Semantics for locking specifications

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Concurrency: essential but error-prone

+Essential for performance (exploit multiple cores)

+Design component of GUIs

- Data races: concurrent access to shared data
  - easy mistake to make
  - leads to corrupted data structures
  - difficult to reproduce and diagnose

Thread-unsafe code

```
class BankAccount {

  int balance;

  void withdraw(int amount) {
    int oldBal = this.balance;
    int newBal = oldBal - amount;
    this.balance = newBal;
  }

  ...
```

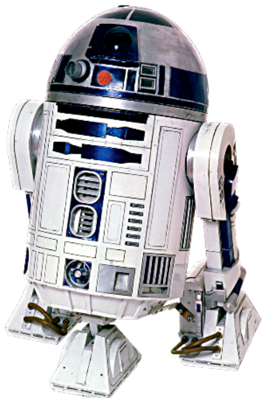
Data race example

Shared account
Initial balance = 500

Thread 1:

sharedAccount.withdraw(50)

```
int oldBal = this 500 ance;
int newBal = o 500 l - ar 50 nt;
this.balance = n 450 l;
```



Thread 2:

sharedAccount.withdraw(100)

```
int oldBal = this 500 ance;
int newBal = o 500 l - a 100 nt;
this.balance = n 400 l;
```

Withdrawals = 150
Final balance = 450

Solution: locking

```
class BankAccount {
  Object acctLock;
  int balance;
  @GuardedBy(“acctLock”) int balance;

  void withdraw(int amount) {
   synchronized (acctLock) {
    int oldBal = this.balance;
    int newBal = oldBal - amount;
    this.balance = newBal;
   }
  }
```

Locking:

- Only one thread can aquire the lock
- No concurrent access to data
- Which lock to hold?

Key issues:

- Names vs. values
- Aliasing

Locking discipline =
which locks to hold when accessing what data

```
@GuardedBy("lock1") int w;
@GuardedBy("lock2") int x;
@GuardedBy("lock2") int y;
                    int z;
```

- Write locking discipline as documentation and for use by tools
- **`@GuardedBy`** [Goetz 2006] is a de-facto standard
  - On GitHub, 35,000 uses in 7,000 files
- Its semantics is informal, ambiguous, and incorrect (allows data races)
- Similar problems with other definitions

Contributions

- Formal semantics for locking disciplines
  - unambiguous
  - prevents data races
  - two variants: value-based, name-based
- Two implementations:
  - type-checker that validates use of locking
  - inference tool that infers locking discipline
- Experiments: programmer-written **`@GuardedBy`**:
  - are often inconsistent with informal semantics
  - permit data races even when consistent

Concurrency background

Each object is associated with a *monitor* or *intrinsic lock*.

specification of locking discipline

synchronized statement or method locks the monitor.

Exiting the statement or method unlocks the monitor.

```
Date d = new Date();

@GuardedBy("d") List lst = ...;

synchronized (d) {
  lst.add(...)
  lst.remove(...)
  otherList = lst;
}
```

guard expression; arbitrary, e.g. **`a.b().f`**

Our implementations handle explicit locks too.

Defining a locking discipline

Informally:
“If program element *x* is annotated by @GuardedBy(*L*),
a thread may only use *x*
while holding the lock *L*.”

```
MyObject lock;
@GuardedBy("lock.field") Pair shared;
@GuardedBy("lock.field") Pair alias;

synchronized (lock.field) {
  shared.a = 22;
  alias = shared;
}
```

Guard expression:

Aliases?	Yes
Reassignment?	No
Side effects?	Yes
Scoping?	Def site

Value protection answers

Element being guarded:

Name or value?	**Value**
Aliases?	Yes
Reassignments?	Yes
Side effects?	Yes

What is a use?

Occurrence of name?	← current
Dereference of name? (**x.f**)	
Dereference of value?	**← better**

```
MyObject lock;
@GuardedBy("lock") Pair shared;
Pair alias;
```

Name protection

... not value protection

```
synchronized (lock) {
  alias = shared;
}
alias.a = ...
```

Suffers a data race

Value protection

... not name protection

```
shared = alias;
synchronized (lock) {
  shared.a = ...
}
```

No data race

Locking discipline semantics providing value protection

$$\underbrace{\overbrace{\texttt{@GuardedBy("lock")}}^{\text{type qualifier}}\ \texttt{Pair}}_{\text{type}}\ \underbrace{\texttt{shared;}}_{\text{variable}}$$

Suppose expression *x* has type: @GuardedBy(*L*) C

A *use* is a dereference

Type system constraint; may lock an alias

When the program dereferences a value that has ever been bound to *x*, the program holds the lock on the value of expression *L*.

