Computer-Aided Reasoning for Software

CSE507

Model Checking II

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Today

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Last lecture

- Model checking basics

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- Software model checking with SLAM

Based on lectures by Tom Ball and Sriram K. Rajamani. See the **SLAM project** webpage for details.

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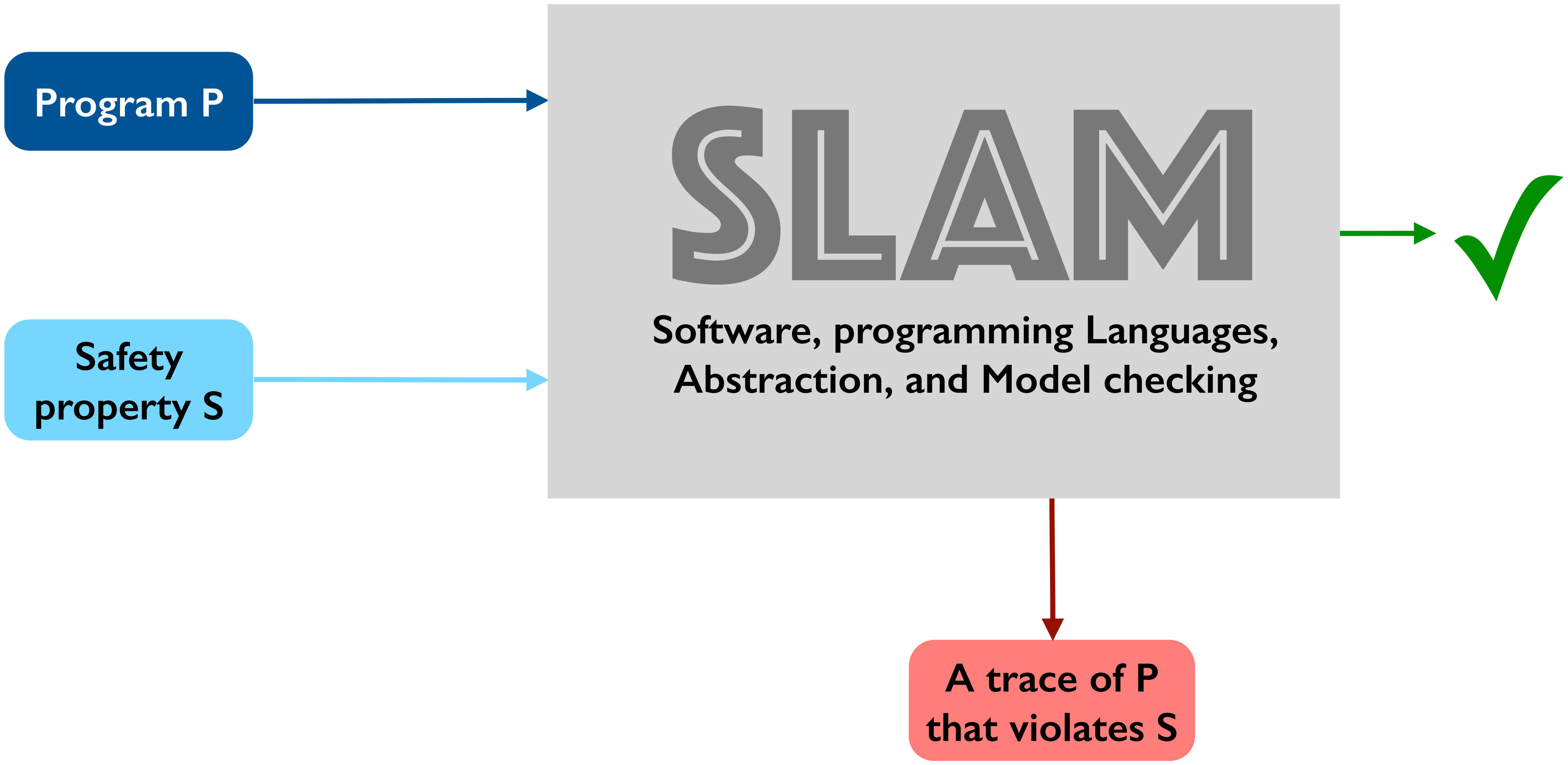
> Based on lectures by Tom Ball and Sriram K. Rajamani. See the **SLAM project** webpage for details.

