Prescient Memory: Exposing Weak Memory Model Behavior by Looking into the Future

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Parallel Programming is Hard

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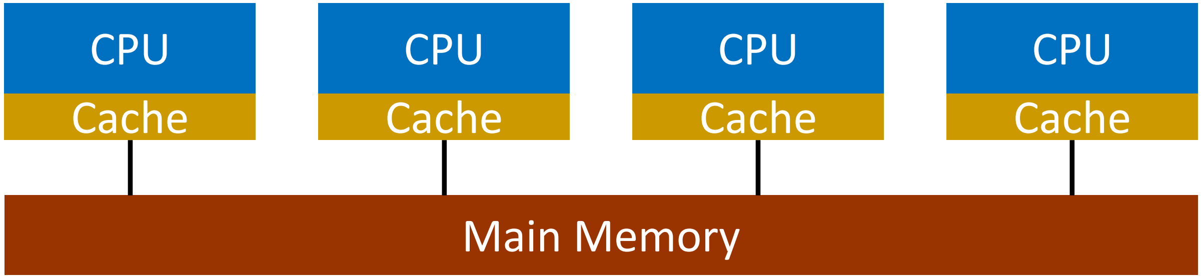
- Shared-memory



Parallel Programming is Hard

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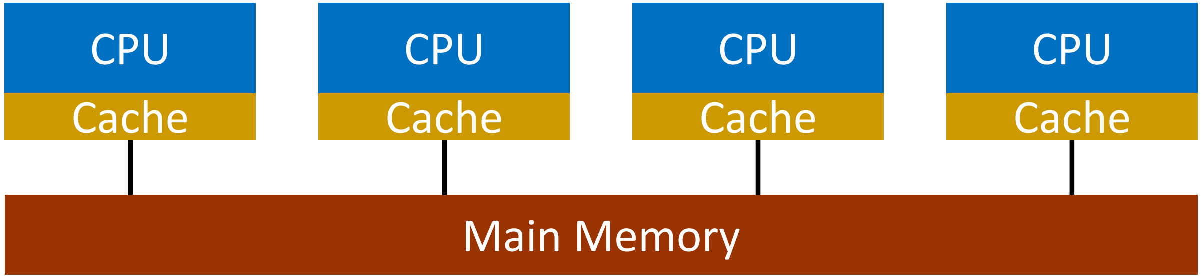
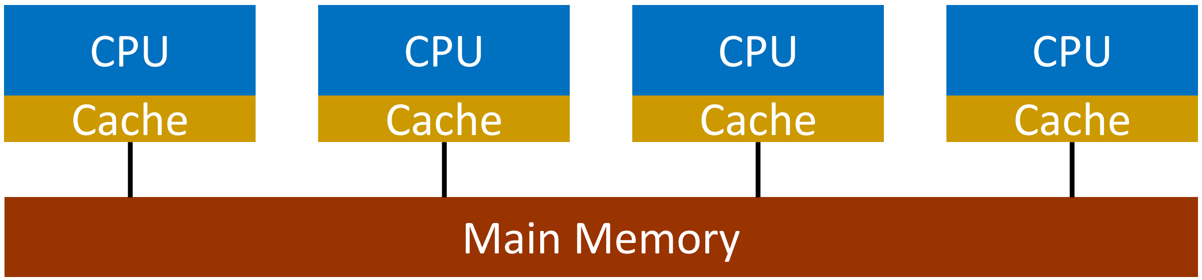


- Difficult to be both correct and scalable

Parallel Programming is Hard

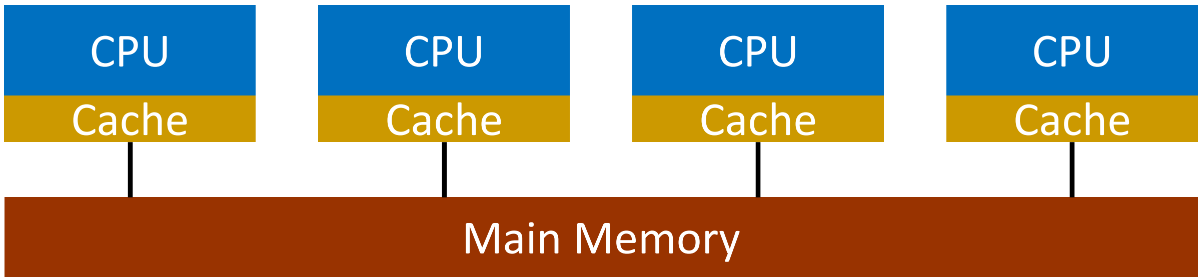
- Shared-memory



- Difficult to be both correct and scalable
  - Data race

Parallel Programming is Hard

- Shared-memory



- Difficult to be both correct and scalable
  - Data race
    - Fundamentally, lacks strong semantic guarantees

Example #1: Weak Semantics

```
Foo data = null;
boolean flag= false;
```

T1

```
data = new Foo();
flag = true;
```

T2

```
if (flag)
  data.bar();
```

Example #1: Weak Semantics

```
Foo data = null;
boolean flag= false;
```

T1

```
data = new Foo();
flag = true;
```

T2

```
if (flag)
  data.bar();
```

Null pointer exception!

Example #1: Weak Semantics

```
Foo data = null;
boolean flag= false;
```

T1

No data dependence

```
data = new Foo();
flag = true;
```

T2

```
if (flag)
  data.bar();
```

Null pointer exception!

Exposing Behaviors of Data Races

- Existing Approaches
  - Dynamic analyses
  - Model checkers

Exposing Behaviors of Data Races

- Existing Approaches
  - Dynamic analyses
    - \- Limitation: coverage
  - Model checkers
    - \- Limitation: scalability

Exposing Behaviors of Data Races

- Existing Approaches
  - Dynamic analyses
    - Limitation: coverage
  - Model checkers
    - Limitation: scalability

- Prescient Memory (PM)

Dynamic analysis with better coverage

Outline

- Memory Models and Behaviors of Data Races
- Design
  - Prescient Memory (PM)
  - PM-profiler
  - PM Workflow
- Evaluation