The referent of *L* must not change while the thread holds the lock.

No reassignment of guard expression.

Side effects permitted (do not affect the monitor).

Locking discipline semantics providing name protection

$$\underbrace{\texttt{@GuardedBy("lock")}}_{\text{variable annotation}}\ \underbrace{\texttt{Pair}}_{\text{type}}\ \underbrace{\texttt{shared;}}_{\text{variable}}$$

Suppose variable *v* is declared as @GuardedBy(*L*)

A *use* is a variable read or write

No aliasing permitted

When the program accesses *v*, which must not be aliased, the program holds the lock on the value of expression *L*.

L may only be “itself” or “this”.

Guarantees L always evaluates to the same value

Key contributions

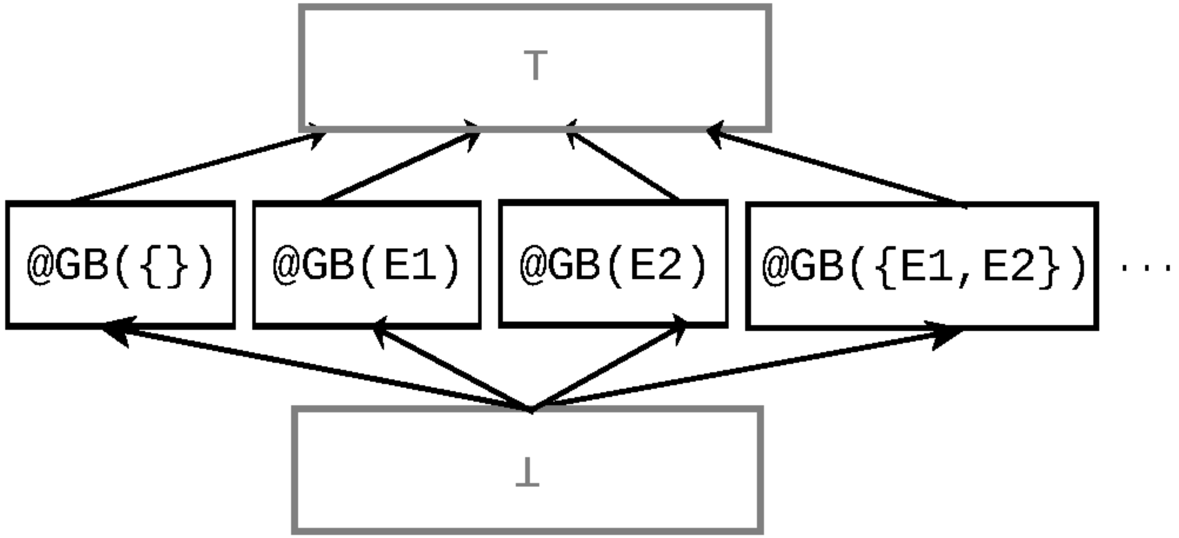
- Two formal semantics (name-based and value-based)
  - Core calculus based on RaceFreeJava [Abadi TOPLAS 2006]
  - Structural Operational Semantics
  - Definitions of accessed variables and dereferenced locations
- Proofs of correctness
  - By contradiction:
    - assume data race
    - show locking discipline must have been violated

Static analysis of a locking discipline

- Goal is to determine facts about values
  - Program is written in terms of facts about variables
- Analysis computes an approximation (an abstraction)
  - of values each expression may evaluate to
  - of locks currently held by the program
- Both abstractions are sound

Enforcement of value semantics via type-checking

[Ernst ICSE 2016]



