Refactoring for Reentrancy

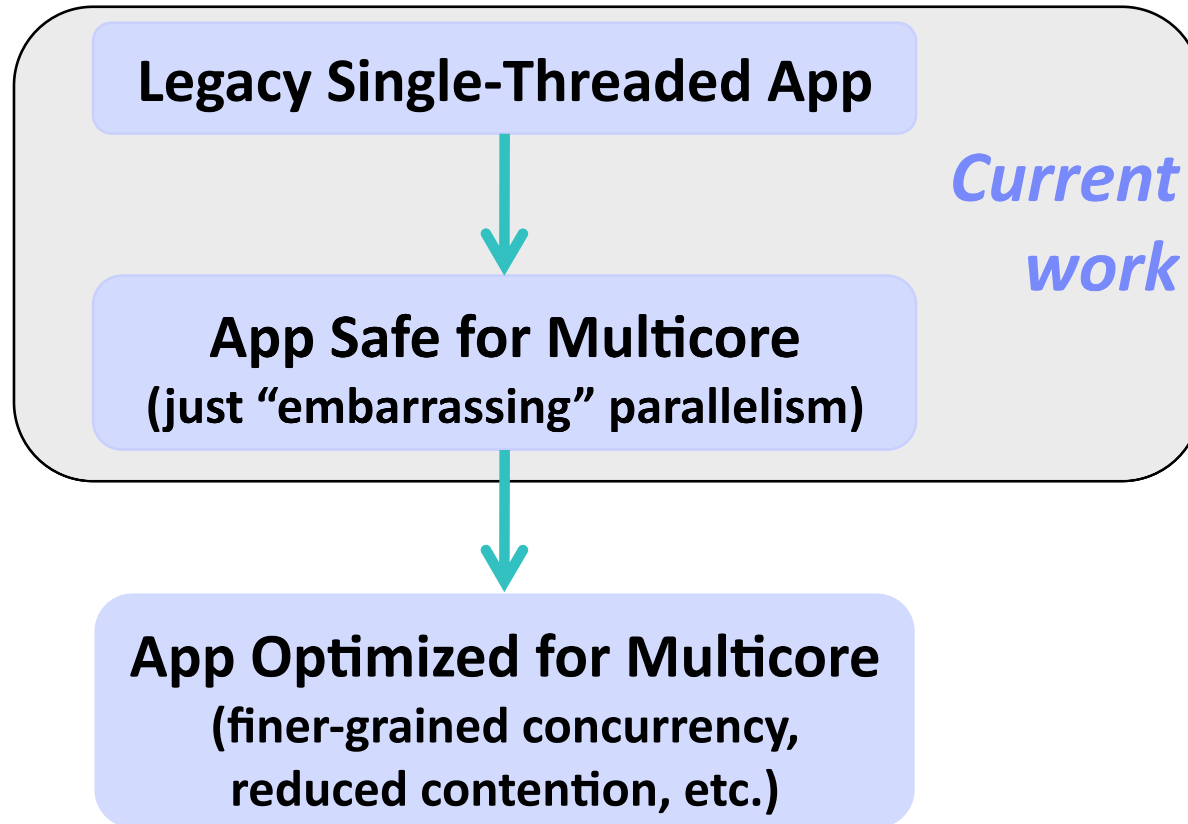
Jan Wloka
IBM Rational

Manu Sridharan, Frank Tip
IBM Research

ESEC / FSE 2009

© 2009 IBM Corporation

Vision: A Migration Path to Multicores



Correctness before performance

© 2009 IBM Corporation

Challenge: Lack of Reentrancy

Definition of reentrant program

distinct program executions do not affect each other, sequentially or concurrently

Mutable global state the key barrier to reentrancy

© 2009 IBM Corporation

Running Example of Non-Reentrancy

Mutable global state

```
class Config {
  static final Map conInfo = new HashMap();
  static void setOption(String name, String value) {
    conInfo.put(name, value);
  }
  static String getOption(String name) {
    return conInfo.get(name);
  }
}

test1() { Config.setOption("foo", "bar"); … }
test2() { assert Config.getOption("foo") == null; … }
```