Memory Model

- Defines possible values that a load can return

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Strong

- Sequential Consistency (SC)
- Impractical to enforce

Memory Model

- Defines possible values that a load can return

Strong

- Sequential Consistency (SC)
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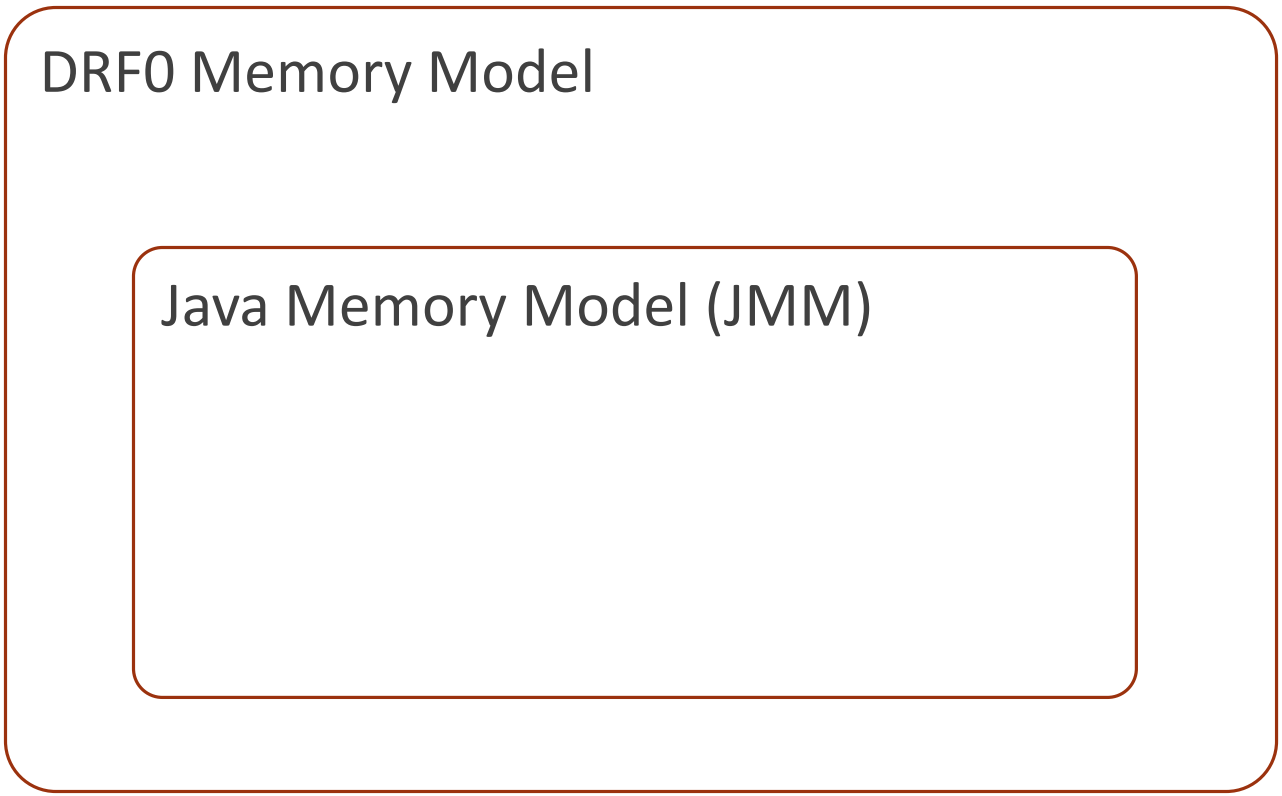
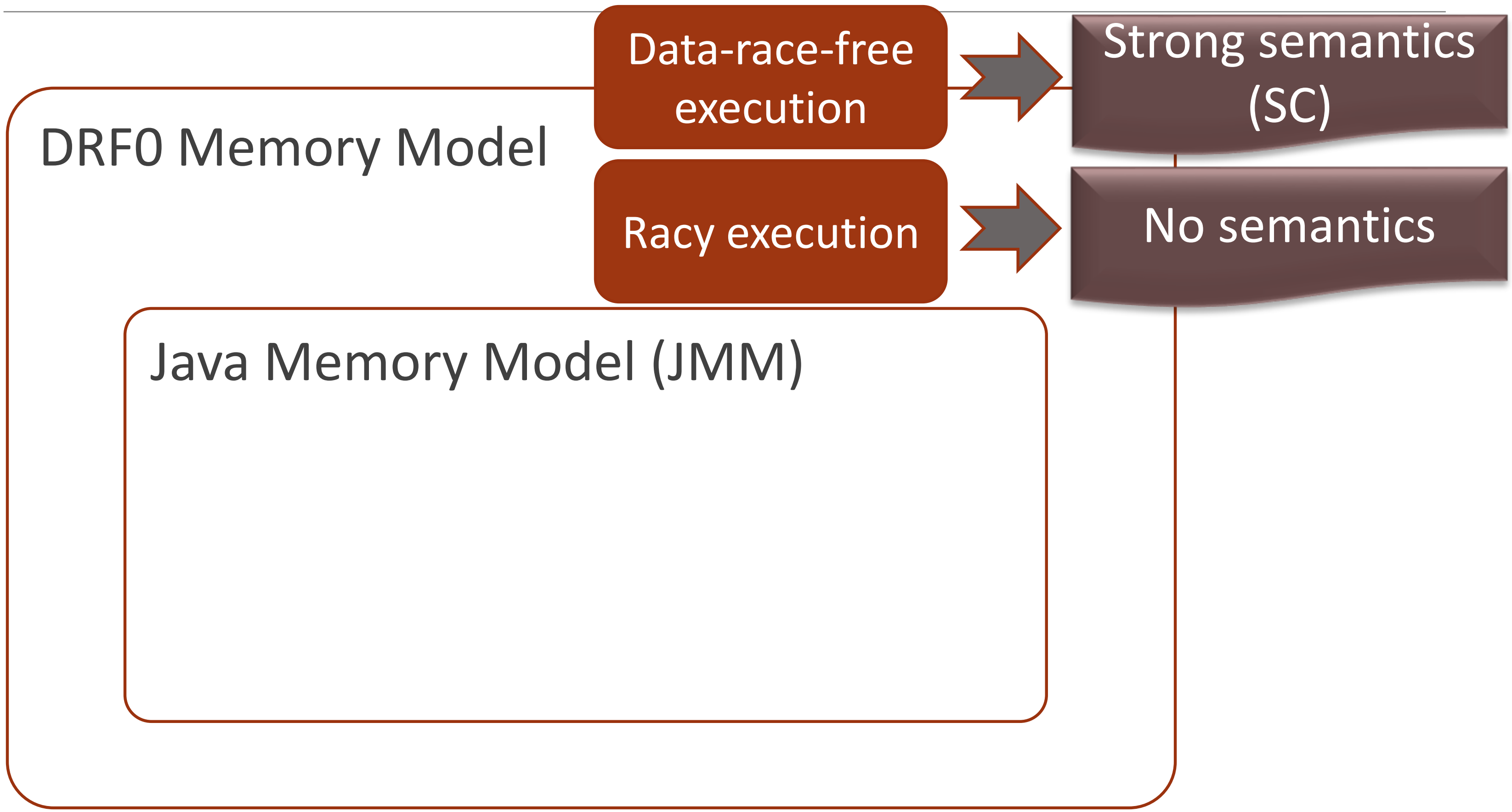
Weak

