Separation Logic for a Java-like Language with Reentrant Locks and Fork/Join

Christian Haack[*] Marieke Huisman[↯] Clément Hurlin[↯]

[*] Radboud Universiteit Nijmegen, The Netherlands

[↯] INRIA Sophia Antipolis - Méditerranée, France

ParSec

Parallelism and Security

June 9, 2008

Motivation

Synchronization in Java can be done in 2 ways:

- `synchronized(`x`){ ... }`
- x`.lock()`/x`.unlock()` (generalize `synchronized` blocks).

Motivation

Synchronization in Java can be done in 2 ways:

- `synchronized(`x`){ ... }`
- x`.lock()`/x`.unlock()` (generalize `synchronized` blocks).

Java locks are *reentrant*: ← our goal

- Acquiring a lock twice is possible.

Contrary to C-threads:

- Acquiring a lock twice results in blocking.

Separation Logic

$x.f \overset{\pi}{\mapsto} v$ (called "points-to predicate") has a dual meaning:

- $x.f$ contains value v.
- Permission π to access field $x.f$.

π is a *fraction* in $(0,1]$:

- 1 is the permission to *write access* a location.
- Any $0 < \pi < 1$ is the permission to *read-only access* a location.

Separation Logic

$x.f \overset{\pi}{\mapsto} v$ (called "points-to predicate") has a dual meaning:

- $x.f$ contains value v.
- Permission π to access field $x.f$.

π is a *fraction* in $(0,1]$:

- 1 is the permission to *write access* a location.
- Any $0 < \pi < 1$ is the permission to *read-only access* a location.

Global invariant:

- For each location $x.f$ the sum of permissions to $x.f$ is $\leqslant 1$.

↳ Prevents read-write and write-write conflicts (data races).

↳ Allows concurrent reads.

Separation Logic

$F * G$ is the *separating conjunction*:

- $F * F$ implies F (weakening).
- But F does not imply $F * F$.

$F \mathrel{-\!\!*} G$ is the *linear implication* (or “*baguette magique*”):

- Reads “consume F yielding G” or “trade F and receive G”
- $F * (F \mathrel{-\!\!*} G)$ implies G

Hoare Rules for Non-Reentrant Locks

$$\frac{}{\Gamma \vdash \{F\}\ c\ \{G\}}$$

- A thread can safely execute command c with initial resource (permissions) F and end with resource G.
- Threads *own* resources and use resources to read/write to the heap.

Hoare Rules for Non-Reentrant Locks

$$\frac{}{\Gamma \vdash \{F\}\ c\ \{G\}}$$

- A thread can safely execute command c with initial resource (permissions) F and end with resource G.
- Threads *own* resources and use resources to read/write to the heap.

To deal with non-reentrant locks, O'Hearn proposed to attach *resource invariants* to locks:

$$\frac{I \text{ is } x\text{'s resource invariant}}{\Gamma \vdash \{F\}\ x.\texttt{lock()}\ \{F * I\}}$$

↳ Locks also own resources.

↳ When a lock is acquired, it *lends* its resource invariant to the acquiring thread.

Reentrant Locks for Object Oriented Programs

Resource invariants are described with *abstract predicates* (Parkinson'05):

```
class C{
  int f;

  pred inv = f ↦¹ _;
}
```

```
class D extends C{
  int g;

  extends pred inv by g ↦¹ _;
}
```

Intuition:

- If x's dynamic type is C, then $x.\mathtt{inv}$ is $x.f \overset{1}{\mapsto} \_$
- If x's dynamic type is D, then $x.\mathtt{inv}$ is $(x.f \overset{1}{\mapsto} \_ * x.g \overset{1}{\mapsto} \_)$
- Resource invariants get stronger in subclasses.