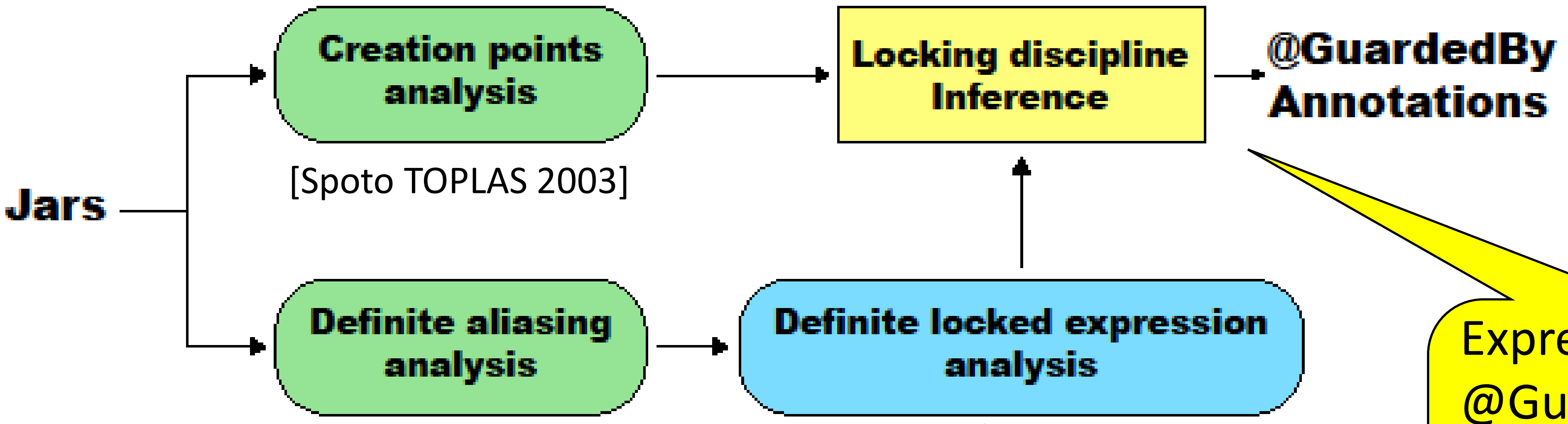
- No two **`@GuardedBy`** annotations are related by subtyping
- Why not @**GB**(*L1*) <: @**GB**(*L1*, *L2*)?
  - Side effects and aliasing

Type rule: If x : @**GB**(*L*) , then *L* must be held when x is dereferenced

Type system also supports

- method pre/postconditions (**`@Holding`** annotations)
- side effect annotations
- type qualifier polymorphism
- reflection
- flow-sensitive type inference

Inference of both semantics via abstract interpretation


Jars
Creation points analysis
Definite aliasing analysis
Definite locked expression analysis
Locking discipline Inference
@GuardedBy Annotations

[Spoto TOPLAS 2003]

[Nikolic ICTAC 2012]

Expression *e* is @GuardedBy(*L*) if *e*'s fields are accessed only when *L* is held

Acquired on entry to **sync(…) { … }**. Released on exit or side effect.

Inference implementation

1. Where is the guarded element used?
    - Name protection: syntactic uses of variable
    - Value protection: estimate via creation points analysis
2. What expressions are locked at those points?
    - Definite aliasing analysis
    - Side effect analysis
    - Viewpoint adaptation (contextualization)

Whole-program analysis

- Makes closed-world assumption
- Type-checking is modular, incremental

Experimental evaluation of value semantics

[Ernst ICSE 2016]

- 15 programs, 1.3 MLOC
  - BitcoinJ, Daikon, Derby, Eclipse, Guava, Jetty, Velicity, Zookeeper, Tomcat, …
  - 5 contain programmer-written **`@GuardedBy`** annotations
- 661 correct annotations
  - Candidates: annotations written by the programmer or inferred by our tool
  - Correct: program never suffers a data race on the element
    - Determined by manual analysis
- Results:
  - Inference: precision 100%, recall 83%
  - Type-checking: precision 100%, recall 99%
  - Programmers: precision 50%, recall 42%

Programmer mistakes

Errors in every program that programmers annotated with respect to both value and name semantics

- Creating external aliases
- Lock writes but not reads
- Syntax errors
- Omitted annotations

Implementations

- Type checker:
  - Lock Checker, distributed with the Checker Framework
  - http://CheckerFramework.org/
  - Live demo: http://eisop.uwaterloo.ca/live
- Inference:
  - Julia abstract interpretation
  - http://juliasoft.com/

Related work

- Name-based semantics: JML, JCIP, rccjava [Abadi TOPLAS 2006], …
- Heuristic checking tools: Warlock, ESC/Modula-3, ESC/Java
- Unsound inference: [Naik PLDI 2006] uses may-alias, [Rose CSJP 2004] is dynamic
- Sound inference for part of Java [Flanagan SAS 2004]
- Type-and-effect type systems: heavier-weight, detects deadlocks too
- Ownership types

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