An Annotation Assistant for Interactive Debugging of Programs with Common Synchronization Idioms

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The QED method [POPL’09]

\[(P_1, I_1) \rightarrow \ldots \rightarrow (P_i, I_i) \rightarrow \ldots \rightarrow (P_n, I_n)\]

**Central idea:** Atomicity as proof tool

**Proof strategy:** Transform program by enlarging atomic blocks

**P_1** certified correct by analyzing **P_n**

- **Soundness:** Starting from **I_n**, **P_n** satisfies all assertions
  \[\rightarrow P_1\] satisfies all assertions

**Difficult to prove**
- Fine-grain concurrency
- Annotations at every interleaving point

**Easy to prove**
- Larger atomic blocks
- Local, sequential analysis within atomic blocks
Synchronization idiom

• Well-known pattern to restrict the amount of concurrency
  – Mutual-exclusion, reentrant locks, readers/writer lock, events
  – Implementations must guarantee the pattern
    • Library or custom implementation

• Example: Readers/writer lock
  – Two kinds of critical sections: Readers, writers
  – At any time: Multiple readers or only one writer
What we propose

• Application of tool to, for example, readers/writer lock
  – Identify the code implementing idiom
  – Annotate critical sections protected by idiom
  – Show atomicity of critical regions
  – **Determine errors about use of idiom**
    • Conflicting actions due to missing synchronization
    • Code disobeying the pattern of readers/writer lock
    • Incorrect implementation of idiom by the program
Example

\[ T_1 \quad x := 0 \ ; \ v := 0 \]

\[ T_2 \quad \text{Update}(1) \quad || \quad \text{Update}(2) \quad || \quad (x_1, v_1) := \text{Read}() \quad || \quad (x_2, v_2) := \text{Read}() \]

\[ T_1 \quad \text{assert } (v_1 == v_2) \implies (x_1 == x_2) \]

\[ \text{Update}(k) \]
\[ \quad \text{-------------} \]
\[ \quad x := k; \]
\[ \quad v := v + 1; \]

\[ \text{Read}() \]
\[ \quad \text{-------------} \]
\[ \quad \text{return } (x, v); \]
Readers/writer lock

\[ T_1 \quad x := 0 \quad ; \quad v := 0 \]

\[ T_2 \quad \text{Update}(1) \quad || \quad \text{Update}(2) \quad || \quad (x_1, v_1) := \text{Read()} \quad || \quad (x_2, v_2) := \text{Read()} \]

\[ T_1 \quad \text{assert} \quad (v_1 == v_2) \implies (x_1 == x_2) \]

Update\( (k) \)
\[
\begin{align*}
\text{AcqWrite}(); \\
x &:= k; \\
lv &:= v; \\
v &:= lv + 1; \\
\text{RelWrite}();
\end{align*}
\]

Read\( () \)
\[
\begin{align*}
\text{AcqRead}(); \\
lx &:= x; \\
lv &:= v; \\
\text{RelRead}(); \\
\text{return} \quad (lx, \ lv);
\end{align*}
\]
Annotions

\[ w = 0 : \text{Write lock free} \]
\[ w = \text{tid} : \text{Write lock held by current thread} \]
\[ r[\text{tid}] = \text{true} : \text{Read lock held by current thread} \]
\[ r[\text{tid}] = \text{false} : \text{Read lock not held by current thread} \]

\textbf{Update} (k)

\begin{verbatim}
    < AcqWrite(); w := tid; >
    < assert w == tid; x := k; >
    < assert w == tid; lv := v; >
    < assert w == tid; v := lv + 1; >
    < assert w == tid; RelWrite(); w := 0; >
\end{verbatim}

\textbf{Read()}

\begin{verbatim}
    < AcqRead(); w := 0; r[\text{tid}] := true; >
    < assert w == 0; lx := x; >
    < assert w == 0; lv := v; >
    < assert w == 0; RelRead(); r[\text{tid}] := false; >
    return (lx, lv);
\end{verbatim}
Annotations indicate conflicting actions not enabled from the same state.

Update by T3 (tid₃)
< assert w == tid₃; x := k₃; >

Read by T4 (tid₄)
< assert w == 0; lx₄ := x; >

Thread id cannot be 0: tid₃ ≠ 0

Update by T2 (tid₂)
< assert w == tid₂; x := k₂; >

Update by T3 (tid₃)
< assert w == tid₃; x := k₃; >

Run by different threads: tid₂ ≠ tid₃
Verifying annotation

Update(k) ----------- atomic {
  AcqWrite(); w := tid;
  assert w == tid; x := k;
  assert w == tid; lv := v;
  assert w == tid; v := lv + 1;
  assert w == tid; RelWrite(); w := 0;
}

Read() ----------- atomic {
  AcqRead(); w := 0; r[tid] := true;
  assert w == 0; lx := x;
  assert w == 0; lv := v;
  assert w == 0; RelRead(); r[tid] := false;
  return (lx, lv);
}
Insufficient synchronization