Reentrant Locks for Object Oriented Programs

Resource invariants are described with *abstract predicates* (Parkinson'05):

```
class C{
  int f;

  pred inv = f ↦¹ _;
}
```

```
class D extends C{
  int g;

  extends pred inv by g ↦¹ _;
}
```

Intuition:

- If x's dynamic type is C, then x.inv is $x.f \overset{1}{\mapsto} \_$
- If x's dynamic type is D, then x.inv is $(x.f \overset{1}{\mapsto} \_ * x.g \overset{1}{\mapsto} \_)$
- Resource invariants get stronger in subclasses.

Resource invariants are represented by the distinguished predicate inv:

```
class Object{
  pred inv = true;
}
```

Separation Logic for Reentrant Locks

O'Hearn's rule does not support reentrant locks:

$\{$`true`$\}$
x`.lock();`
$\{I\}$ (I is x's resource invariant)
x`.lock();`
$\{I * I\}$ $\leftarrow$ wrong!
`...`

Separation Logic for Reentrant Locks

4 formulas to speak about locks (where S is a *multiset*):

$$F \ ::= \ \ldots \mid \texttt{lockset(}S\texttt{)} \mid S \; \texttt{contains} \; x \mid x.\texttt{Initialized} \mid x.\texttt{Fresh} \mid \ldots$$

- *F linear*: F does not imply $F * F$.
- *F copyable*: F implies $F * F$.

For each thread, we track the set of currently held locks:

- `lockset(`S`)`: S is the multiset of currently held locks. (linear)
- S `contains` x: lockset S contains lock x. (copyable)

Separation Logic for Reentrant Locks

4 formulas to speak about locks (where S is a *multiset*):

$$F \ ::= \ \ldots \mid \texttt{lockset}(S) \mid S\ \texttt{contains}\ x \mid x.\texttt{Initialized} \mid x.\texttt{Fresh} \mid \ldots$$

- *F linear*: F does not imply $F * F$.
- *F copyable*: F implies $F * F$.

For each thread, we track the set of currently held locks:

- $\texttt{lockset}(S)$: S is the multiset of currently held locks. (linear)
- $S\ \texttt{contains}\ x$: lockset S contains lock x. (copyable)

For each lock, we track its abstract lock state:

- $x.\texttt{Fresh}$: ticket to initialize x's resource invariant. (linear)
- $x.\texttt{Initialized}$: x's resource invariant is initialized. (copyable)

Initializing Locks

$$\frac{C\texttt{<}\bar{\pi}\texttt{>} <: \Gamma(x)}{\Gamma \vdash \begin{array}{c}\{\texttt{true}\}\\ x\texttt{=new}\ C\texttt{<}\bar{\pi}\texttt{>}\\ \{x.\texttt{init} * C\ \texttt{isclassof}\ x * \circledast_{\Gamma(u)<:\texttt{Object}}\, x\,\texttt{!=}\,u * x.\texttt{Fresh}\}\end{array}}\ (\text{New})$$

↳ After creation a lock cannot be acquired: $x.\texttt{Initialized}$ misses to match (Lock)'s precondition.

$$\frac{}{\Gamma \vdash \begin{array}{c}\{\texttt{lockset}(S) * x.\texttt{inv} * x.\texttt{Fresh}\}\\ x.\texttt{commit}\\ \{\texttt{lockset}(S) * \texttt{!}(S\ \texttt{contains}\ x) * x.\texttt{Initialized}\}\end{array}}\ (\text{Commit})$$

↳ $x.\texttt{commit}$ is a no-op.

↳ After being committed a lock can be acquired: (Commit)'s postcondition matches (Lock)'s precondition.

Acquiring Locks

$$\frac{}{\Gamma \vdash \begin{array}{c}\{\texttt{lockset}(S) * \texttt{!}(S\ \texttt{contains}\ x) * x.\texttt{Initialized}\} \\ x.\texttt{lock()} \\ \{\texttt{lockset}(x \cdot S) * x.\texttt{inv}\}\end{array}}\ \text{(Lock)}$$

↳ Threads obtain resource invariants only when *initially acquiring* a lock (precondition $\texttt{!}(S\ \texttt{contains}\ x)$).