Problem: `test2` fails if run after `test1`, but passes if run alone

Race conditions on `conInfo` if tests run in parallel

© 2009 IBM Corporation

Existing Approaches to Reentrancy

Approach # 1: **get rid of mutable global state**

- A possible solution for new projects
- But, for existing code, too intrusive and hard to automate

Approach # 2: **separate OS processes / classloaders**

- Strong isolation between executions
- But, further optimization difficult (e.g., adding shared state)

© 2009 IBM Corporation

Our Approach: Thread-Local State

Idea: Replace all mutable globals with thread-local variables

- Implicit per-thread copy of each variable
- Available on most threading platforms (Java, pthreads, etc.)

Result: code is reentrant if executions run in fresh threads

Key advantage: ***enables local optimizations***

- Selectively replace thread locals with shared state + locking
- ***Correctness before performance***

Challenge: ***handling real-world language / programs***

- In particular, initialization and library usage

© 2009 IBM Corporation

Contributions

Reentrancer Design

- **Goal**: *practical tool for real-world programs*
- Mostly automated
- Targets Java, but applicable to other languages

Reentrancer Implementation and Evaluation

- Runs on *realistic benchmarks* (up to 83 KLOC)
- Fixed observed reentrancy issues
- Enabled parallel speedup for 3 of 5 benchmarks

© 2009 IBM Corporation

Reentrancer Phases

1. **Check preconditions**
   a) Detect potential violations **(automatic)**
   b) Inspect / fix warnings **(manual)**
2. **Make code reentrant (automatic)**
   a) Encapsulate mutable global state
   b) Introduce lazy initialization
   c) Introduce thread locals
3. **Create fresh thread per execution (manual)**

© 2009 IBM Corporation

Preconditions 1: Static Initialization

Issue: thread locals must be initialized as globals were

Challenge: initializers can have complex and fragile behavior

```
class A { static final int x = B.y + 1; }

class B { static final int y = A.x + 2; }
```

Solution: change to **explicit lazy initialization**

- Makes thread-local introduction a separate, simple phase
- *Not* behavior preserving for “fragile” dependences like above
- Precondition check warns if behavior may change
  - Indicates badness in general

© 2009 IBM Corporation

Preconditions 2: Library Usage

Issue: Library usage can break reentrancy (e.g., file I/O)

Challenges

1. Cannot refactor library code
2. Hard to detect all non-reentrant library routines

Solution: **warn about calls to blacklisted methods**

- **Doesn't require expensive whole-program analysis**
- Catches most common cases
- Always double-check with test suite!

© 2009 IBM Corporation

Running Example

```
class Config {
  private static final Map conInfo = new HashMap();
  private static final String versionStr = “2.0”;
  static {
    conInfo.put(“version”, versionStr);
  }
  static void setOption(String name, String value) {
    System.out.println(name + “:” + value);
    conInfo.put(name, value);
  }
  static String getOption(String name) {
    return conInfo.get(name);
  }
}
```


© 2009 IBM Corporation

Step 1(a): Detect Violations (automatic)

```
class Config {
  private static final Map conInfo = new HashMap();
  private static final String versionStr = “2.0”;
  static {
    conInfo.put(“version”, versionStr);
  }
  static void setOption(String name, String value) {
    System.out.println(name + “:” + value);
    conInfo.put(name, value);
  }
  static String getOption(String name) {
    return conInfo.get(name);
  }
}
```


© 2009 IBM Corporation

Step 1(b): Fix Warnings (manual)

```
class Config {
  private static final Map conInfo = new HashMap();
  private static final String versionStr = “2.0”;
  static {
    conInfo.put(“version”, versionStr);
  }
  static void setOption(String name, String value) {
    // System.out.println(name + “:” + value);
    conInfo.put(name, value);
  }
  static String getOption(String name) {
    return conInfo.get(name);
  }
}
```


© 2009 IBM Corporation

Step 2(a): Encapsulate Mutable Globals (automatic)

```
class Config {
  private static final Map conInfo = new HashMap();
  private static final String versionStr = “2.0”;
  static {
    conInfo.put(“version”, versionStr);
  }
  static void setOption(String name, String value) {
    conInfo.put(name, value);
  }
  static String getOption(String name) {
    return conInfo.get(name);
  }
}
```