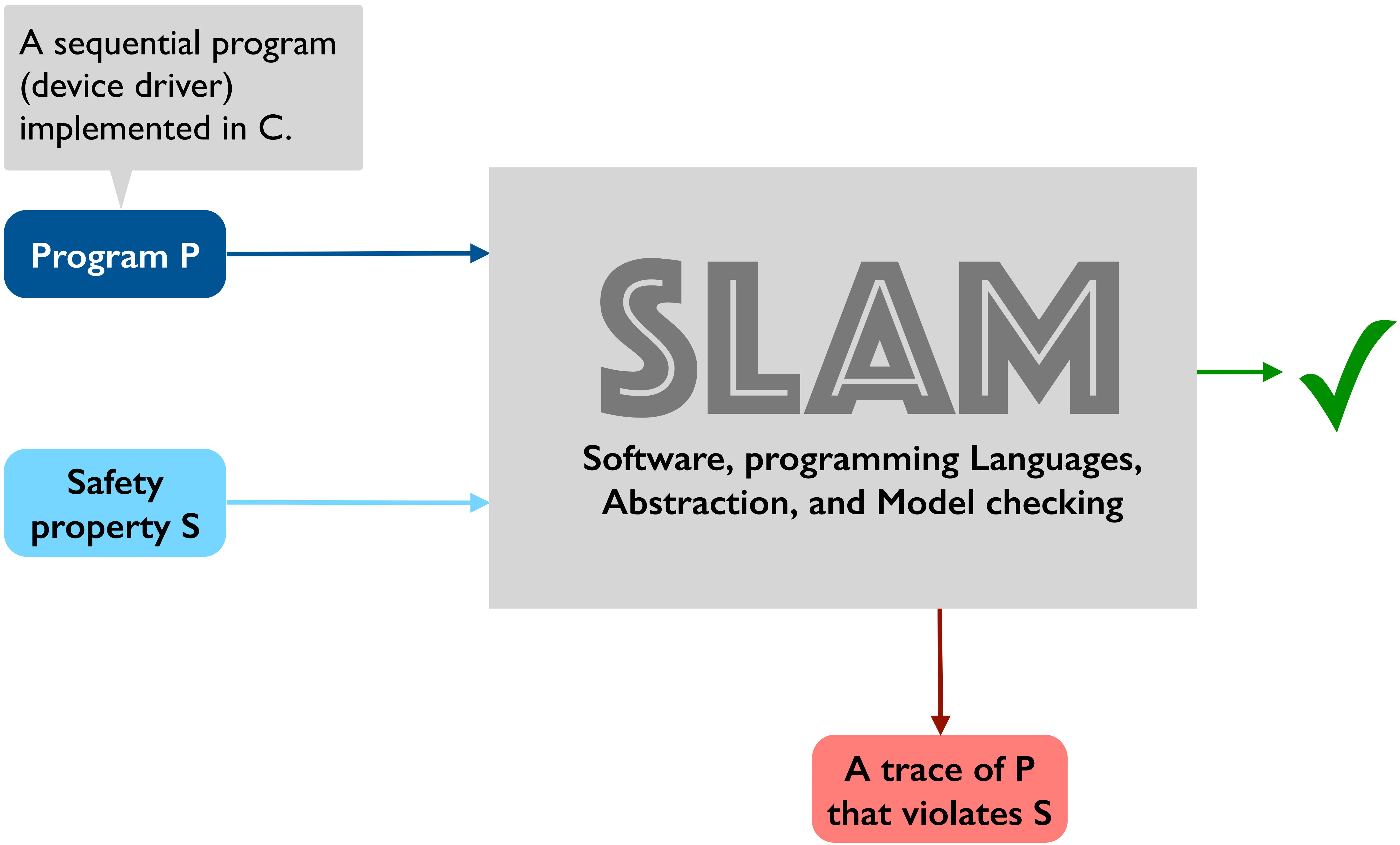
Reminders

- **Homework 3** is due on today at 11pm
- Project demos will be held on Dec 08, 10:30-12:20, in MGH 254