- Enables compiler & hardware optimizations
- DRF0, C++11, Java

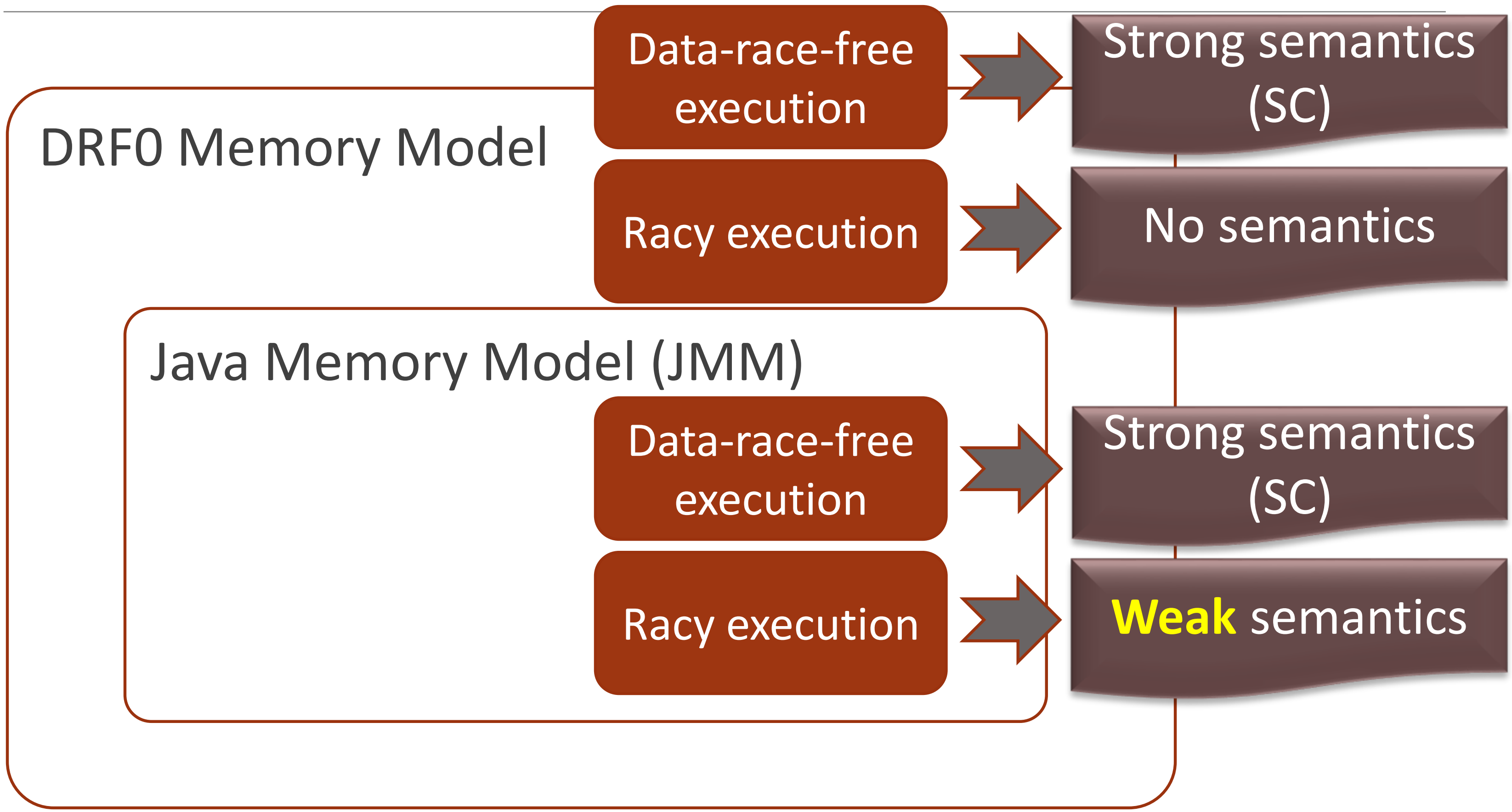
Behaviors Allowed by Memory Models



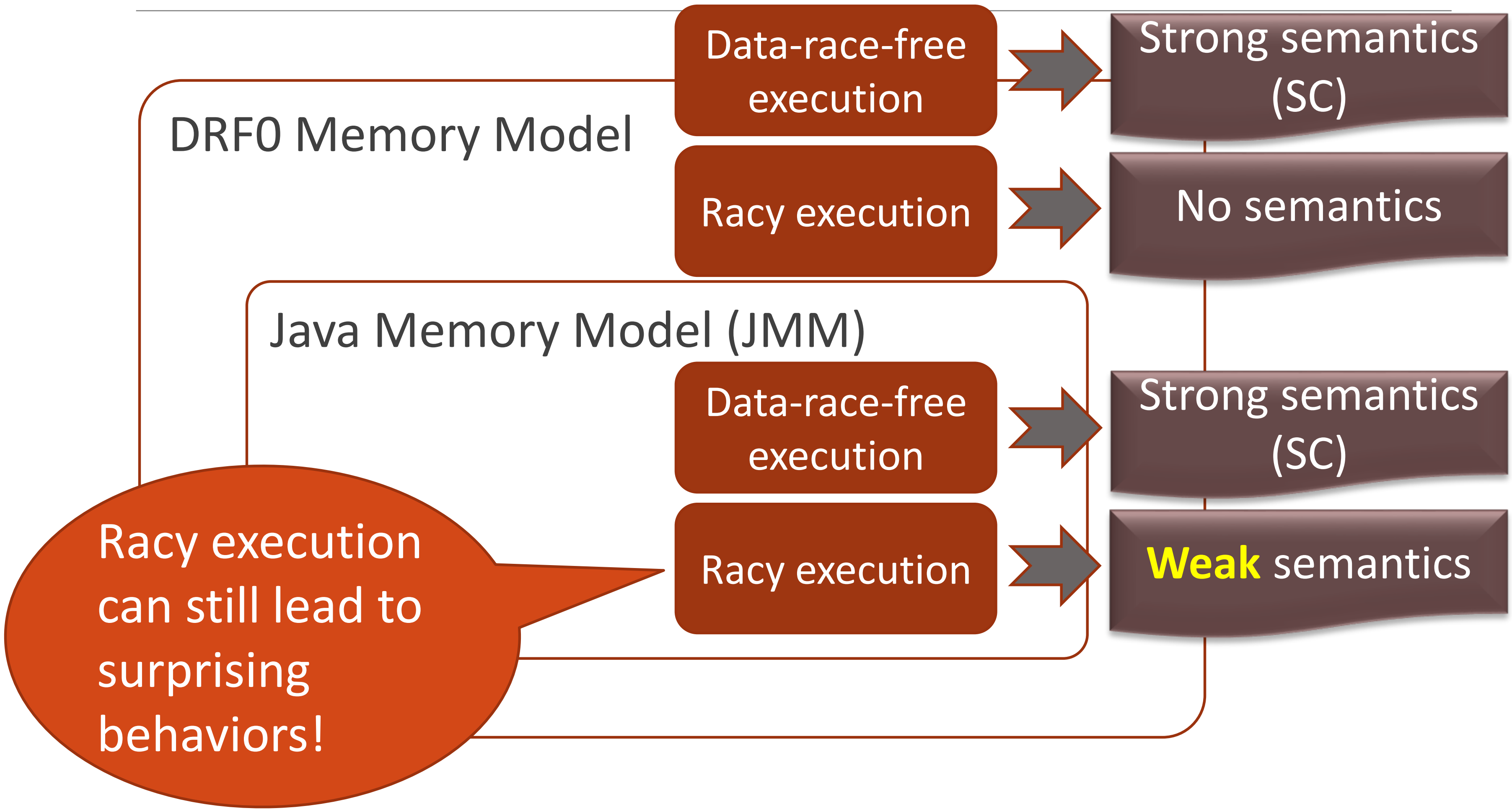
Behaviors Allowed by Memory Models



Behaviors Allowed by Memory Models



Behaviors Allowed by Memory Models



Behaviors Allowed in JMM #1: Revisit

```
Foo data = null;
boolean flag= false;
```

T1

```
data = new Foo();
flag = true;
```

T2

```
if (flag)
  data.bar();
```

Behaviors Allowed in JMM #1: Revisit

```
Foo data = null;
boolean flag= false;
```

T1

```
data = new Foo();
flag = true;
```

T2

```
if (flag)
  data.bar();
```

stale value

latest value

Behaviors Allowed in JMM #1: Revisit

```
Foo data = null;
boolean flag= false;
```

T1

```
data = new Foo();
flag = true;
```

T2

```
if (flag)
  data.bar();
```

stale value

latest value

Null pointer exception!

Behaviors Allowed in JMM #1: Revisit

```
Foo data = null;
boolean flag= false;
```

T1

```
data = new Foo();
flag = true;
```

T2

```
if (flag)
  data.bar();
```

Returning stale value can trigger the exception

Behaviors Allowed in JMM #2

int data = flag = 0;

T1

```
r = data;
flag = 1;

assert r == 0;
```

T2

```
while (flag == 0) {}
data = 1;
```

Behaviors Allowed in JMM #2

```
int data = flag = 0;
```

T1

```
r = data;
flag = 1;

assert r == 0;
```

T2

```
while (flag == 0) {}
data = 1;
```

Behaviors Allowed in JMM #2

int data = flag = 0;

latest value

T1

r = data;
flag = 1;

future value

T2

while (flag == 0) {}
data = 1;

assert r == 0;

Behaviors Allowed in JMM #2

```
int data = flag = 0;
```

latest value

T1

```
r = data;
flag = 1;
```

future value

```
assert r == 0;
```

T2

```
while (flag == 0) {}
data = 1;
```

Valid due to lack of happens-before ordering

Behaviors Allowed in JMM #2

int data = flag = 0;

latest value

T1

r = data;
flag = 1;

assert r == 0;

T2

while (flag == 0) {}
data = 1;

future value

Assertion failure!

Behaviors Allowed in JMM #2

int data = flag = 0;

T1	T2
r = data; flag = 1;	while (flag == 0) {} data = 1;

assert r == 0;

Assertion failure!

Behaviors Allowed in JMM #2

```
int data = flag = 0;
```

T1

```
r = data;
flag = 1;
assert r == 0;
```

T2

```
while (flag == 0) {}
data = 1;
```

Requires returning future value or reordering to trigger the assertion failure

Example #3

int x = y = 0;

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 1) {
  r3 = y;
  x = r3;
} else x = 1;
```

assert r2 == 0;

Example #3

int x = y = 0;

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 1) {
  r3 = y;
  x = r3;
} else x = 1;

assert r2 == 0;
```

JMM disallows r2 == 1 because of causality requirements

– Ševčík and Aspinall, ECOOP, 2008

Example #3

However, in a JVM, after redundant read elimination

int x = y = 0;

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 1) {
  r3 = r2;
  x = r3;
} else x = 1;


assert r2 == 0;
```

Example #3

However, in a JVM, after redundant read elimination

int x = y = 0;

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 1) {
  r3 = r2;
  x = r3;
} else x = 1;
```

```
r2 = y;
If (r2 == 1)
  x = r2;
else x = 1;
```

```
assert r2 == 0;
```

Example #3

int x = y = 0;

However, in a JVM, after redundant read elimination

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 1) {
  r3 = r2;
  x = r3;
} else x = 1;
```

```
r2 = y;
If (r2 == 1)
  x = r2;
else x = 1;
```

```
r2 = y;
x = 1;
```

assert r2 == 0;

Example #3

int x = y = 0;

However, in a JVM, after redundant read elimination

T1

