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

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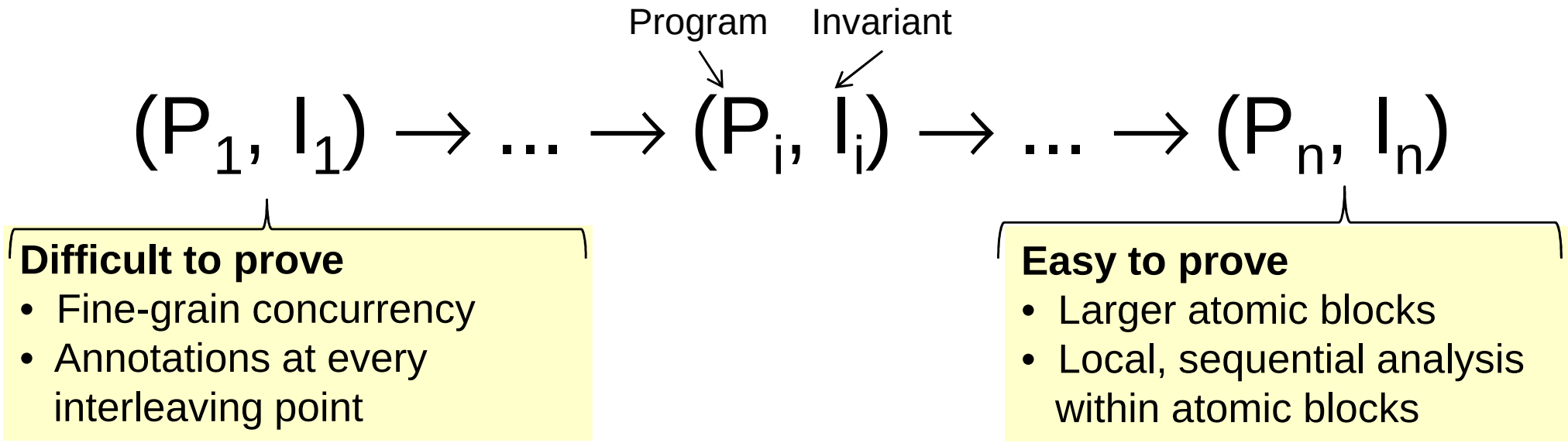
The QED method [POPL'09]



- 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
    → P_1 satisfies all assertions

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


```
T1  x := 0  ;  v := 0

   T2              T3                    T4                          T5
Update(1)  ||  Update(2)  ||  (x1,v1) := Read()  ||  (x2,v2) := Read()

T1  assert (v1 == v2) ==> (x1 == x2)
```

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

```
Read()
----------
return (x, v);
```

Readers/writer lock


```
T1  x := 0  ;  v := 0

   T2              T3                    T4                          T5
Update(1)  ||  Update(2)  ||  (x1,v1) := Read()  ||  (x2,v2) := Read()

T1  assert (v1 == v2) ==> (x1 == x2)
```

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

```
Read()
----------
AcqRead();
lx := x;
lv := v;
RelRead();
return (lx, lv);
```

Annotations


```
w == 0          : Write lock free
w == tid        : Write lock held by current thread
r[tid] == true  : Read lock held by current thread
r[tid] == false : Read lock not held by current thread
```

```
Update(k)
-----------
< 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()
-----------
< 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);
```

Conflict check

Annotations indicate conflicting actions not enabled from the same state.

Update by T3 (tid_3)
< assert w == tid_3; x := k_3; >

Read by T4 (tid_4)
< assert w == 0; lx_4 := x; >

Thread id cannot be 0: **tid_3 != 0**

Update by T2 (tid_2)
< assert w == tid_2; x := k_2; >

Update by T3 (tid_3)
< assert w == tid_3; x := k_3; >

Run by diffierent threads: **tid_2 != tid_3**

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

```
Read()
-----------
lx := x;
lv := v;
return (lx, lv);
```

⟶ 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)
-----------
< 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; >
```

Conflict on **x** !

```
Read()
-----------
lx := x;
lv := v;
return (lx, lv);
```

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


```
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

```
Update(k)                          Read()
-----------                        -----------
AcqWrite();                        < AcqRead(); w := 0; r[tid] := true; >
x := k;          Conflict on x !   < assert w == 0; lx := x; >
lv := v;                           < assert w == 0; lv := v; >
v := lv + 1;                       < assert w == 0; RelRead(); r[tid]:=false; >
RelWrite();                        return (lx, lv);
```

Specifying idiom

- Idiom template: Abstract description of idiom using auxiliary variables
  - Independent of implementation of idiom

- Synchronization state
  - **`w: int`**
    - **`w == 0`** : Write lock free
    - **`w == tid`** : Write lock held by **`tid`**
  - **`r: int -> bool`**
    - **`r[tid] == false`**: Read lock not held by **`tid`**
    - **`r[tid] == true`** : Read lock held by **`tid`**

- Invariant: **`(exists t!=0. w == t) ==> (forall u. !r[u])`**
- Atomic operations:
  - Acquire write: **`w == 0 --> w == tid`**
  - Release write: **`w == tid -->  w == 0`**
  - Acquire read: **`!r[tid] --> r[tid]`**
  - Release read: **`r[tid] --> r[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;
}

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
    - **`reads > 0 && write == false`**
  - P_W: States where writer lock is held
    - **`reads == 0 && write == true`**
- Associating abstract description with implementation
  - Invariant:

    1. P_R ==> !P_W

    2. !P_W <==> (w == 0)

    3. P_R ==> (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