Overview of SLAM



Overview of SLAM



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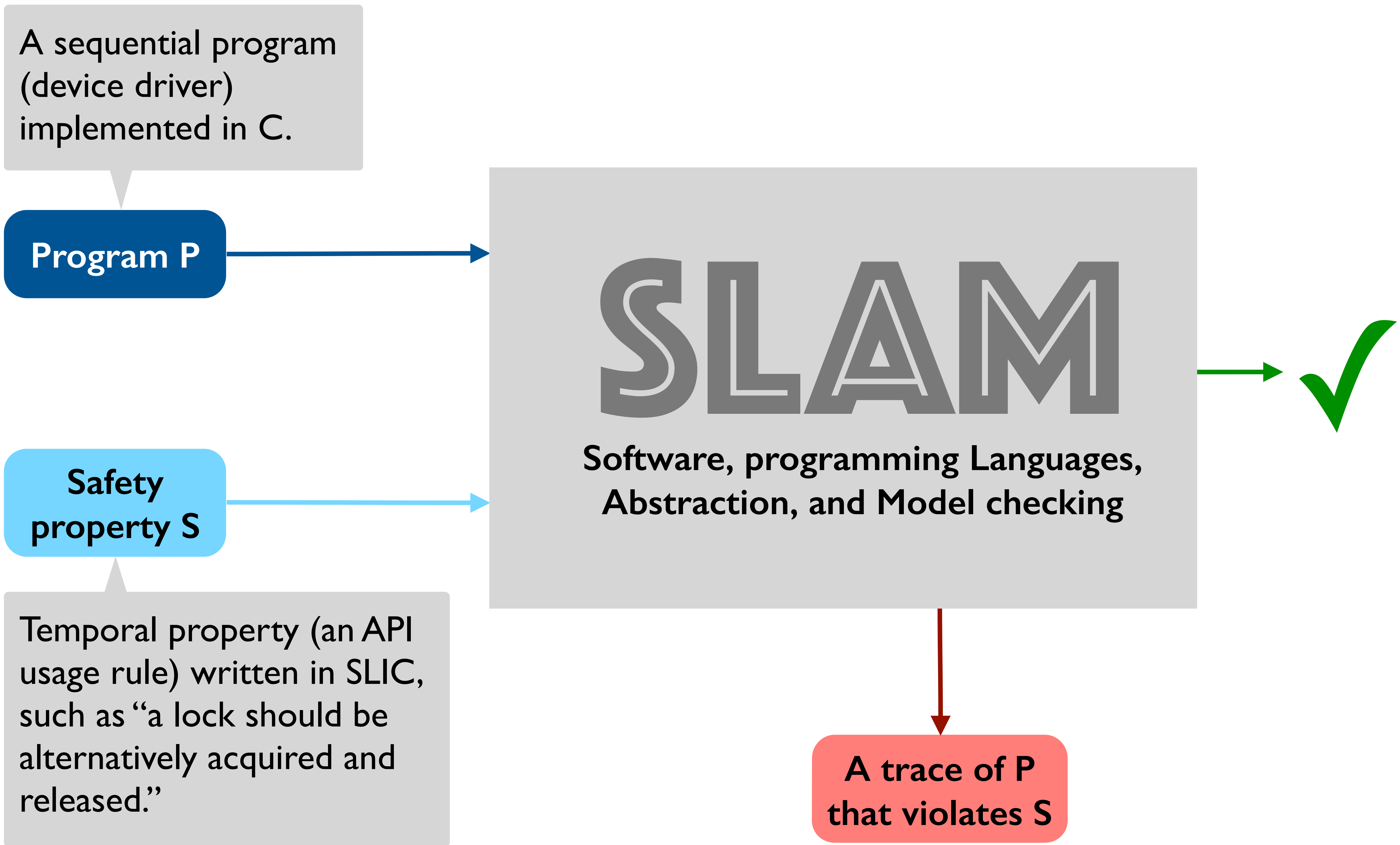