```
r1 = x;
y = r1;
```

T2

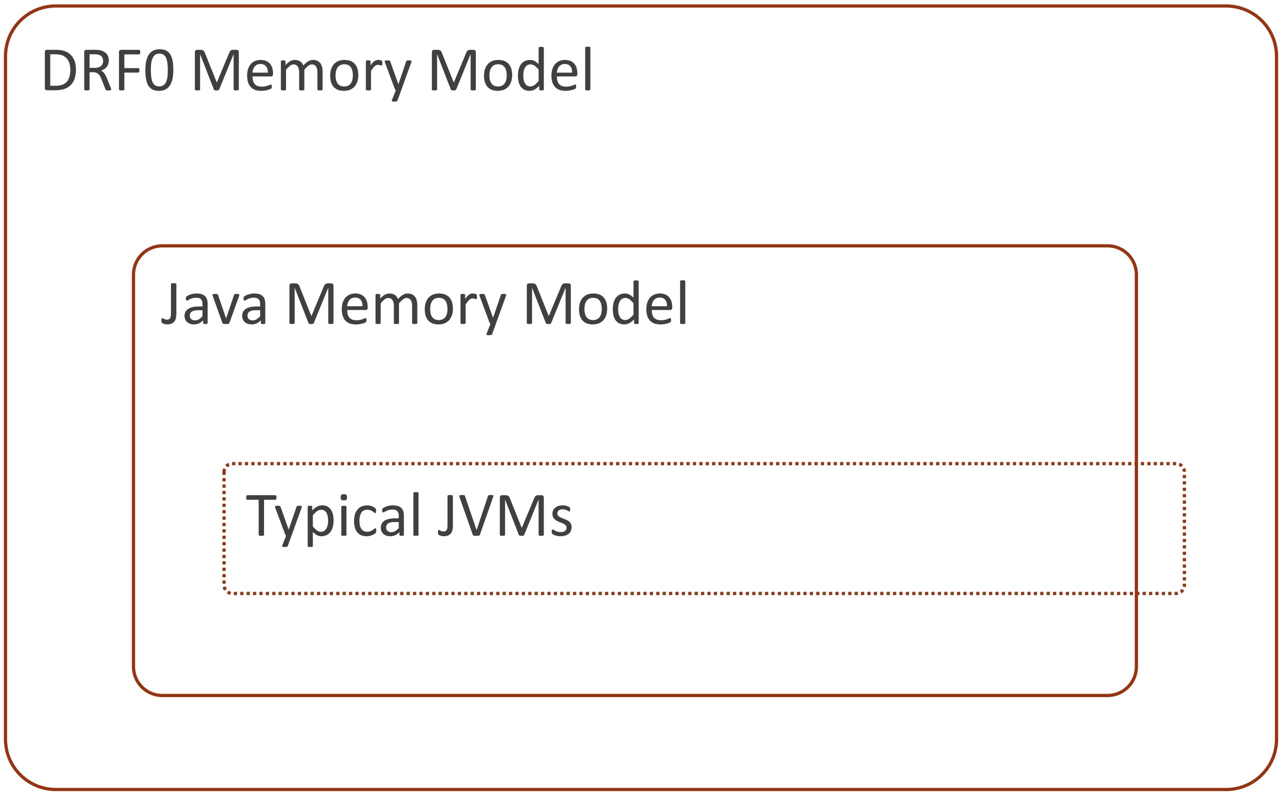
```
r2 = y;
if (r2 == 1) {
  r3 = r2;
  x = r3;
} else x = 1;

assert r2 == 0;
```

```
r2 = y;
If (r2 == 1)
  x = r2;
else x = 1;
```

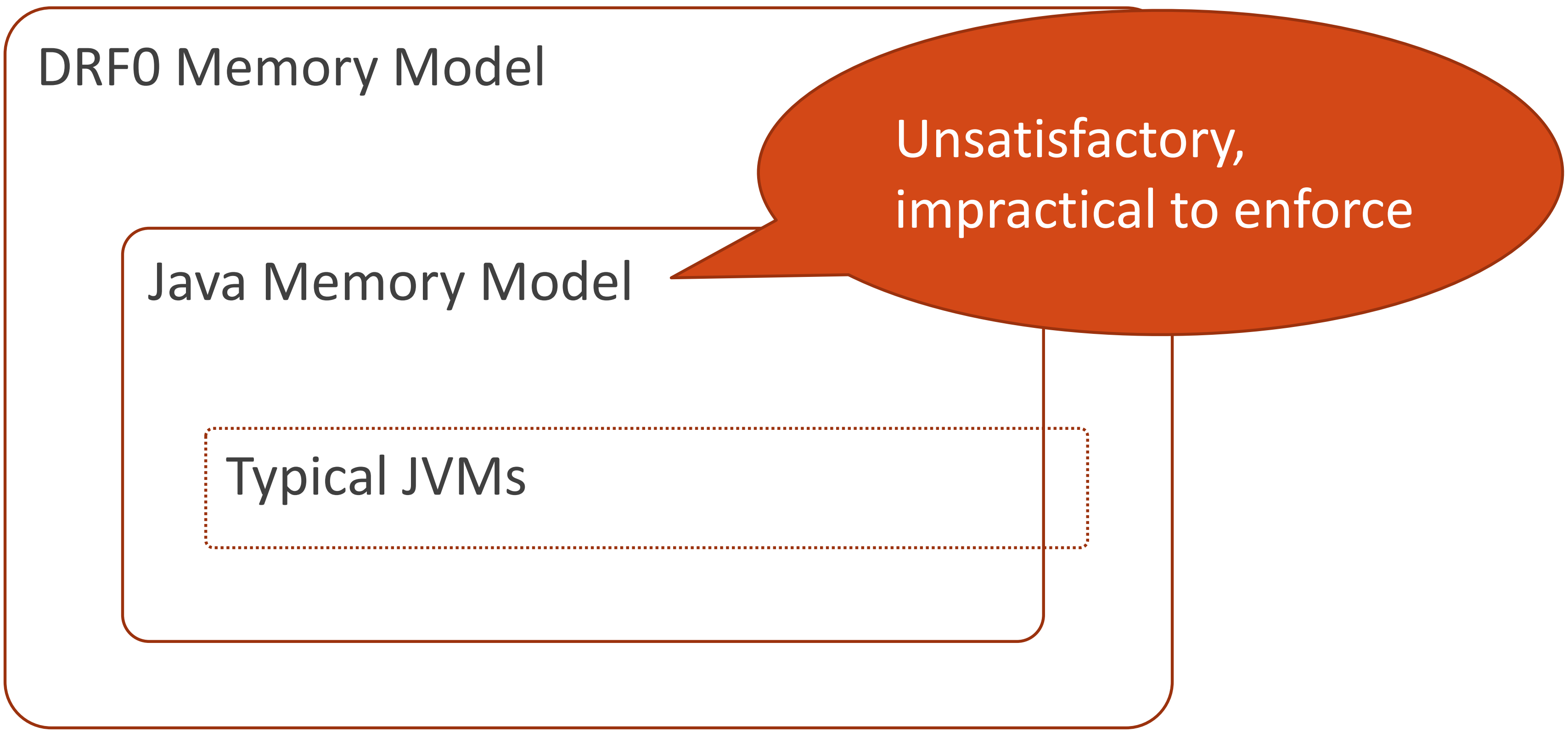
```
r2 = y;
x = 1;
```

Assertion failure possible!

Behaviors Allowed by Memory Models and JVMs



Behaviors Allowed by Memory Models and JVMs



Exposing Behaviors of Example #3

Consider future value

int x = y = 0;

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 1) {
  r3 = y;
  x = r3;
} else x = 1;
```

assert r2 == 0;

Exposing Behaviors of Example #3

Consider future value

int x = y = 0;

T1

```
r1 = x;  // r1 = 1
y = r1;  // y = 1
```

T2

```
r2 = y;      // r2 = 1
if (r2 == 1) {
  r3 = y;   // r3 = 1
  x = r3;   //  x = 1
} else x = 1;
```

```
assert r2 == 0;
```

Exposing Behaviors of Example #3

Consider future value

int x = y = 0;

T1

```
r1 = x;  // r1 = 1
y = r1;  // y = 1
```

r1 = 1 justified!

