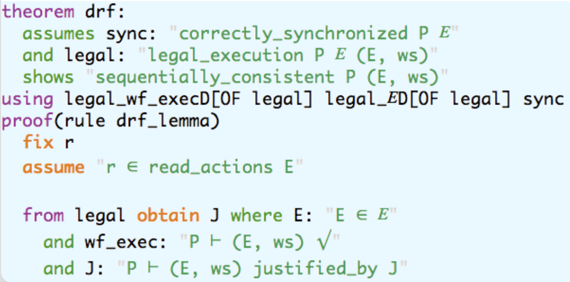
Karlsruhe Institute of Technology

A Unified, Machine-Checked Formalisation of Java and the Java Memory Model

Andreas Lochbihler

funded by DFG grants Sn11/10-1,2

PROGRAMMING PARADIGMS GROUP



```
theorem drf:
  assumes sync: "correctly_synchronized P ℰ"
  and legal: "legal_execution P ℰ (E, ws)"
  shows "sequentially_consistent P (E, ws)"
using legal_wf_execD[OF legal] legal_ℰD[OF legal] sync
proof(rule drf_lemma)
  fix r
  assume "r ∈ read_actions E"

  from legal obtain J where E: "E ∈ ℰ"
    and wf_exec: "P ⊢ (E, ws) √"
    and J: "P ⊢ (E, ws) justified_by J"
```

KIT – University of the State of Baden-Wuerttemberg and
National Research Center of the Helmholtz Association

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Why do we need a memory model?

initially: `x = y = 0;`

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`j = y;`	`i = x;`

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interleaving semantics

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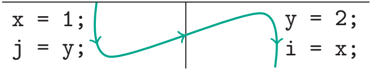

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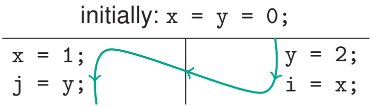

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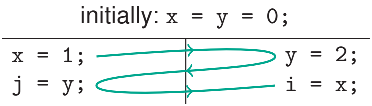

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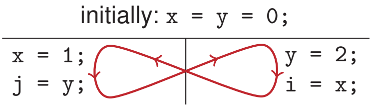

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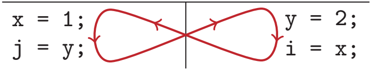

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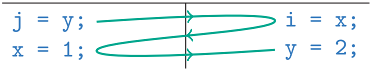
compiler and hardware reorder statements



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Why do we need a memory model?

Java memory model

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`i == 0`	✓	✓
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compiler and hardware reorder statements

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The Java memory model: goals

1. allow compiler optimisations
2. interleaving semantics for data-race-free programs (DRF guarantee)
3. give semantics to **all** Java programs
4. support type safety and security architecture

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2. interleaving semantics for data-race-free programs (DRF guarantee)
   ~~proofs with holes~~ **formally proven for Java-like language**
   [Manson et al. 05; Aspinall, Ševčík 07; Huisman, Petri 07]

3. give semantics to **all** Java programs
   ~~informal, loose~~ connection with Java-like language **formalised**
   main cause for technical complexity

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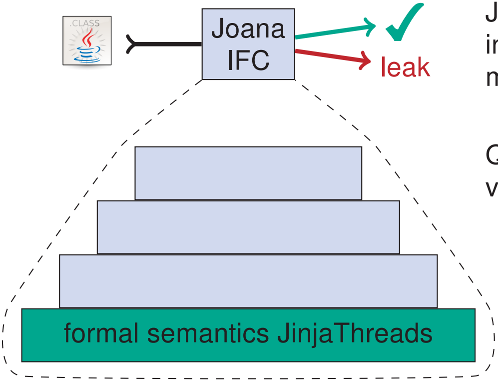
   open

Quis custodiet ipsos custodes?



Joana: [Hammer, Snelting 09]
information flow control for
multithreaded Java

Quis custodiet:
verify IFC algorithm

- analyses assume interleaving semantics

⇒ DRF guarantee makes them applicable to DRF programs

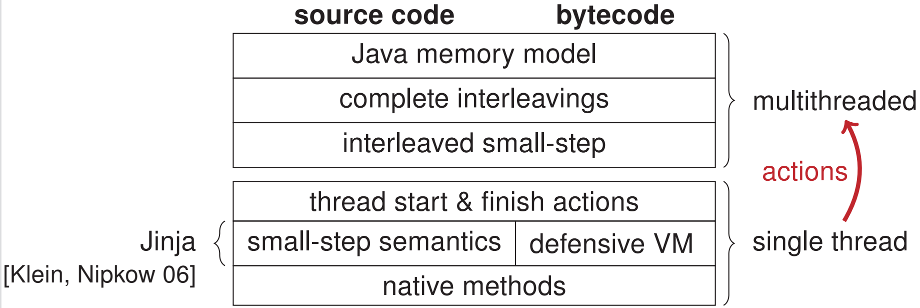
JinjaThreads

sequential features

- classes, objects, fields, arrays
- inheritance and late binding
- exceptions
- imperative features

concurrency

- thread creation
- synchronisation
- wait-notify
- join, interruption



source code **bytecode**

Java memory model

complete interleavings

interleaved small-step

thread start & finish actions

small-step semantics | defensive VM

native methods

multithreaded

actions

single thread

Jinja [Klein, Nipkow 06]