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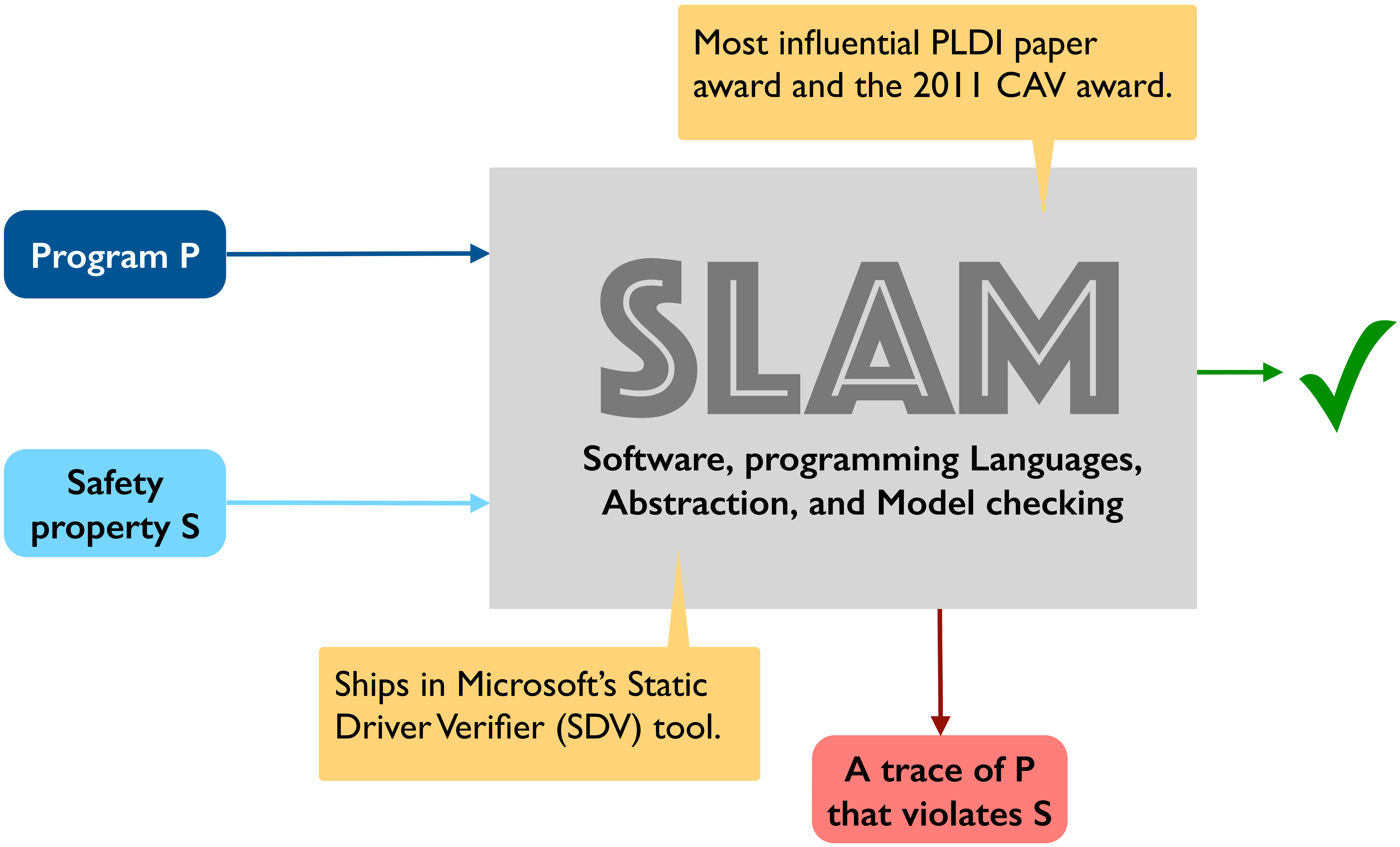
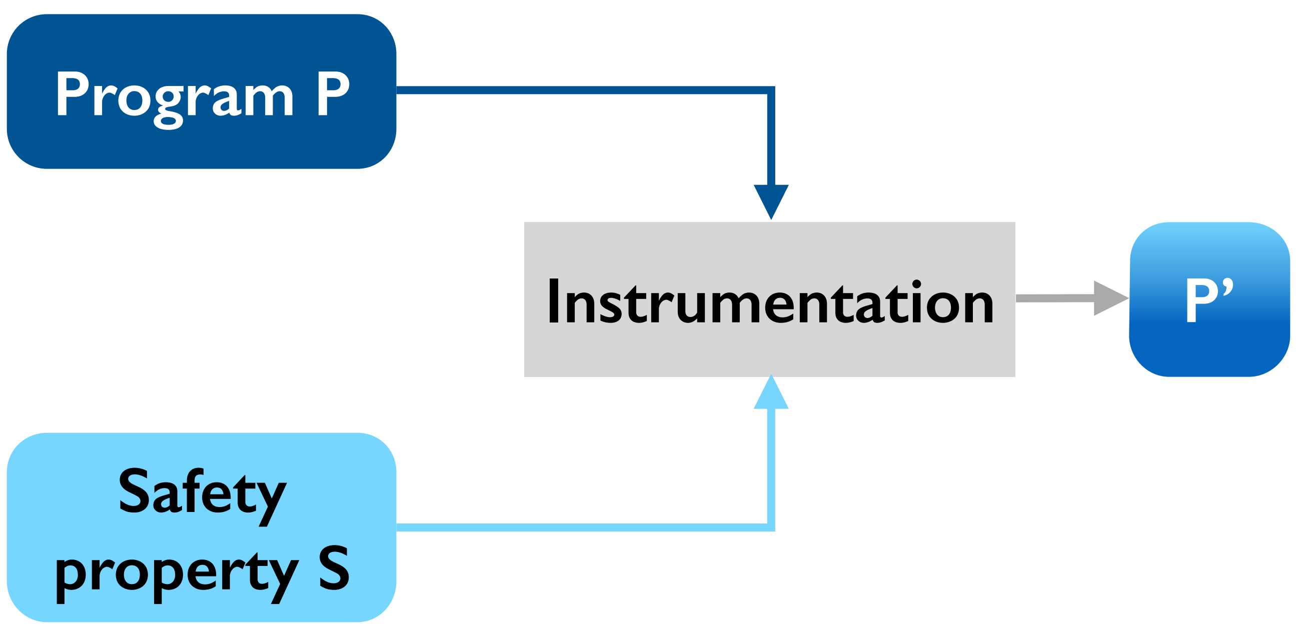