T2

```
r2 = y;      // r2 = 1
if (r2 == 1) {
  r3 = y;   // r3 = 1
  x = r3;   //  x = 1
} else x = 1;

assert r2 == 0;
```

Assertion failure!

Exposing Behaviors of Example #3

int x = y = 0;

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 1) {
  r3 = y;
  x = r3;
} else x = 1;
assert r2 == 0;
```

Requires returning future value or compiler optimization and reordering to trigger the assertion failure

Exposing Behaviors with Dynamic Analyses

- Typical approaches
  - Simulate weak memory models behaviors [1,2,3]
  - Explore multiple thread interleavings [4, 5]

1. Adversarial Memory, Flanagan & Freund, PLDI'09
2. Relaxer, Burnim et al, ISSTA'11
3. Portend+, Kasikci et al, TOPLAS'15
4. Replay Analysis, Narayanasamy et al, PLDI'07
5. RaceFuzzer, Sen, PLDI'08

Exposing Behaviors with Dynamic Analyses

- Typical approaches
  - Simulate weak memory models behaviors [1,2,3]
  - Explore multiple thread interleavings [4, 5]
- Coverage Limitation
  - Return stale values only, not future values
  - Cannot expose assertion failures in Examples #2, #3

1. Adversarial Memory, Flanagan & Freund, PLDI'09
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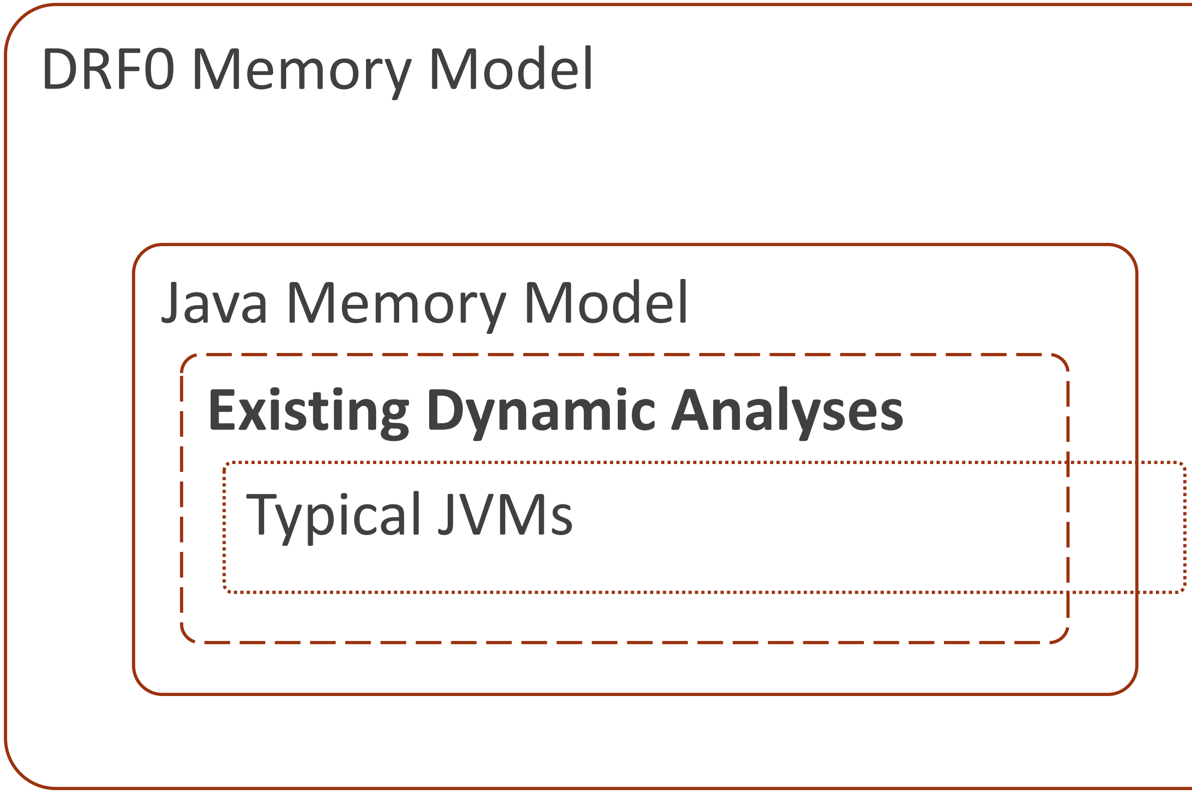
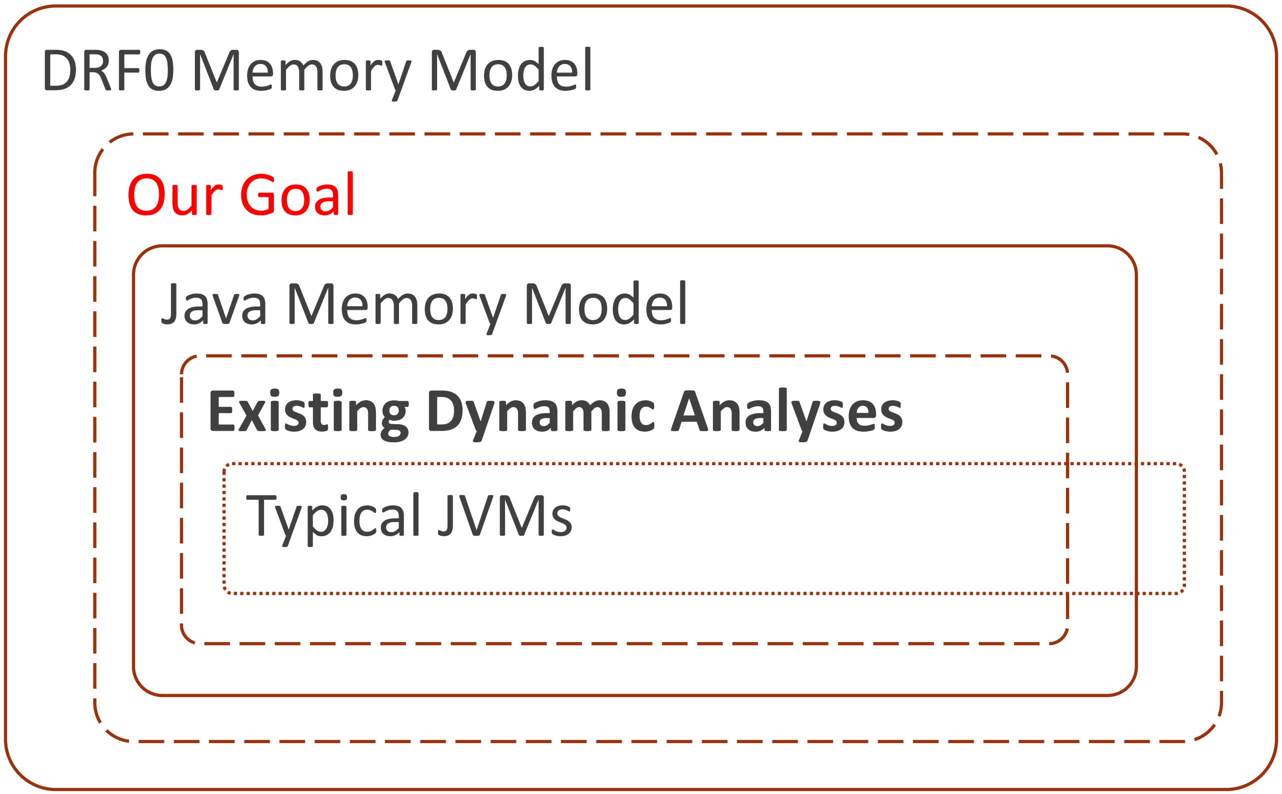
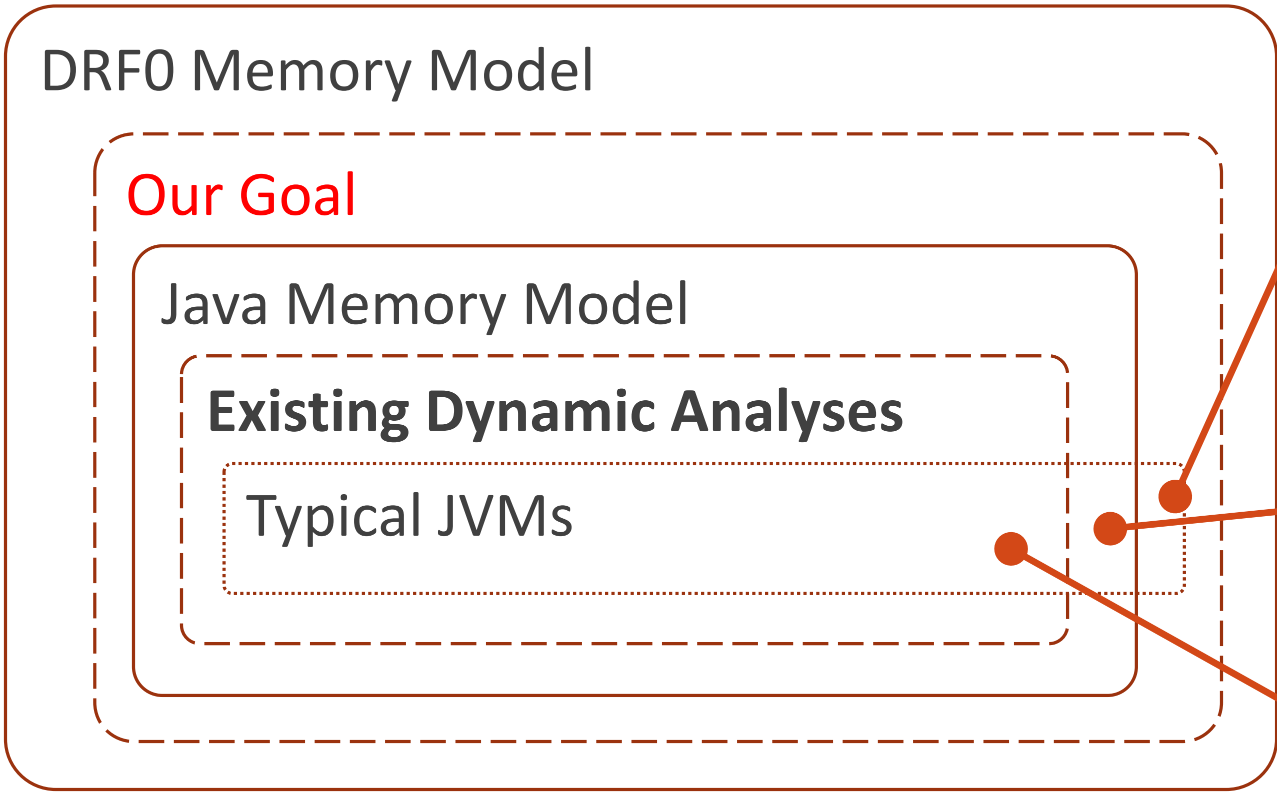
Relationship among memory models and exposed behaviors



Relationship among memory models and exposed behaviors



Relationship among memory models and exposed behaviors



Example #3