↳ Nothing special to handle subclassing.

$$\frac{}{\Gamma \vdash \{\texttt{lockset}(x \cdot S)\}x.\texttt{lock()}\{\texttt{lockset}(x \cdot x \cdot S)\}}\ \text{(Re-Lock)}$$

↳ Reentrant acquirement (precondition $\texttt{lockset}(x \cdot S)$): x's resource invariant is not obtained.

Releasing Locks

$$\frac{}{\Gamma \vdash \{\texttt{lockset}(x \cdot x \cdot S)\} x.\texttt{unlock()} \{\texttt{lockset}(x \cdot S)\}} \text{(Re-Unlock)}$$

↳ Releasing x but x's reentrancy level > 1 (precondition $\texttt{lockset}(x \cdot x \cdot S)$): invariant not abandoned.

$$\frac{}{\Gamma \vdash \{\texttt{lockset}(x \cdot S) * x.\texttt{inv}\} x.\texttt{unlock()} \{\texttt{lockset}(S)\}} \text{(Unlock)}$$

↳ If x's reentrancy level is not known to be > 1, x's resource invariant is abandoned.

Reasoning about the Absence of Aliasing

Problem: (Lock)'s precondition requires that x is not in the current lockset.

↳ To establish this precondition, one has to show that x does not alias any member of the current lockset.

↳ Separation logic tries to avoid the need to reason about the absence of aliasing! We sneak some of this back into the program logic.

↳ Our next example shows that we can still deal with fine-grained concurrency in spite of this.

Reasoning about the Absence of Aliasing

Problem: (Lock)'s precondition requires that x is not in the current lockset.

↳ To establish this precondition, one has to show that x does not alias any member of the current lockset.

↳ Separation logic tries to avoid the need to reason about the absence of aliasing! We sneak some of this back into the program logic.

↳ Our next example shows that we can still deal with fine-grained concurrency in spite of this.

- We have classes parametrized by specification values (= Java + permissions + locksets).
- We can encode ownership type-system to help us deal with aliasing.

Lock Coupling: A Test Case for Fine-grained Concurrency

Lock coupling list algorithm:

- Standard test case for fine-grained concurrency (Gotsman et al'07, Parkinson et al'07).
- No single lock that guards the entire list.
- List-traversing methods acquire each of the node locks right before accessing the node, and release it again after moving to the next node.

↳ The precondition of traversal methods requires that none of the list nodes is in the current lockset:

```
class List{
  pred nodes_unlocked<Lockset S> = ???;

  requires nodes_unlocked<S>;
  ensures  nodes_unlocked<S>;
  void traverse(){...}
}
```

Lock Coupling: A Solution with Type-based Ownership

```
class Node<Object owner>{
  public int val;
  public Node<owner> next;

  extends pred inv by (∃ Node<owner> x)(val ↦¹ _  * next ↦¹ x * x.Initialized)
}


class List{
  Node<this> header;
  extends pred inv by (∃ Node<this> x)(header ↦¹ x * x.initialized);
  pred nodes_unlocked<Lockset s> = lockset(S) * (∀ Object owner,Node<owner> x)
                                                (S contains x -* owner != this);

  requires nodes_unlocked<S>;
  ensures  nodes_unlocked<S>;
  void traverse(){...}
}
```

- We universally quantify over a type parameter: we exploit that in our language type system and program logic are inter-dependent.

Start/Join

- Multithreading in Java:
  - Threads should define the `run()` method.
  - When `start()` is called on a thread, the new thread is forked and its `run()` method executes in parallel with the rest of the program.
  - A thread `t` is finished when `t.join()` returns.
- We use `run()`'s precondition as `start()`'s precondition.
- We use `run()`'s postcondition as `join()`'s postcondition.

Start/Join

- Parent threads pass resources to newly created threads.
- Alive threads take back resources of terminated threads.

