  }
}
```

*<S, closed, U>*

*<S, init, U>* *<S, closed, ¬U>* *<S, init, ¬U >*

*<S, connected, U>* *<S, closed, ¬U>* *<S, init, ¬U >* *<S, connected, ¬U>*

*<S, connected, U>* *<S, err, ¬U>* ✗ ….

*<S, closed, U>*

Live analysis to the rescue

- Preliminary live analysis oracle
- On-the-fly remove unreachable configurations

Unique Abstraction

***What about aliasing?***

```
class SocketHolder {Socket s; }
Socket makeSocket() { return new Socket(); // A }
open(Socket s) {
  s.connect();
}
talk(Socket s) {
  s.getOutputStream()).write("hello");
}
dispose(Socket s) { h.s.close(); }
main() {
  while(…) {
     SocketHolder h = new SocketHolder();
     h.s = makeSocket();
     Socket s = makeSocket();
     open(h.s);
     talk(h.s);
     dispose(h.s);
     open(s);
     talk(s);
  }
}
```

*<A, init, U>*
*<A, init , ¬U >*
*<A, init, ¬U > <A, connected, ¬U >*
*<A, err, ¬U> × ….*




Access Path Must Abstraction

***AS := { < Abstract Object, TypeState, Unique, Must, May> }***

- Unique Abstraction +
  - *Must :=* **set of symbolic access paths (x.f.g….) that *must* point to the object**
  - *May :=* **false iff *all* possible access paths appear in *Must* set**
- Flow functions
  - **Only track access paths to "interesting" objects**
    - Limits computational work dramatically
    - Less precise than shape analysis
  - **Always sound to discard Must set and set May := true**
    - Allows k-limiting. Crucial for scalability.
  - **Parameters**
    - *Width*: maximum cardinality of *Must* Set
    - *Depth*: maximum length of an individual access path
    - "*interesting" objects*: which objects to track precisely
      - currently: typestate objects
  - **Typestate transition for *e.op()* if ($e \in Must$) $\vee$ ($May \wedge mayPointTo(e,l)$)**
  - **Strong Updates**