```
r1 = x;        r2 = y;
y = r1;        if (r2 == 1) {
                 r3 = y;
                 x = r3;
               } else x = 1;
```

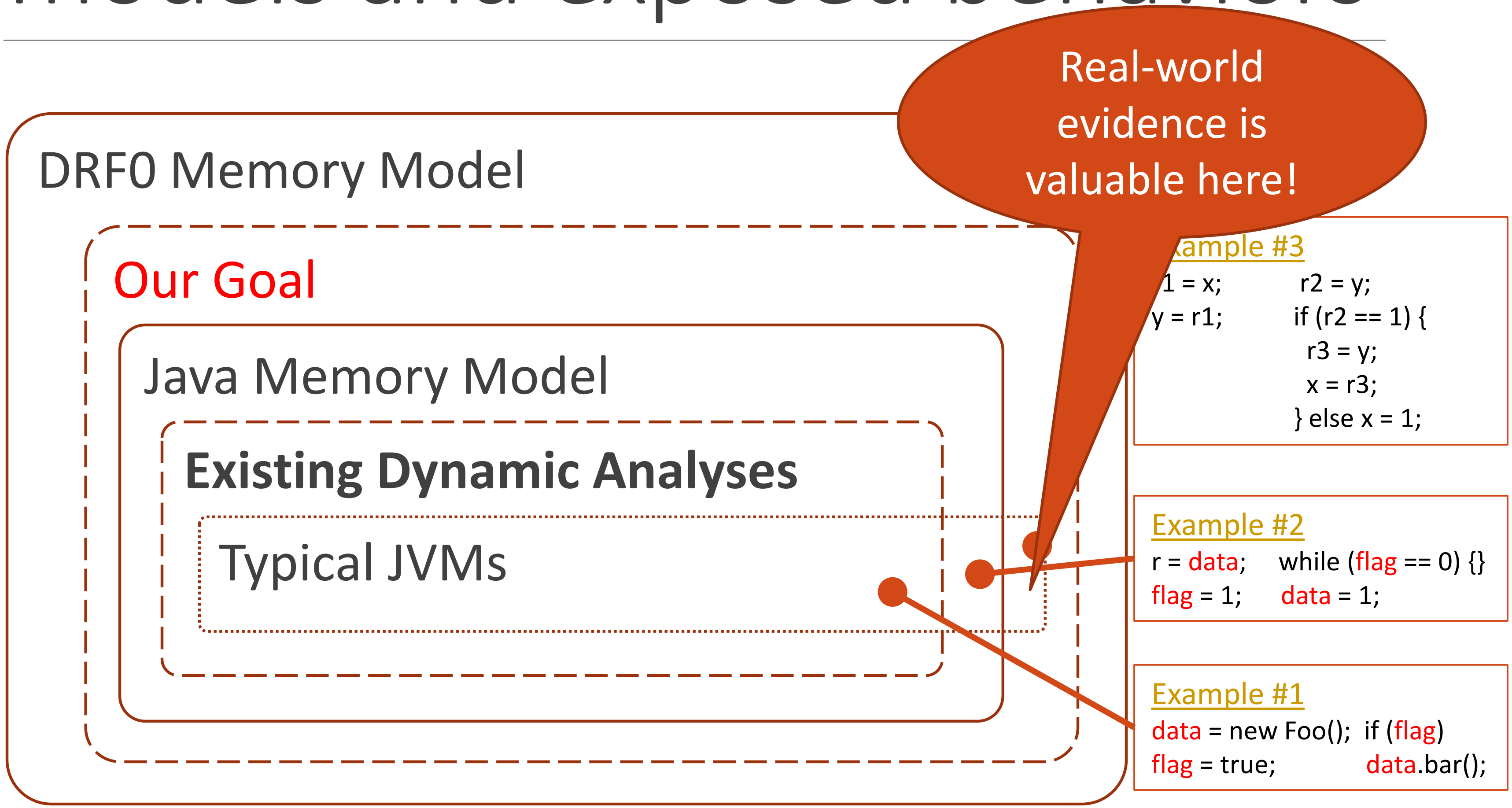
Example #2

```
r = data;     while (flag == 0) {}
flag = 1;     data = 1;
```

Example #1

```
data = new Foo();  if (flag)
flag = true;         data.bar();
```

Relationship among memory models and exposed behaviors



Outline

- Memory Models and Behaviors of Data Races
- Design
  - Prescient Memory (PM)
  - PM-profiler
  - PM Workflow
- Evaluation

Prescient Memory: Key Idea

- *Speculatively* “guess” a future value at a load
- *Validate* the speculative value at a later store

Prescient Memory: Key Idea

- *Speculatively* “guess” a future value at a load

- ***<u>Validate</u>*** the speculative value at a later store

Returning Future Values is Tricky

int x = y = 0;

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 0)
  x = 1;
```

assert r1 == 0 || r2 == 0;

Returning Future Values is Tricky

int x = y = 0;

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 0)
  x = 1;
```

assert r1 == 0 || r2 == 0;

Returning Future Values is Tricky

int x = y = 0;

T1

```
r1 = x; // r1 = 1
y = r1; // y = 1
```

T2

```
r2 = y;  // r2 = 1
if (r2 == 0)
  x = 1;
```

assert r1 == 0 || r2 == 0;

Returning Future Values is Tricky

int x = y = 0;

T1