© 2009 IBM Corporation

Step 2(a): Encapsulate Mutable Globals (automatic)

```
class Config {
  private static final Map conInfo = new HashMap();
  private static final String versionStr = “2.0”;
  static Map getConInfo() {
    return conInfo;
  }
  static {
    getConInfo().put(“version”, versionStr);
  }
  static void setOption(String name, String value) {
    getConInfo().put(name, value);
  }
  static String getOption(String name) {
    return getConInfo().get(name);
  }
}
```


© 2009 IBM Corporation

On Mutability

If state is immutable, no need to transform

Immutable means deeply immutable [Tschantz&Ernst, OOPSLA05]

- all abstract state of object
- `final` is not enough

Simple type-based analysis to detect immutability

© 2009 IBM Corporation

Step 2(b): Introduce Lazy Initialization (automatic)

```
class Config {
  private static Map conInfo = new HashMap();
  private static final String versionStr = “2.0”;
  static Map getConInfo() {
    return conInfo;
  }
  static {
    getConInfo().put(“version”, versionStr);
  }
  …
```


© 2009 IBM Corporation

Step 2(b): Introduce Lazy Initialization (automatic)

```
class Config {
  private static Map conInfo;
  private static final String versionStr = “2.0”;
  static Map getConInfo() {
    lazyInit(); return conInfo;
  }
  static boolean initRun = false;
  static void lazyInit() {
    if (!initRun) {
      initRun = true;
      conInfo = new HashMap();
      getConInfo().put(“version”, versionStr);
    }
  } …
```


© 2009 IBM Corporation

Step 2(c): Introduce Thread Locals (automatic)

```
class Config {
  private static Map conInfo;
  private static final String versionStr = “2.0”;
  static Map getConInfo() {
    lazyInit(); return conInfo;
  }
  static boolean initRun = false;
  static void lazyInit() {
    if (!initRun) {
      initRun = true;
      conInfo = new HashMap();
      getConInfo().put(“version”, versionStr);
    }
  } …
```


© 2009 IBM Corporation

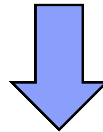
Step 2(c): Introduce Thread Locals (automatic)

```
class Config {
  static ThreadLocal<Map> conInfo = new ThreadLocal<Map>();
  private static final String versionStr = “2.0”;
  static Map getConInfo() {
    lazyInit(); return conInfo.get();
  }
  static ThreadLocal<Boolean> initRun =
                       new ThreadLocal<Boolean>();
  static void lazyInit() {
    if (!initRun.get()) {
      initRun.set(true);
      conInfo.set(new HashMap());
      getConInfo().put(“version”, versionStr);
    }
  } …
}
```


© 2009 IBM Corporation

Step 3: Create Fresh Thread per Execution (manual)

```
test1() { Config.setOption("foo", "bar"); … }
test2() { assert Config.getOption("foo") == null; … }
```



```
test1() {
  runInFreshThread(new Runnable() { public void run() {
    Config.setOption("foo", "bar"); …
  } });
}
test2() {
  runInFreshThread(new Runnable() { public void run() {
    assert Config.getOption("foo") == null; …
  } });
}
```


© 2009 IBM Corporation

Experiments: Implementation

Precondition Checker

- Built on WALA (http://wala.sf.net)
- Emits warnings for violations

Code Refactoring

- Extension to Eclipse JDT
- Handles many Java corner cases (interface fields, boxing/unboxing)

© 2009 IBM Corporation

Experiments: Methodology

Five single-threaded benchmarks, up to 83 KLOC

For each benchmark:

1. Establish reentrancy problem(s)
2. Inspect / fix precondition check warnings
3. Run refactoring
4. Ensure test suite passes
5. Ensure reentrancy problem(s) fixed
6. Measure performance