The SLAM process



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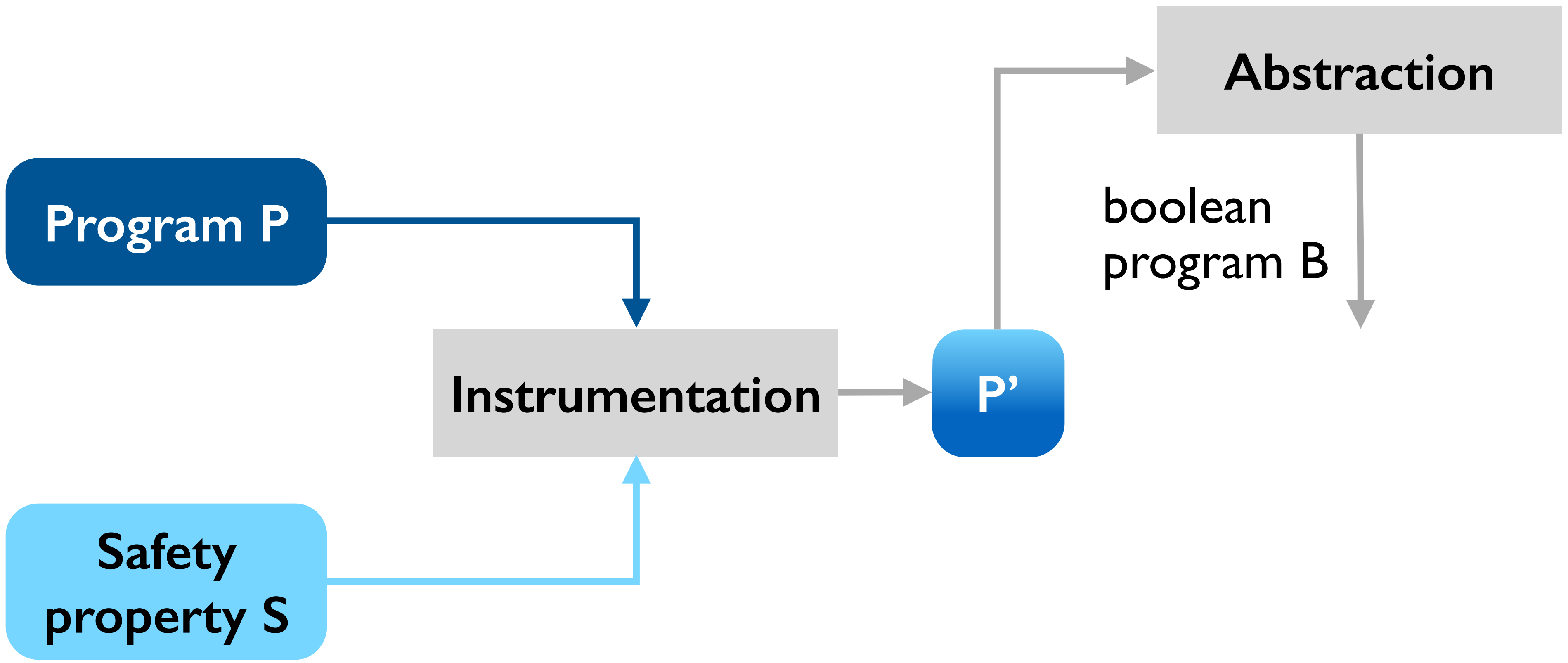

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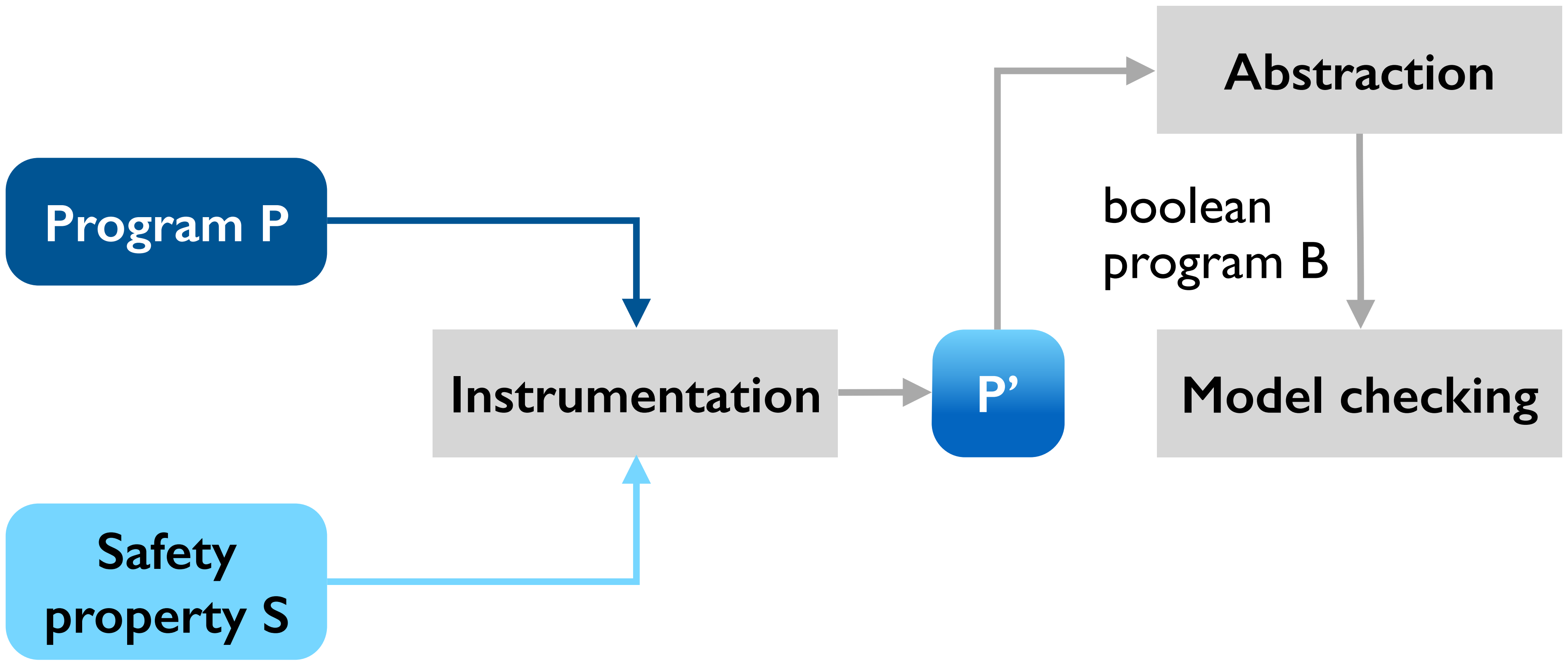