    - allowed for ***e.op()*** when $e \in Must$ or unique logic allows it
- Works sometimes (91%)

Access Path Must Abstraction

***Better aliasing!***

```
class SocketHolder {Socket s; }
Socket makeSocket() { return new Socket(); // A }
init(Socket t) {
  t.connect();
}
talk(Socket u) {
  u.getOutputStream()).write("hello");
}
dispose(Socket s) { h.s.close(); }
main() {
  while(…) {
     SocketHolder h = new SocketHolder();
     h.s = makeSocket();
     Socket s = makeSocket();
     init(h.s);
     talk(h.s);
     dispose(h.s);
     init(s);
     talk(s);
  }
}
```

*<A, init , ¬U, {h.s, t}, ¬May> <A, init, ¬U, {s}, ¬May >*

*<A, connected , ¬U, {h.s, t}, ¬May> <A, init, ¬U, {s}, ¬May >*

*<A, connected , ¬U, {h.s, u}, ¬May> <A, init, ¬U, {s}, ¬May >*

*<A, connected , ¬U, {h.s, u}, ¬May>* ✔ *…*

*<A, init, U, {h.s}, ¬May>*

*<A, init , ¬U, {h.s}, ¬May> <A, init, ¬U, {s}, ¬May >*

*<A, connected , ¬U, {h.s}, ¬May> <A, init, ¬U, {s}, ¬May >*




***What about destructive updates?***

Access Path Must Abstraction

```
class SocketHolder {  Socket s;  }
Socket makeSocket() { return new Socket(); // A }
open(Socket l) {
   l.connect();
}
talk(Socket s) { s.getOutputStream()).write("hello"); }
dispose(Socket s) { h.s.close(); }
main() {
  Set<SocketHolder> set = new HashSet<SocketHolder>();
  while(…) {
     SocketHolder h = new SocketHolder();
     h.s = makeSocket();
     set.add(h);
  } ;
  for (Iterator<SocketHolder> it = set.iterator(); …) {
     Socket g = it.next().s;
     open(g);
     talk(g);
     dispose(g);
  }
}
```

*<A, init, U, {h.s}, ¬May>*

*<A, init , U, {h.s}, May>*

*<A, init, ¬U, {}, May >*

*<A, init, ¬U, {}, May >, <A, connected, ¬U, {}, May >*

***<A, err, ¬U, {}, May > …***

Access Path Focus Abstraction

***AS := { < Abstract Object, TypeState, Unique, Must, May, MustNot> }***

- **Access Path Must Abstraction +**