```
r1 = x; // r1 = 1
y = r1; // y = 1
```

r1 = 1 not justified

T2

```
r2 = y;  // r2 = 1
if (r2 == 0)
  x = 1;
```

assert r1 == 0 || r2 == 0;

Returning Future Values is Tricky

int x = y = 0;

T1

r1 = x; // r1 = 1
y = r1; // y = 1

T2

r2 = y; // r2 = 1
if (r2 == 0)
  x = 1;

Invalid execution!

r1 = 1 not justified

assert r1 == 0 || r2 == 0;

Returning Future Values is Tricky

int x = y = 0;

T1	**T2**
r1 = x;	
y = r1;	
	r2 = y;
	if (r2 == 0)
	x = 1;

Should never fail!

assert r1 == 0 || r2 == 0;

Returning Future Values is Tricky

```
int x = y = 0;
```

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 0)
  x = 1;
```

```
assert r1 == 0 || r2 == 0;
```

Validating speculative values is necessary to prevent nonsensical results

Prescient Memory: Key Idea

- *Speculatively* “guess” a future value at a load

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Prescient Memory: Key Idea

- *Speculatively* "guess" a future value at a load

- *Validate* the speculative value at a later store

Valid future value ⇔ { Store writes the same value / Store races with load }

Prescient Memory: Key Idea

- *Speculatively* “guess” a future value at a load
  - Maintain a per-variable speculative read history
  - Records <logical timestamp, speculative value>
- *Validate* the speculative value at a later store

Valid future value ⇔

Store writes the same value

Store races with load

PM Example

int x = y = 0;
S[x] = Ø

T1 Timestamp: K_1

1: r = x;
2: y = 1;

T2 Timestamp: K_2

3: while (y == 0) {}

4: x = 1;

assert r == 0;

PM Example

int x = y = 0;
S[x] = Ø

T1 Timestamp: K_1

T2 Timestamp: K_2

1: r = x; 1 ⇠ predict(…) // guess value 1
2: y = 1; S[x] = {<K_1, 1>}

3: while (y == 0) {}

4: x = 1;

assert r == 0;

PM Example

int x = y = 0;
S[x] = Ø

T1 Timestamp: K_1

1: r = x;
2: y = 1;

1 ⇠ predict(…) // guess value 1
S[x] = {<K_1, 1>}

T2 Timestamp: K_2

3: while (y == 0) {}

4: x = 1;

validate S[x]:
$K_1 \not\sqsubseteq K_2$ && 1 == 1

1 is a valid future value!

assert r == 0;

Challenges

- How to guess a future value?

predict(...) ?

Challenges

- How to guess a future value?
  - Which *load* should return a future value?
  - What *value* should be returned?

Challenges

- How to guess a future value?
  - Which *load* should return a future value?
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- Solution
  - *Profile* possible future values in a prior run

Profiling Future Values

Helper Dynamic Analysis: PM-profiler

- Maintains a per-variable concrete read history

- At a load, records:
  - <logical timestamp, instruction ID, set of visible values>

Profiling Future Values

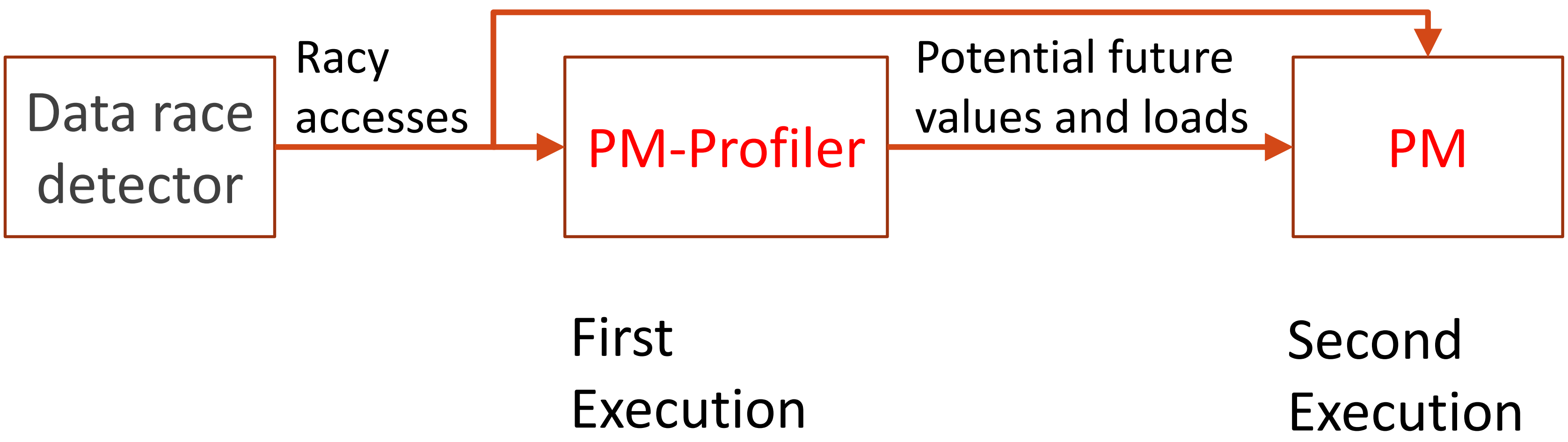
Helper Dynamic Analysis: PM-profiler

- At a store, detects:

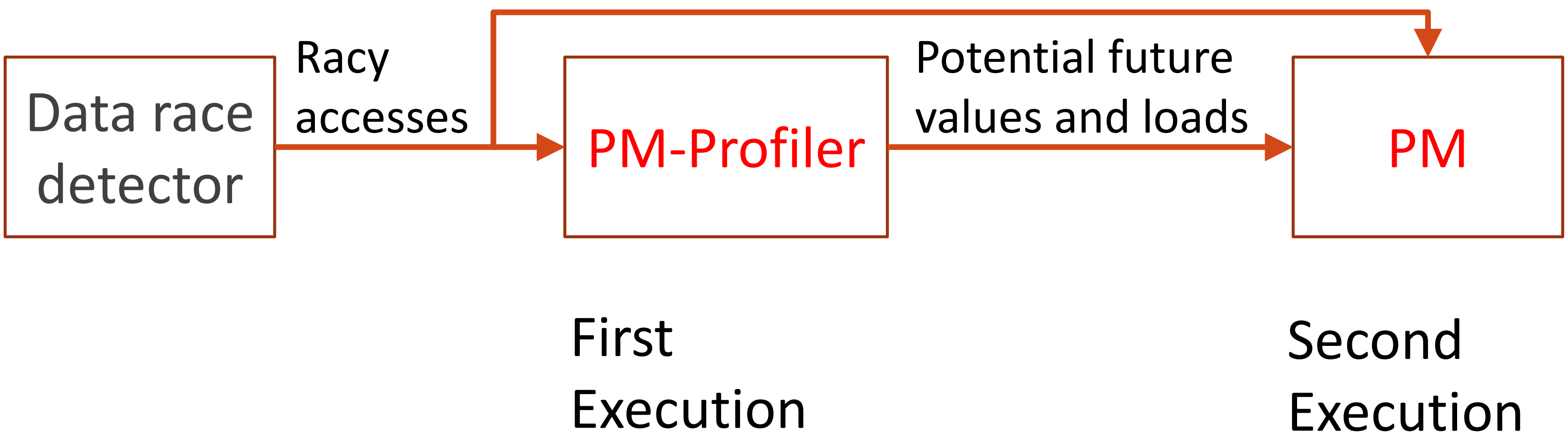
Potential future value for a previous load ⟺

- Store races with the previous load
- Store writes a value distinct from visible values of the previous load