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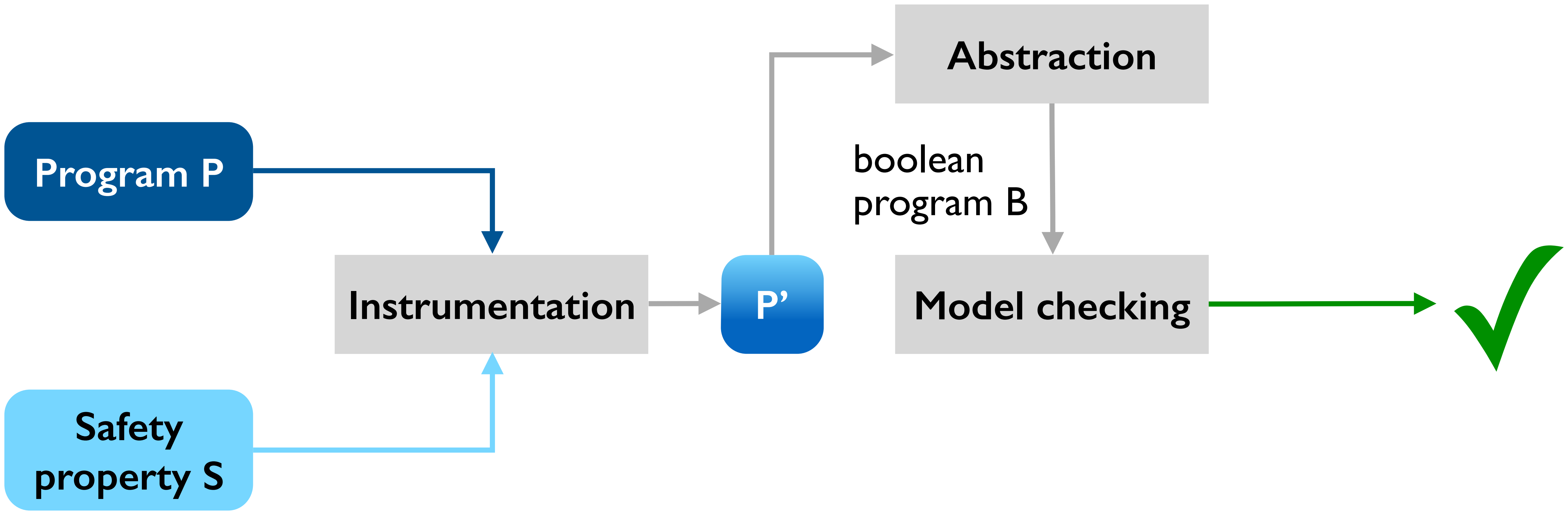