  - ***MustNot* :=** set of symbolic access paths that *must not* point to the object
- **Flow functions**
  - **Focus** operation when "interesting" things happen
    - "materialization", "focus", "case splitting"
    - ***e.op()* on < *A, T, u, Must, May, MustNot*>, generate 2 factoids:**
      - ***< A, δ(T), u, Must U {e}, May, MustNot>***
      - ***< A, T, u, Must, May, MustNot U {e} >***
    - Interesting Operations
      - Typestate changes
      - Observable polymorphic dispatch
    - Allows k-limiting. Crucial for scalability
    - Allowed to limit exponential blowup due to focus
      - Current heuristic: discard *MustNot* before each focus operation
- **Works sometimes (95.6%)**




Access Path Focus Abstraction

***Recover from destructive updates***

```
class SocketHolder {  Socket s;  }
Socket makeSocket() { return new Socket(); // A }
open(Socket t) {
   t.connect();
}
talk(Socket s) {
  s.getOutputStream()).write("hello");
}
dispose(Socket s) { h.s.close(); }
main() {
  Set<SocketHolder> set = new HashSet<SocketHolder>();
  while(…) {
     SocketHolder h = new SocketHolder();
     h.s = makeSocket();
     set.add(h);
  }
  for (Iterator<SocketHolder> it = set.iterator(); …) {
     Socket g = it.next().s;
     open(g);
     talk(g);
     dispose(g);
  }
}
```

*<A, init, ¬U, {}, May, {} >*

*<A, init, ¬U, {}, May, {¬t} >, <A, connected, ¬U, {t}, May, {}>*

*<A, init, ¬U, {}, May, {¬g,¬s}>, <A, connected, ¬U, {g,s}, May, {}>* ✓

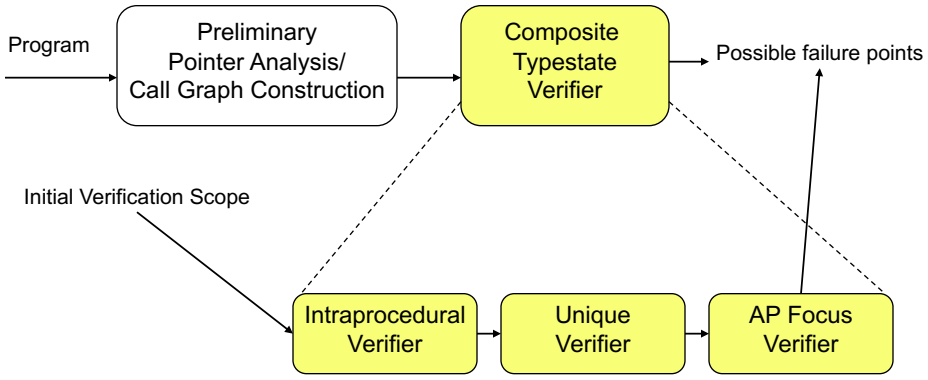
*<A, init, U, {h.s}, ¬May, {}>*

*<A, init, U, {h.s}, May, {}>*

*<A, init, ¬U, {}, May, {}>*

*<A, init, ¬U, {}, May, {¬g}>, <A, connected, ¬U, {g}, May, {}>*

## Analysis Overview

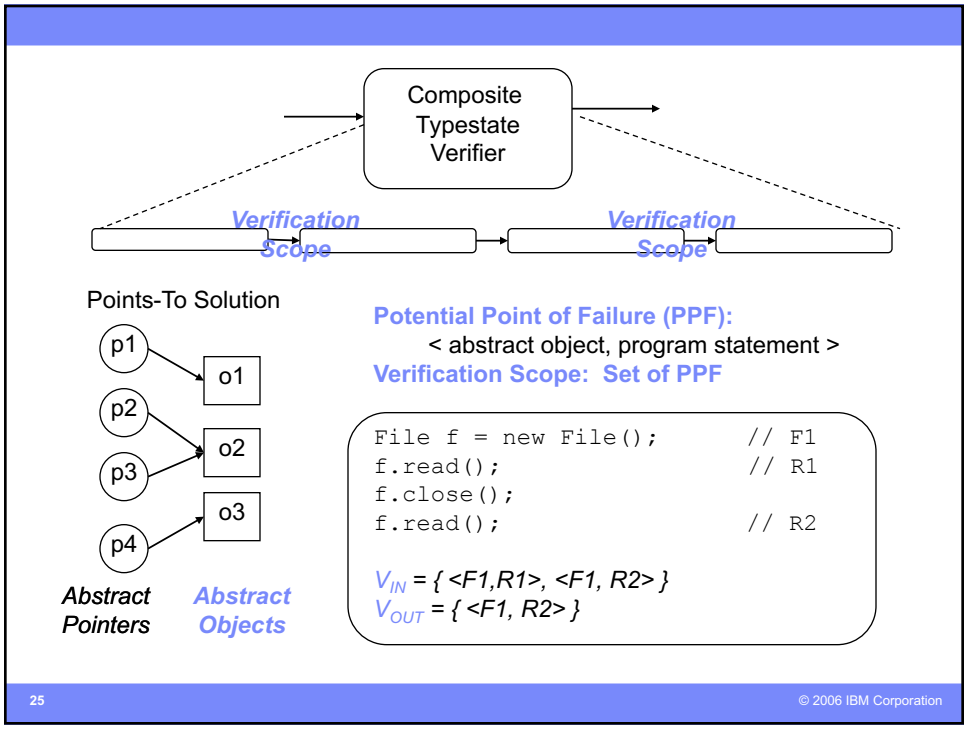






## Intraprocedural Verifier

- **Single-procedure version of Access Path Focus abstraction**