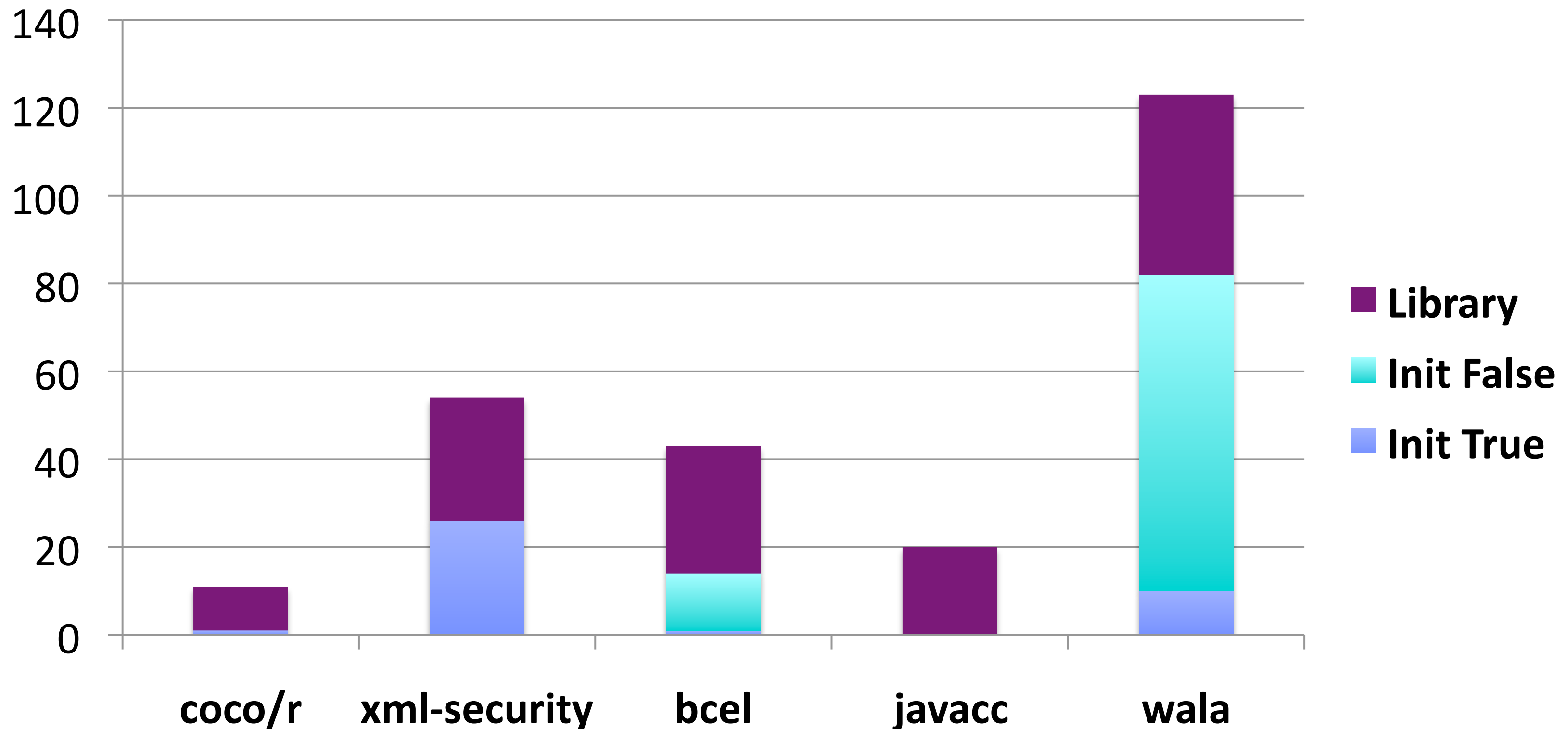
© 2009 IBM Corporation

Experiments: Key Questions

1. Precondition violations
   a) How many?
   b) How many false positives?
2. How much code is changed by refactoring?
3. Performance of running test suite
   a) Before vs. after on one core?
   b) Before vs. after on two cores?