$F \;::=\; \dots \mid \texttt{Join}(x, \pi) \mid \dots$

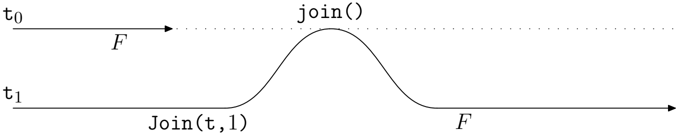
↳ Ticket to take back fraction π of x's resource when x terminates.

$\pi \cdot F$

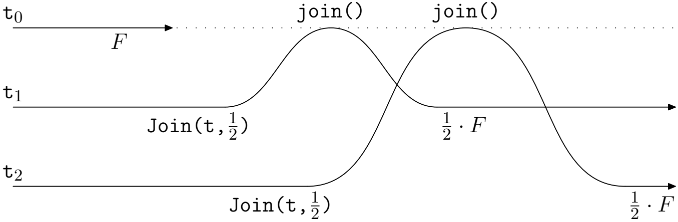
↳ Formula F *scaled by* π (defined as a derived form)

$$\frac{\Gamma \vdash x : C \qquad F \text{ is } \texttt{run}\text{'s postcondition in class C}}{\{x \,\texttt{!=}\, \texttt{null} * \texttt{Join}(x, \pi)\}\; x.\texttt{join}()\; \{\pi \cdot F\}} \text{ (Join)}$$

Start/Join: Two Examples



Thread $\texttt{t}_1$ takes back $\texttt{t}_0$'s resource.



Threads $\texttt{t}_1$ and $\texttt{t}_2$ both take back half of $\texttt{t}_0$'s resource.

Semantics of Formulas

$\mathscr{R}; s \models F$

↳ Resource $\mathscr{R}$ satisfies F.

Resources are quintets $(h, \mathscr{P}, \mathscr{L}, \mathscr{F}, \mathscr{I})$. Resources are owned by threads.

↳ h is the part of the heap owned by the thread considered.

↳ $\mathscr{P}$ is a *permission table*: it contains permissions to access h and join threads.

↳ $\mathscr{L}$ is an *abstract lock table*: it keeps track of the lockset of the thread considered.

↳ $\mathscr{F}$ is a *fresh set*: it is the set of objects that can be be initialized by the thread considered.

↳ $\mathscr{I}$ is an *initialized set*: it is the global set of initialized objects.

Semantics of Formulas

Semantics of locksets:

$$
\begin{array}{rcl}
[\![\texttt{nil}]\!]_h^s & \triangleq & \lambda x.\, 0 \\
[\![S \cdot S']\!]_h^s & \triangleq & \lambda x.\, [\![S]\!]_h^s(x) + [\![S']\!]_h^s(x)
\end{array}
$$

$$
\begin{array}{lcllll}
(h, \mathscr{P}, \mathscr{L}, \mathscr{F}, \mathscr{I}); s & \models & x.f \overset{\pi}{\mapsto} v & \text{iff} & [\![x.f]\!]_h^s = v \text{ and } [\![\pi]\!] \leqslant \mathscr{P}([\![x]\!]_h^s, f) \\
(h, \mathscr{P}, \mathscr{L}, \mathscr{F}, \mathscr{I}); s & \models & \texttt{lockset}(S) & \text{iff} & \mathscr{L}(t) = [\![S]\!]_h^s \text{ for some } t \\
(h, \mathscr{P}, \mathscr{L}, \mathscr{F}, \mathscr{I}); s & \models & S \;\texttt{contains}\; x & \text{iff} & [\![S]\!]_h^s([\![x]\!]_h^s) > 0 \\
(h, \mathscr{P}, \mathscr{L}, \mathscr{F}, \mathscr{I}); s & \models & x.\texttt{Initialized} & \text{iff} & [\![x]\!]_h^s \in \mathscr{I} \\
(h, \mathscr{P}, \mathscr{L}, \mathscr{F}, \mathscr{I}); s & \models & x.\texttt{Fresh} & \text{iff} & [\![x]\!]_h^s \in \mathscr{F} \\
(h, \mathscr{P}, \mathscr{L}, \mathscr{F}, \mathscr{I}); s & \models & \texttt{Join}(x, \pi) & \text{iff} & [\![\pi]\!] \leqslant \mathscr{P}([\![x]\!]_h^s, \texttt{join})
\end{array}
$$