Prescient Memory Workflow

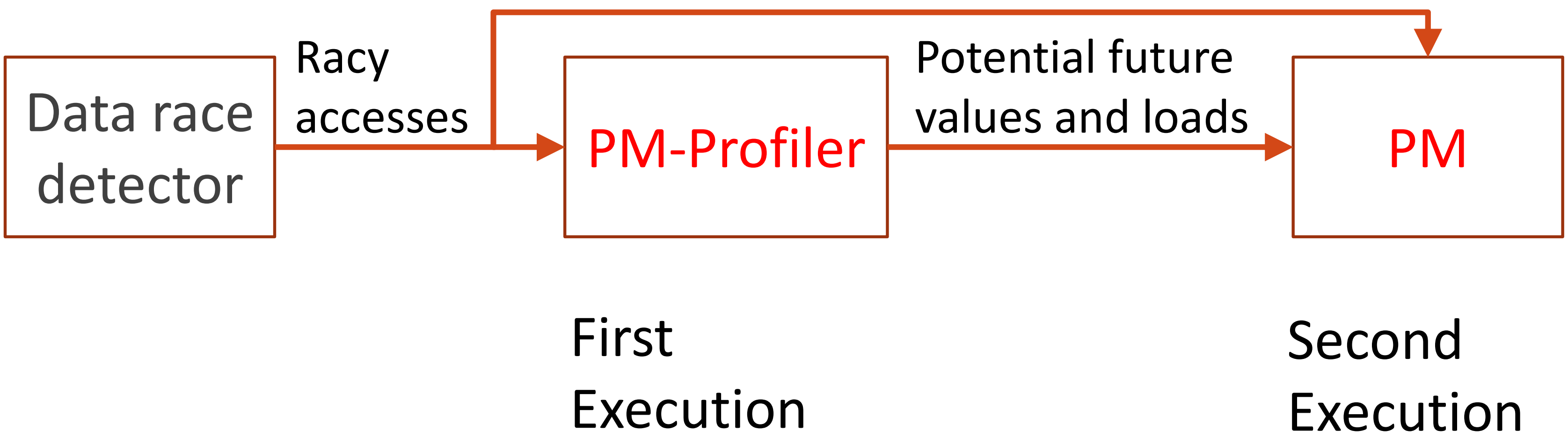


Prescient Memory Workflow



Run-to-run nondeterminism affects validatable future values

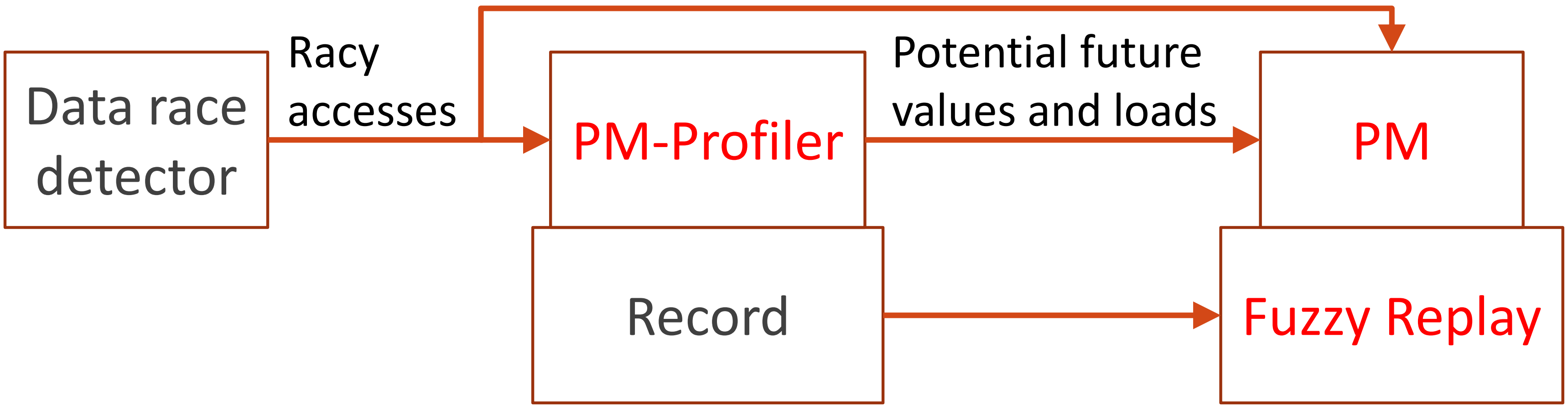
Prescient Memory Workflow



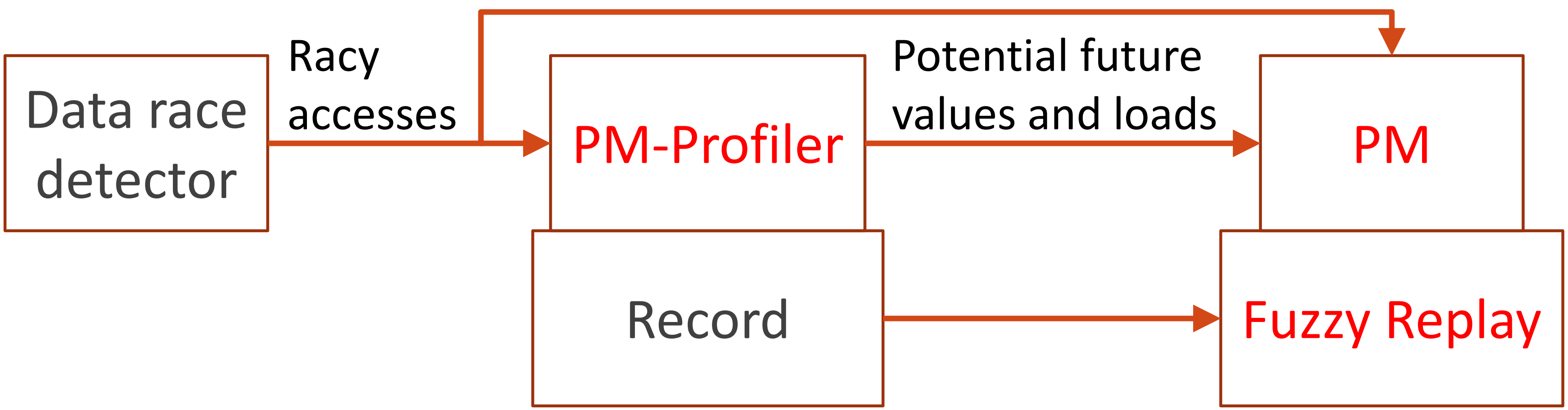
Run-to-run nondeterminism affects validatable future values

- Solution: record and replay

Prescient Memory Workflow



Prescient Memory Workflow



Returning a future value could diverge from the record execution

- Best-effort, fuzzy replay

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Methodology and Implementation

- Compare with

  Adversarial Memory (AM) [Flanagan & Freund, PLDI'09]: a dynamic analysis that only uses stale values

Methodology and Implementation

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- Platform

  Jikes RVM 3.1.3

  DaCapo Benchmark 2006, 2009 and SPEC JBB 2000 & 2005

  4-Core Intel Core i5-2500

  Record and Replay [Replay, Bond et al. PPPJ’15]

Methodology and Implementation

- Compare with

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  4-Core Intel Core i5-2500

  Record and Replay [Replay, Bond et al. PPPJ’15]

- Implementation limitation

  Does not support reference-type fields

Exposed Erroneous Behaviors

Program	AM	PM
hsqldb	Non-termination	Data corruption
hsqldb	None	Performance bug
avrora	Data corruption	Data corruption
lusearch (GNU Classpath)	Performance bug	None
sunflow	Null ptr exception	Null ptr exception
jbb2000	Non-termination	Data corruption
jbb2000	Data corruption	Data corruption
jbb2005 (GNU Classpath)	Data corruption	Data corruption
jbb2005 (GNU Classpath)	Data corruption	None

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sunflow	Null ptr exception	Null ptr exception
jbb2000	Non-termination	Data corruption
jbb2000	Data corruption	Data corruption
jbb2005 (GNU Classpath)	Data corruption	Data corruption
jbb2005 (GNU Classpath)	Data corruption	None

PM found 3 new erroneous behaviors!

Exposed Erroneous Behaviors

Program	AM	PM	
hsqldb	Non-termination	Data corruption	✓
hsqldb	None	Performance bug	
avrora	Data corruption	Data corruption	✓
lusearch (GNU Classpath)	Performance bug	None	✗
sunflow	Null ptr exception	Null ptr exception	✓
jbb2000	Non-termination	Data corruption	✓
jbb2000	Data corruption	Data corruption	✓
jbb2005 (GNU Classpath)	Data corruption	Data corruption	✓
jbb2005 (GNU Classpath)	Data corruption	None	✗

PM exposes most bugs that AM found.

Exposed Erroneous Behaviors

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jbb2005 (GNU Classpath)	Data corruption	Data corruption
jbb2005 (GNU Classpath)	Data corruption	None

Paper contains detailed analysis of each bug.

Conclusion

- First dynamic analysis to expose legal behaviors due to future values in large, real programs
- Successfully found new harmful behaviors due to future values in real programs
- Reaffirms that "benign" races are harmful
- Helps future revisions to language specifications by finding evidence of controversial behaviors in real programs