© 2009 IBM Corporation

Results: Precondition Violation Warnings

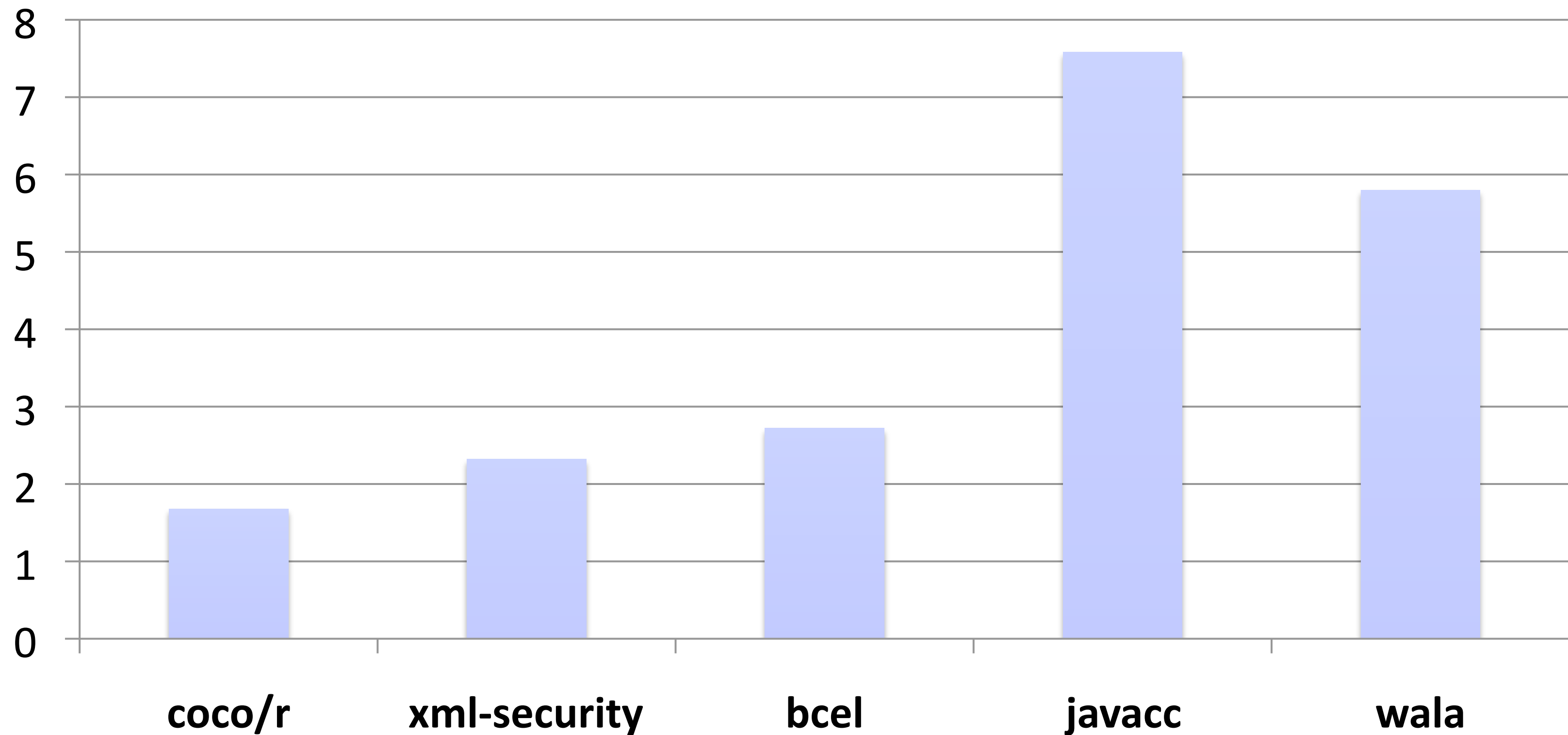


False positives due to <u>weak immutability inference</u>

Most warnings benign

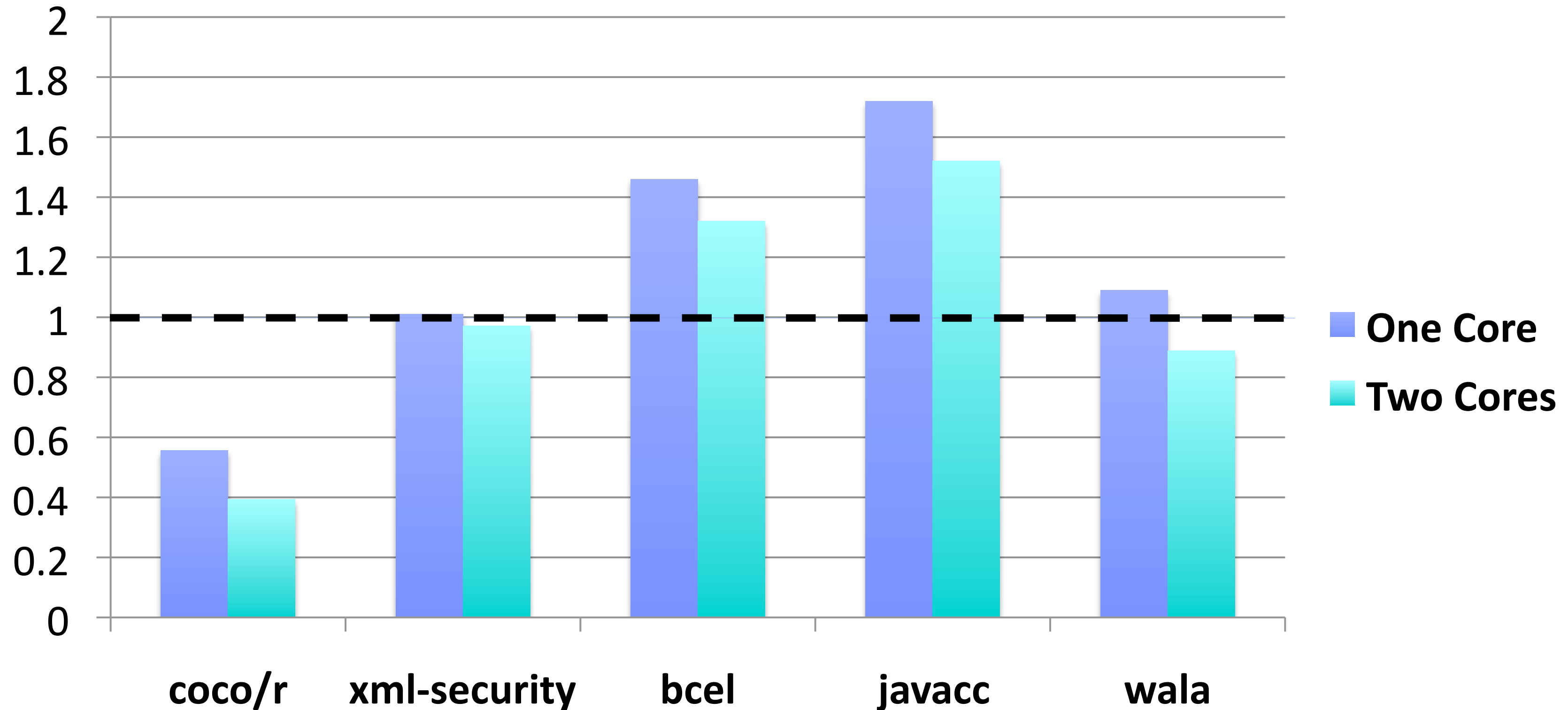
© 2009 IBM Corporation

Results: Code Churn



© 2009 IBM Corporation

Results: Test Suite Runtime After Refactoring



<u>Parallel speedup</u> for 3 of 5 benchmarks

coco/r anomaly: removed fresh class loaders

© 2009 IBM Corporation

Related Work

Refactoring to `java.util.concurrent` [DME09]

Cilk++ hyperobjects [FHLL09]

Java immutability [TE05,ZPAAKE07,QTE08]