- **Worst-case assumptions at method entry, calls**
  - Mitigated by live analysis
- **Works sometimes (66%)**


Composite
Typestate
Verifier
Verification
Scope
Verification
Scope
Points-To Solution
p1
p2
p3
p4
o1
o2
o3
Abstract
Pointers
Abstract
Objects
Potential Point of Failure (PPF):
< abstract object, program statement >
Verification Scope: Set of PPF
File f = new File(); // F1
f.read(); // R1
f.close();
f.read(); // R2
V_IN = { <F1,R1>, <F1, R2> }
V_OUT = { <F1, R2> }
25
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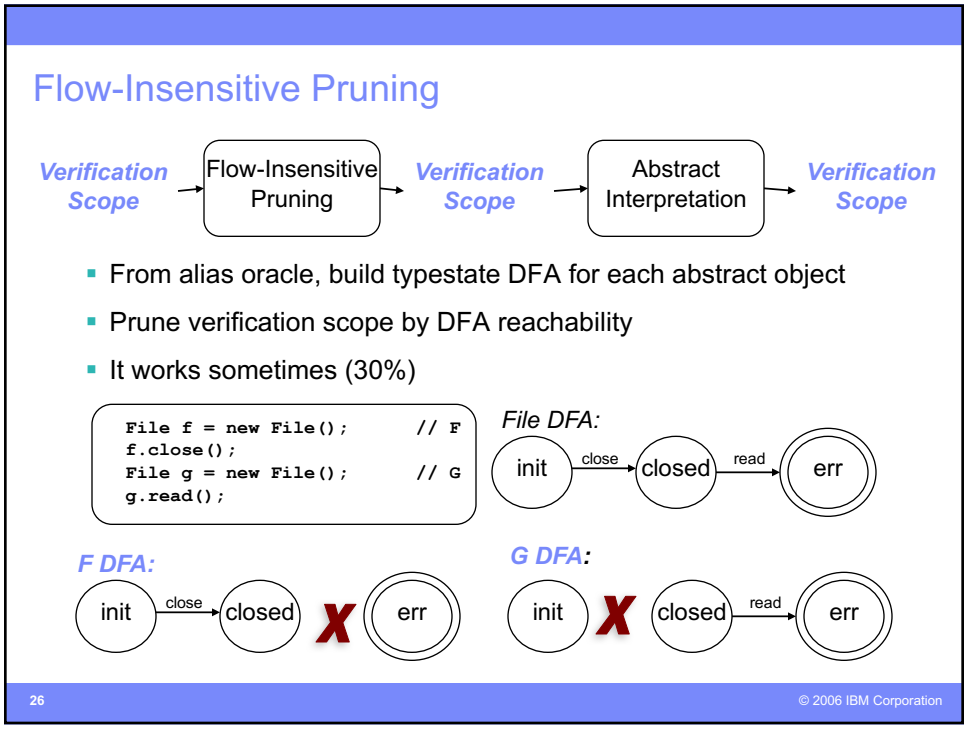
Flow-Insensitive Pruning
Verification Scope
Flow-Insensitive Pruning
Verification Scope
Abstract Interpretation
Verification Scope
From alias oracle, build typestate DFA for each abstract object
Prune verification scope by DFA reachability
It works sometimes (30%)
File f = new File(); // F
f.close();
File g = new File(); // G
g.read();
File DFA:
init
close
closed
read
err
F DFA:
init
close
closed
err
G DFA:
init
closed
read
err
26
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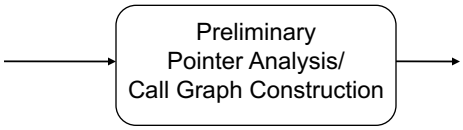
## Sparsification

- **Separation (solve for each abstract object separately)**
- **"Slicing": discard branches of supergraph that cannot affect abstract semantics**
  - Identify program variables that might appear k-limited access path
    - K-step reachability from typestate objects from prelim. pointer analysis
  - Identify call graph nodes that might
    - modify these variables
    - cause typestate transitions (depends on incoming verification scope)
  - Discard any nodes that cannot (transitively) affect abstract interpretation
  - **Reduces median supergraph size by 50X**



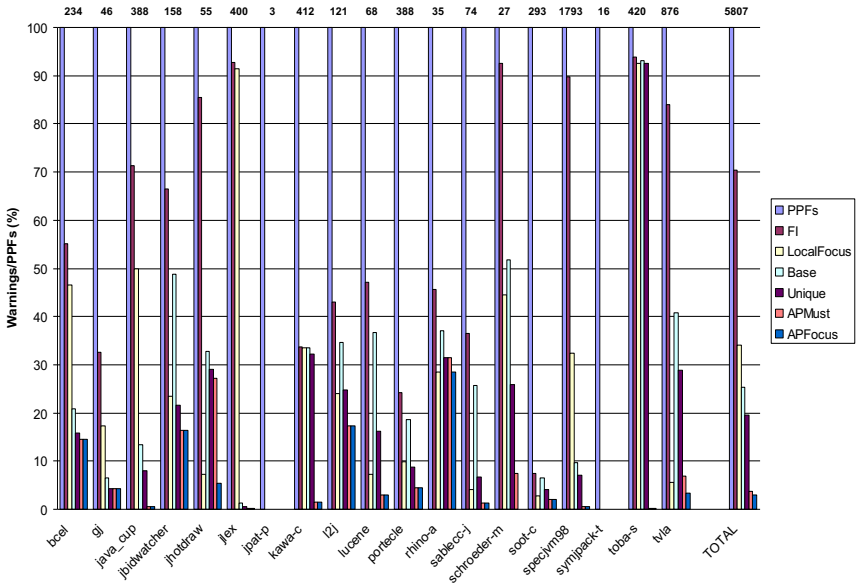

- Typestate verifiers rely on **call graph, fallback alias oracle**