Connecting JinjaThreads with the JMM

initially: `y = 0;`

```
T t2 = new T();
t2.start();
t2.join();
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```
class T extends Thread {
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non-deterministic value *v*

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B. flatten & purge irrelevant actions

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`t2.start();`
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	`class T extends Thread {`
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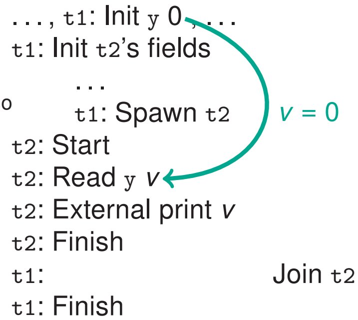
C. reconstruct orders $\leq_{hb}$, $\leq_{so}$ match reads and writes



…, `t1`: Init `y` 0, …

`t1`: Init `t2`'s fields

…

`t1`: Spawn `t2`

`t2`: Start

`t2`: Read `y` v

`t2`: External print v

`t2`: Finish

`t1`: Join `t2`

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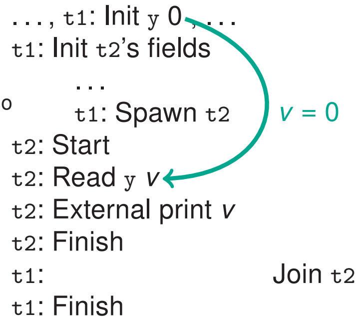
D. impose JMM
legality constraints



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$v = 0$

DRF guarantee

sequential consistency (SC) every read sees most recent write

data race two conflicting actions unrelated in $\leq_{\mathrm{hb}}$
read/write, write/read, write/write to non-volatile location

data race free (DRF) no data race in any *SC* execution of the program

DRF guarantee DRF programs *behave* like under interleaving semantics.

Theorem
No data race in SC executions $\Longrightarrow$ *all executions are SC.*

implications for Java programmers:

- Always synchronise and forget about the JMM.
- Mark all synchronisation variables (`volatile`, `synchronized`).
- Use only allowed synchronisation primitives.

Implicit communication channels

1. run-time type information as global state

initially: `x = false; y = null;`

`x = true;`	`r1 = x;` `y = (r1 ? new A() : new B());`	`r2 = y.f();`

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⇒ `r1 == true`

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2. synchronisation via `Thread.start`

initially: `x = new Thread(); y = 0;`

```
y = 1;       | try { x.start();
x.start();   | } catch (IllegalThreadStateException _) { r = y; }
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data race?

intuition: no JMM: yes

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dispatch to `A.f()`
⇒ `r1 == true`

disallowed synchronisation

2. synchronisation via `Thread.start`

initially: `x = new Thread(); y = 0;`

`y = 1;` `x.start();`	`try { x.start();` `} catch (IllegalThreadStateException _) { r = y; }`

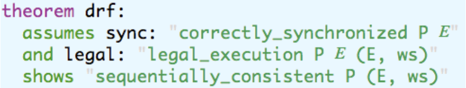
data race?

disallowed synchronisation

DRF guarantee

Theorem (DRF guarantee)

No data race in SC executions
$\Longrightarrow$ *all executions are SC.*



```
theorem drf:
  assumes sync: "correctly_synchronized P E"
  and legal: "legal_execution P E (E, ws)"
  shows "sequentially_consistent P (E, ws)"
```

Java memory model
complete interleavings
interleaved small-step

single-thread semantics

DRF guarantee

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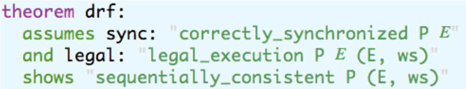

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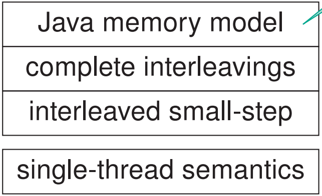
Assumptions on complete interleavings:
1. SC completions for SC prefix
2. unique initialisations before read in SC prefix



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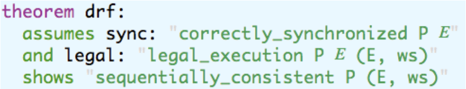