© 2009 IBM Corporation

Conclusions

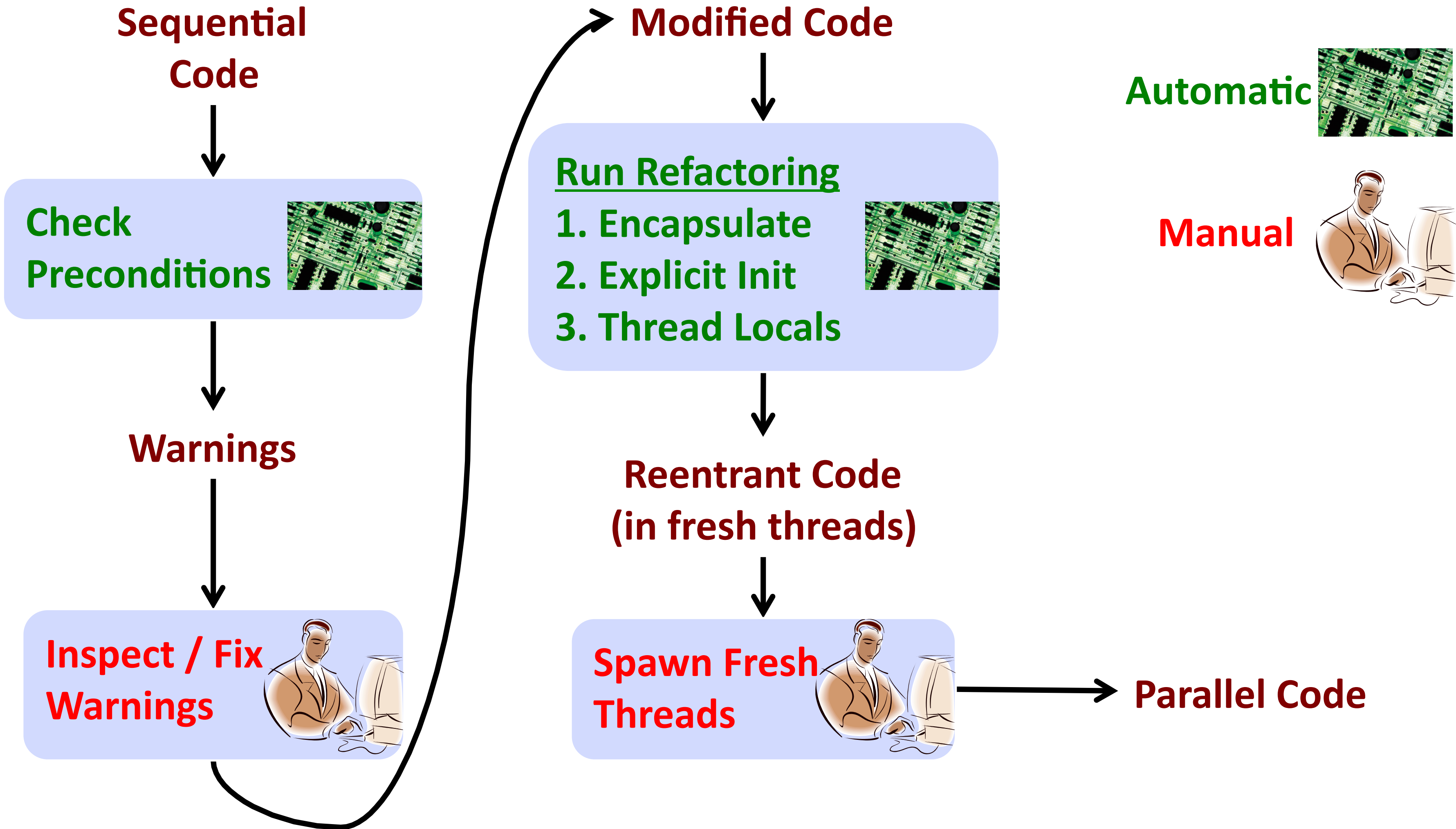
- Reentrancy via **changing globals to thread-locals**
  - **Correctness before performance**
- Prototype implementation works and enables parallel speedups
- Future work
  - Better immutability inference
  - More incremental workflow

© 2009 IBM Corporation

Thanks!

© 2009 IBM Corporation

Reentrancer Steps



© 2009 IBM Corporation

Future Work

- Better immutability inference (e.g., for arrays)
- More performance evaluation
  - Test manual optimizations
  - Run on more processors
- Better workflow
  - Right now, all code transformed at once
  - Need more incremental transformation with previews, etc.

© 2009 IBM Corporation