- Current implementation: flow-insensitive, partially context-sensitive pointer-analysis
  - Subset-based, field-sensitive Andersen's
  - SSA local representation
  - On-the-fly call graph construction
  - Unlimited object sensitivity for
    - Collections
    - Containers of typestate objects (e.g. IOStreams)
  - One-level call-string context for some library methods
    - Arraycopy, clone, …
  - Heuristics for reflection (e.g. Livshits et al 2005)
- Details matter a lot
  - e.g. context-insensitive preliminary: later stages time out, terrible precision

## Typestate Properties for J2SE libraries

| Name | Description |
|---|---|
| **Enumeration** | Call `hasNextElement` before `nextElement` |
| **InputStream** | Do not read from a closed `InputStream` |
| **Iterator** | Do not call `next` without first checking `hasNext` |
| **KeyStore** | Always initialize a `KeyStore` before using it |
| **PrintStream** | Do not use a closed `PrintStream` |
| **PrintWriter** | Do not use a closed `PrintWriter` |
| **Signature** | Follow initialization phases for `Signature` |
| **Socket** | Do not use a `Socket` until it is connected |
| **Stack** | Do not peek or pop an empty `Stack` |
| **URLConn** | Illegal operation performed when already connected |
| **Vector** | Do not access elements of an empty `Vector` |

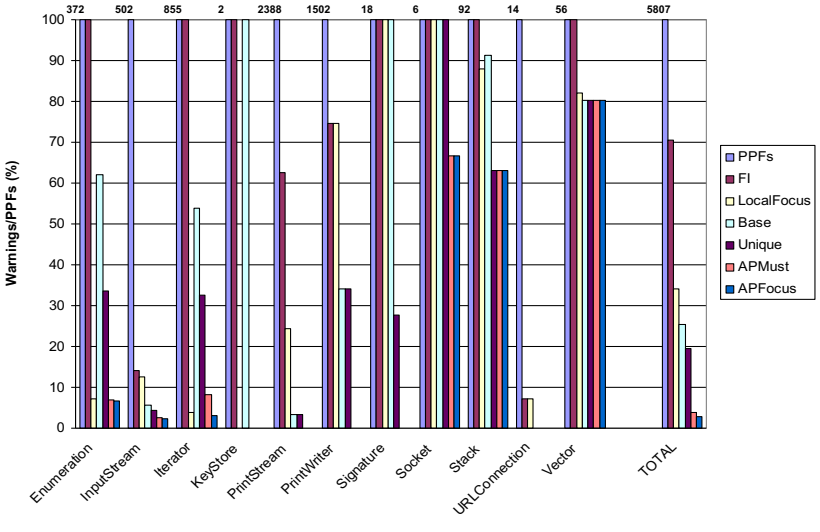



| Benchmark | Classes | Methods | Bytecode Statements | Contexts |
|---|---|---|---|---|
| **bcel** | 1,723 | 7,130 | 1,474,264 | 13,725 |
| **gj** | 230 | 2,362 | 139,305 | 2,521 |
| **java_cup** | 123 | 661 | 53,296 | 990 |
| **jbidwatcher** | 1,182 | 4,994 | 1,029,507 | 7,030 |
| **jhotdraw** | 1,688 | 6,337 | 1,400,640 | 11,203 |
| **jlex** | 111 | 473 | 44,736 | 776 |
| **jpat-p** | 64 | 225 | 17,783 | 269 |
| **kawa-c** | 612 | 3,027 | 141,527 | 3,438 |