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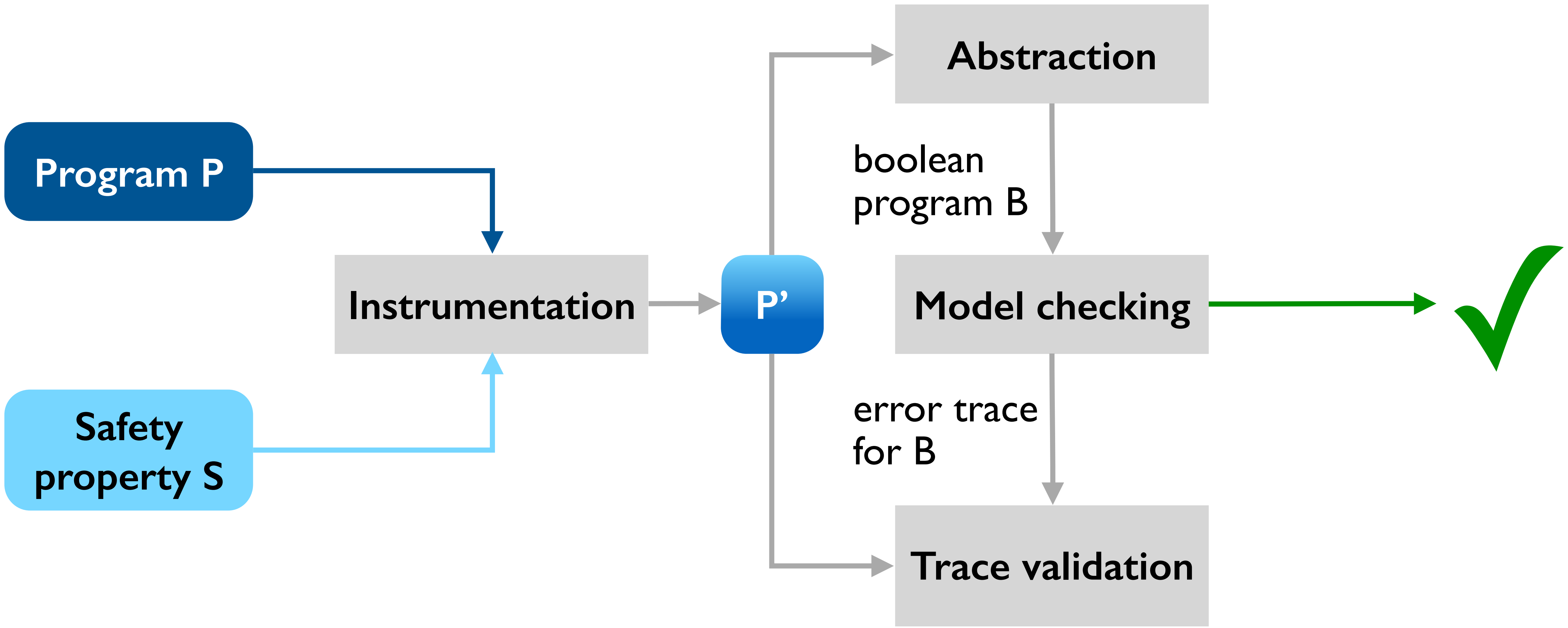

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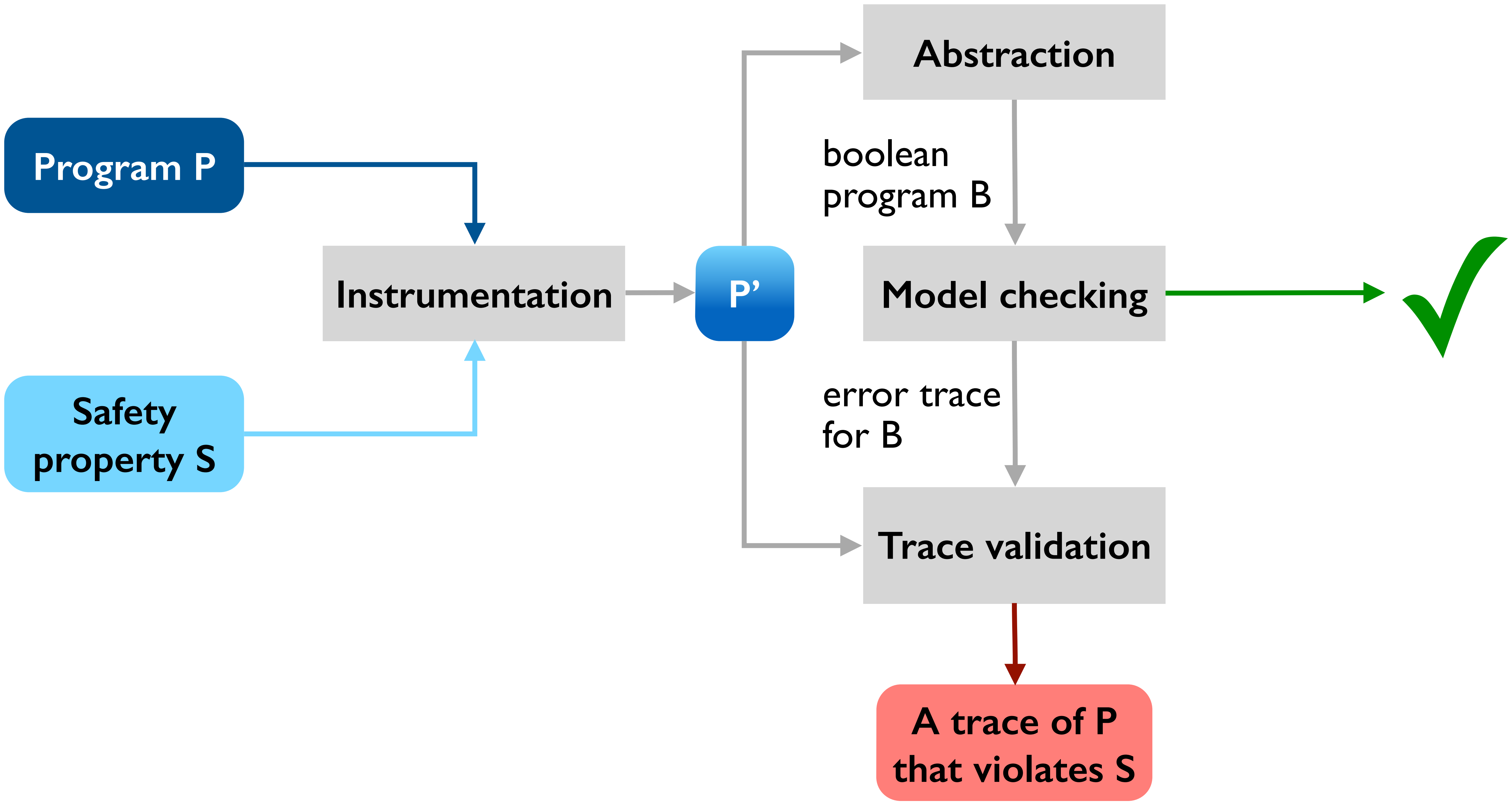