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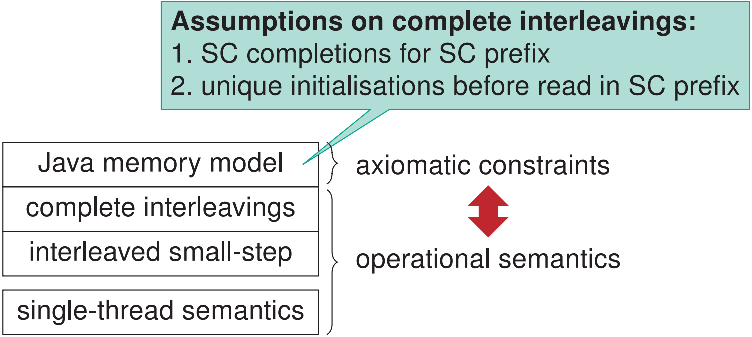

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Java memory model

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axiomatic constraints

operational semantics

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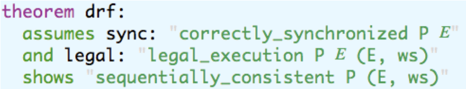

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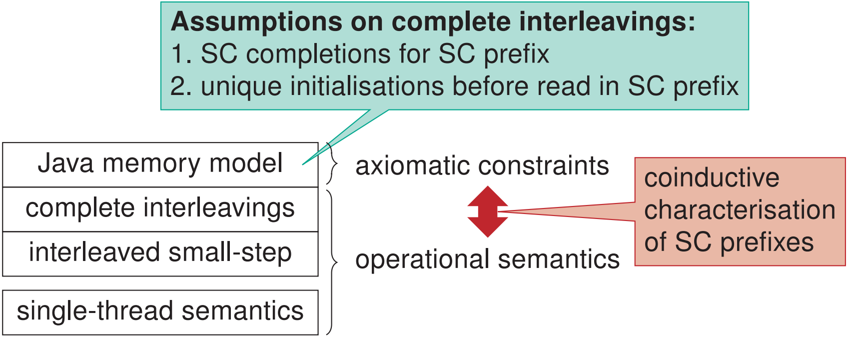

Assumptions on complete interleavings:

1. SC completions for SC prefix
2. unique initialisations before read in SC prefix

coinductive characterisation of SC prefixes

DRF guarantee

Theorem (DRF guarantee)

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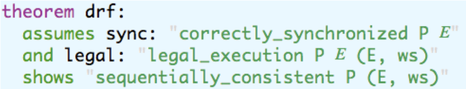

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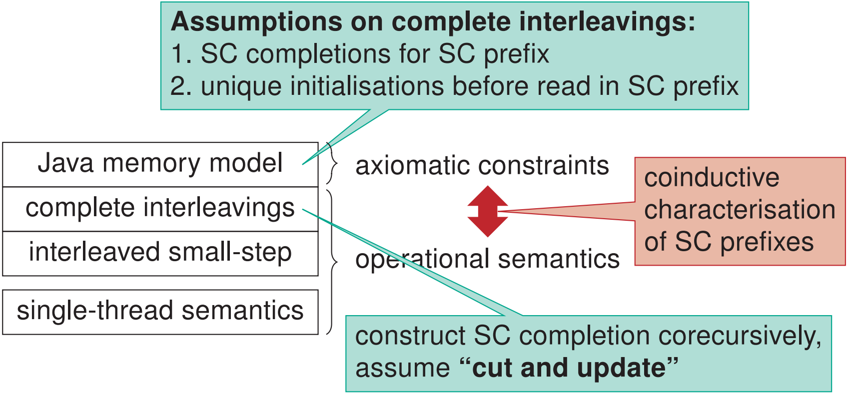

Assumptions on complete interleavings:
1. SC completions for SC prefix
2. unique initialisations before read in SC prefix

coinductive characterisation of SC prefixes

construct SC completion corecursively, assume “**cut and update**”

DRF guarantee

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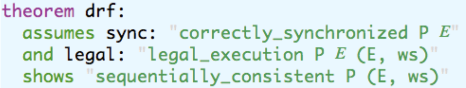

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Assumptions on complete interleavings:
1. SC completions for SC prefix

Insights:

- proofs abstract from form of *allowed* synchronisation
- allocations (initialisations) complicate proofs
- special treatment irrelevant for DRF programs

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construct SC completion corecursively, assume **“cut and update”**

Conclusion

Results:

1. rigorous link between Java and JMM
   complete set of Java multithreading
2. DRF guarantee holds definitely
   ⇒ DRF guarantee formally available, e.g., for program analyses
3. all definitions and proofs machine-checked

Outlook: JMM too weak for programs with races [forthcoming PhD thesis]

type safety weak version holds
but unallocated memory can be accessed

security architecture compromised, values can appear out of thin air