Update \(k\)

\[
\begin{align*}
\text{AcqWrite();} \\
x &:= k; \\
lv &:= v; \\
v &:= lv + 1; \\
\text{RelWrite();}
\end{align*}
\]

Read()

\[
\begin{align*}
lx &:= x; \\
lv &:= v; \\
\text{return (lx, lv);} \\
\end{align*}
\]

\[ \rightarrow \text{Read region not protected by lock} \]

- **Symptom**: Read not annotated
  - Update and Read conflict: Atomicity computation fails
  - Tool shows the conflicting lines, missing annotation

Update \(k\)

\[
\begin{align*}
< \text{AcqWrite();} & \ w := \text{tid}; > \\
< \text{assert w == tid; } x &:= k; > \quad \text{Conflict on x!} \\
< \text{assert w == tid; } lv &:= v; > \\
< \text{assert w == tid; } v &:= lv + 1; > \\
< \text{assert w == tid; RelWrite();} & \ w := 0; > \\
\end{align*}
\]

Read()

\[
\begin{align*}
lx &:= x; \\
lv &:= v; \\
\text{return (lx, lv);} \\
\end{align*}
\]
Incorrect use of idiom

Update (k)
------------
x := k;
lv := v;
v := lv + 1;
RelWrite();

→ Missing acquire before release

• **Symptom:** Tool checks if idiom is used correctly before annotating
  – Warning about missing acquire
Incorrect implementation

```c
AcqWrite()
------------
atomic {
    await (reads == 0);
    write := true;
}
```

Should have been: `(reads == 0 && write == false)`

- **Symptom:** Update not annotated
  - Update and Read conflict: Atomicity computation fails
  - Tool shows the conflicting lines, missing annotation

```c
Update(k)
----------
AcqWrite();
x := k;
lv := v;
v := lv + 1;
RelWrite();
```

```c
Read()
----------
< AcqRead(); w := 0; r[tid] := true; >
< assert w == 0; lx := x; >
< assert w == 0; lv := v; >
< assert w == 0; RelRead(); r[tid]:=false; >
return (lx, lv);
```
Specifying idiom

• **Idiom template**: Abstract description of idiom using auxiliary variables
  – Independent of implementation of idiom

• **Synchronization state**
  - \( w: \text{int} \)
    - \( w == 0 \): Write lock free
    - \( w == \text{tid} \): Write lock held by \( \text{tid} \)
  - \( r: \text{int} \rightarrow \text{bool} \)
    - \( r[\text{tid}] == \text{false} \): Read lock not held by \( \text{tid} \)
    - \( r[\text{tid}] == \text{true} \): Read lock held by \( \text{tid} \)

• **Invariant**: \((\text{exists } t!=0.\; w == t) \implies (\forall u. \; !r[u])\)

• **Atomic operations**:
  - Acquire write: \( w == 0 \rightarrow w == \text{tid} \)
  - Release write: \( w == \text{tid} \rightarrow w == 0 \)
  - Acquire read: \( !r[\text{tid}] \rightarrow r[\text{tid}] \)
  - Release read: \( r[\text{tid}] \rightarrow r[\text{tid}] \)
  - Non-synch actions: \( w \) and \( r \) remain unchanged
Implementing readers/writer lock

Globals: reads: int, write: bool

AcqWrite()
-------------
atomic {
    await (reads == 0 && write == false);
    write := true;
}

RelWrite()
-------------
atomic {
    write := false;
    reads := reads + 1;
}

AcqRead()
-------------
atomic {
    await (write == false);
    reads := reads + 1;
}

RelRead()
-------------
atomic {
    reads := reads - 1;
}
Connecting specification to implementation

- Identifying code implementing readers/writer lock
  - Idiom formulas
  - \( P_R \): States where reader lock is held
    - \( \text{reads} > 0 \land \text{write} = \text{false} \)
  - \( P_W \): States where writer lock is held
    - \( \text{reads} = 0 \land \text{write} = \text{true} \)
- Associating abstract description with implementation
  - Invariant:
    1. \( P_R \implies \neg P_W \)
    2. \( \neg P_W \iff (w = 0) \)
    3. \( P_R \implies (\exists t. r[t]) \)
  - Transition: How actions of the program modifies \( r \) and \( w \)
Conclusion

• Manually annotating program is difficult, error-prone
  – Too weak: Insufficient to show non-interference
  – Too strong: Adds false non-interference

• Automated annotations: Precise and reflects idiom’s semantics
  – Useful hints on the use of idiom
  – Idiom template: Generic handling of idiom independent of implementations

• Evidence from the literature
  – Idiom implementations, programs using idioms

• Supported idioms:
  – Mutual-exclusion, reentrant locks, readers/writer lock, events

• Future work: Barriers, fork/join parallelism