| **l2j** | 838 | 4,247 | 877,077 | 6,438 |
| **lucene** | 1,783 | 6,694 | 1,474,334 | 12,576 |
| **portecle** | 1,800 | 6,737 | 1,481,249 | 13,430 |
| **rhino-a** | 196 | 1,293 | 92,225 | 1,645 |
| **sablecc-j** | 391 | 2,144 | 96,201 | 2,747 |
| **schroeder-m** | 1,459 | 5,215 | 1,367,432 | 9,682 |
| **soot-c** | 665 | 2,764 | 144,554 | 3,272 |
| **specjvm98** | 965 | 4,673 | 979,159 | 8,152 |
| **symjpack-t** | 74 | 305 | 80,508 | 351 |
| **toba-s** | 163 | 760 | 65,415 | 1,169 |
| **tvla** | 346 | 2,077 | 139,474 | 12,874 |

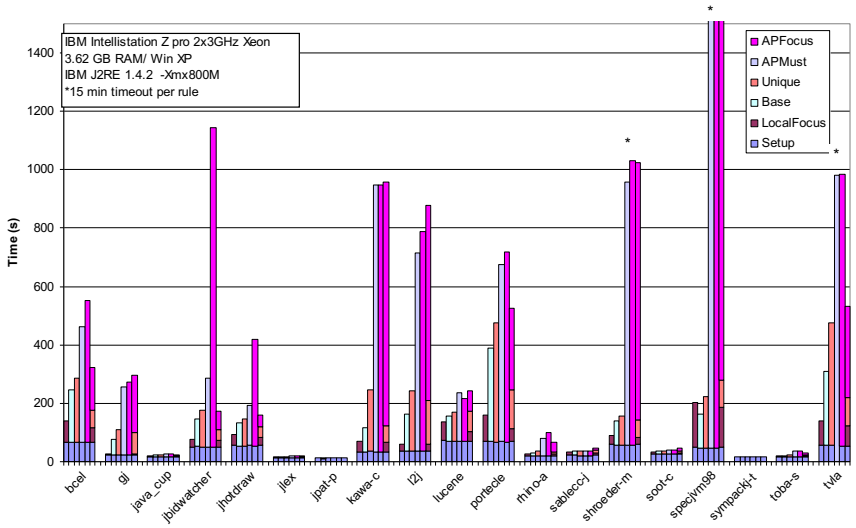








## Running time







## Limitations

- **Limitations of analysis (~50%)**
  - Aliasing
  - Path sensitivity
  - Return values

```
if (!stack.isEmpty()) stack.pop();
vector.get(vector.size()-1);
```

Not always straightforward (encapsulation)

```
if (!foo.isAnEmptyFoo()) foo.popFromAStack();
```

- **Limitations of typestate abstraction (~50%)**
  - Application logic bypasses DFA, still OK

```
if (itsABlueMoon) stack.pop();
vector.get(numberOfPixels/2);
try {
   emptyStack.pop();
catch (EmptyStackException e) {
   System.out.println("I expected that.");
}
```

## Some related work

- **ESP**
  - Das *et al.* PLDI 2002
    - Two-phase approach to aliasing (unsound strong updates)
    - Path-sensitivity ("property simulation")
  - Dor *et al.* ISSTA 2004
    - Integrated typestate and alias analysis
    - Tracks overapproximation of *May* aliases
- **Type Systems**
  - Vault/Fugue
    - Deline and Fähndrich:`adoption` and `focus`
  - CQUAL
    - Foster *et al.* 02: linear types
    - Aiken *et al.* 03: `restrict` and `confine`
- **Alias Analysis**
  - Landi-Ryder 92, Choi-Burke-Carini 93, Emami-Ghiya-Hendren 95, Wilson-Lam 95, ….
  - Shape Analysis: Chase-Wegman-Zadeck 90, Hacket-Rugina 05, TVLA (Sagiv-Reps-Wilhelm), …