Preservation

$$\frac{\mathscr{R} = (h, \mathscr{P}, abs(l), \mathscr{F}, \mathscr{I}) \quad \mathscr{R}'; \varnothing \models \circledast_{o \in ready(\mathscr{R})} o.\texttt{inv} \\ \mathscr{R} \vdash (t_0 \mid \ldots \mid t_n) : \diamond \quad \mathscr{R} \# \mathscr{R}'}{\langle h, l, t_0 \mid \ldots \mid t_n \rangle : \diamond} \text{(State)}$$

- $t_0 \mid \ldots \mid t_n$ is the program's thread pool.
  - The thread pool is verified w.r.t. $\mathscr{R}$.
- h is the program's heap.
  - The program is verified w.r.t. to h: $\mathscr{R} = (h, \ldots)$
- l is the program's *concrete lock table*.
  - The program is verified w.r.t. to an abstraction of l: $\mathscr{R} = (\ldots, abs(l), \ldots)$

- $\mathscr{R}'$ is a resource that satisfy the resource invariants of unheld locks (looked up by $ready(\mathscr{R})$)
- $\mathscr{R} \# \mathscr{R}'$: $\mathscr{R}$ and $\mathscr{R}'$ are *compatible*.

Preservation

$$\frac{}{\mathscr{R} \vdash \varnothing : \diamond} \text{ (Empty Pool)} \qquad \frac{\mathscr{R} \vdash t_0 : \diamond \quad \mathscr{R}' \vdash (t_1 \mid \ldots \mid t_n) : \diamond}{\mathscr{R} * \mathscr{R}' \vdash (t_0 \mid t_1 \mid \ldots \mid t_n) : \diamond} \text{ (Cons Pool)}$$

$$\frac{\mathscr{R}; s \models F \quad \{F\}\, c\, \{G\}}{\mathscr{R} \vdash o \; is \; (s \; in \; c) : \diamond} \text{ (Thread)}$$

↳ $o \; is \; (s \; in \; c)$ represents a thread.

- o: thread identifier
- s: thread-local stack
- c: command to execute.

Achievements

- A concurrent separation logic for multithreaded Java.
- Combination of abstract predicates with class axioms and value-parametrized types, to express relations between abstract predicates and dependencies between object interfaces.
- Flexible combination of abstract predicates and fractional permissions, through permission-parametrized predicates.
- Support for read-sharing of `join's` postcondition (not supported in Gotsman et al.'s work).
- Separation logic rules for re-entrant locks (in progress).
- Soundness proof.
- Challenge examples proven (concurrent iterator, lock coupling algorithm, worker thread).

Future Work

- Generation of proof obligations
- Automatic support for solving proof obligations
- Richer specification language
- Formalization in Coq (some initial work already) ?
- Compilation to Concurrent CMinor ?

Lock Coupling Implementation

```
class List{
  public Node<this> header;

  extends pred inv by (∃ Node<this> x)(header ↦¹ x * x.initialized);

  requires lockset(S) * (∀ Object owner,Node<owner> x)(S contains x -* owner!=this);
  ensures  lockset(S) * (∀ Object owner,Node<owner> x)(S contains x -* owner!=this);
  public void delete(int n){
    lock();
    Node<this> current = header;
    current.lock();
    if(current.val==n){
      header=current.next;
      unlock(); current.unlock();
      return;
    }
    unlock();
    Node<this> prev = current;
    current = prev.next;
    current.lock();
    while(current.next != null && current.val != n){
      prev.unlock();
      prev=current;
      current=prev.next;
      current.lock();
    }
    prev.next = current.next;
    prev.unlock();
  }
}
```