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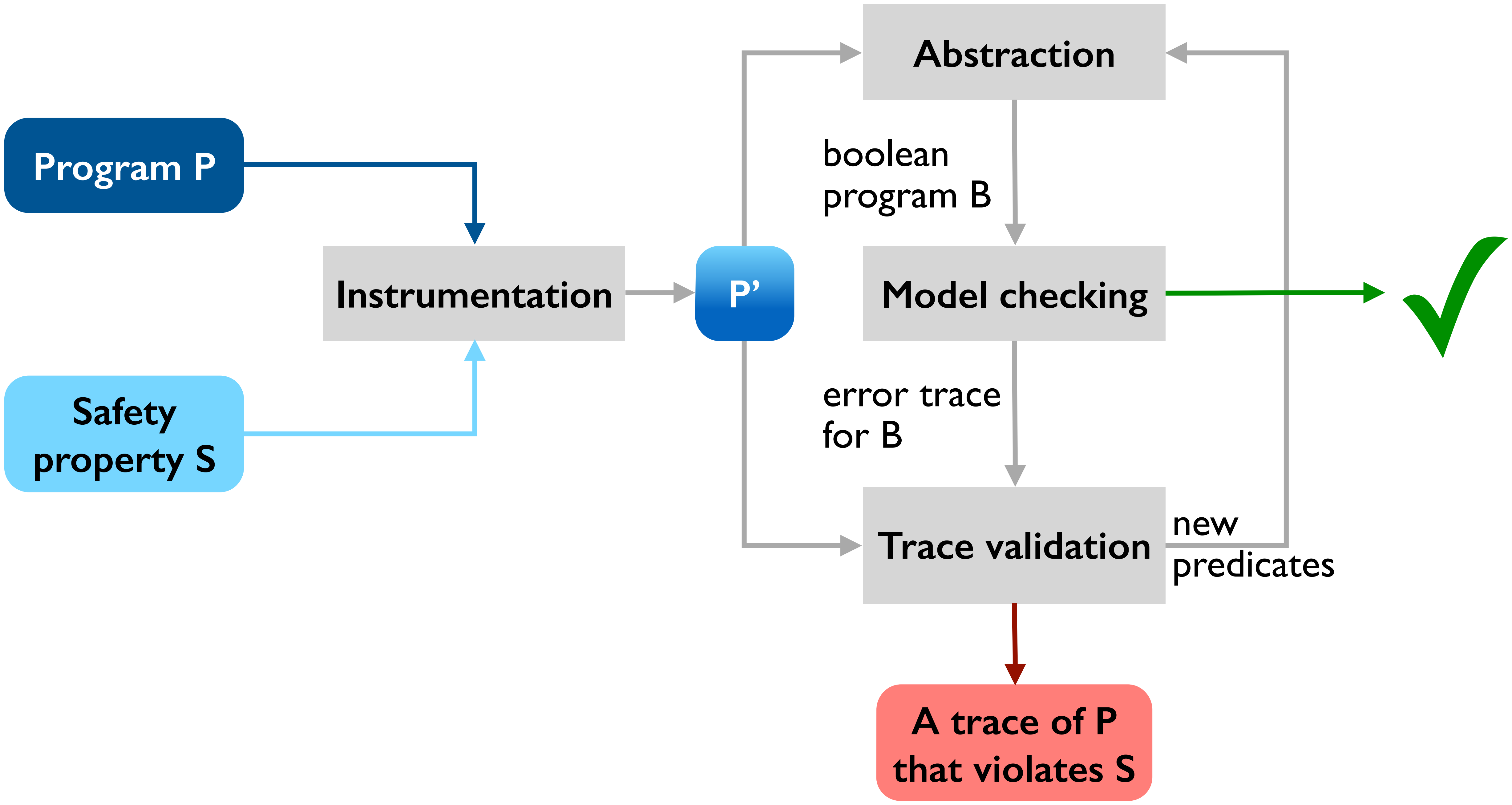

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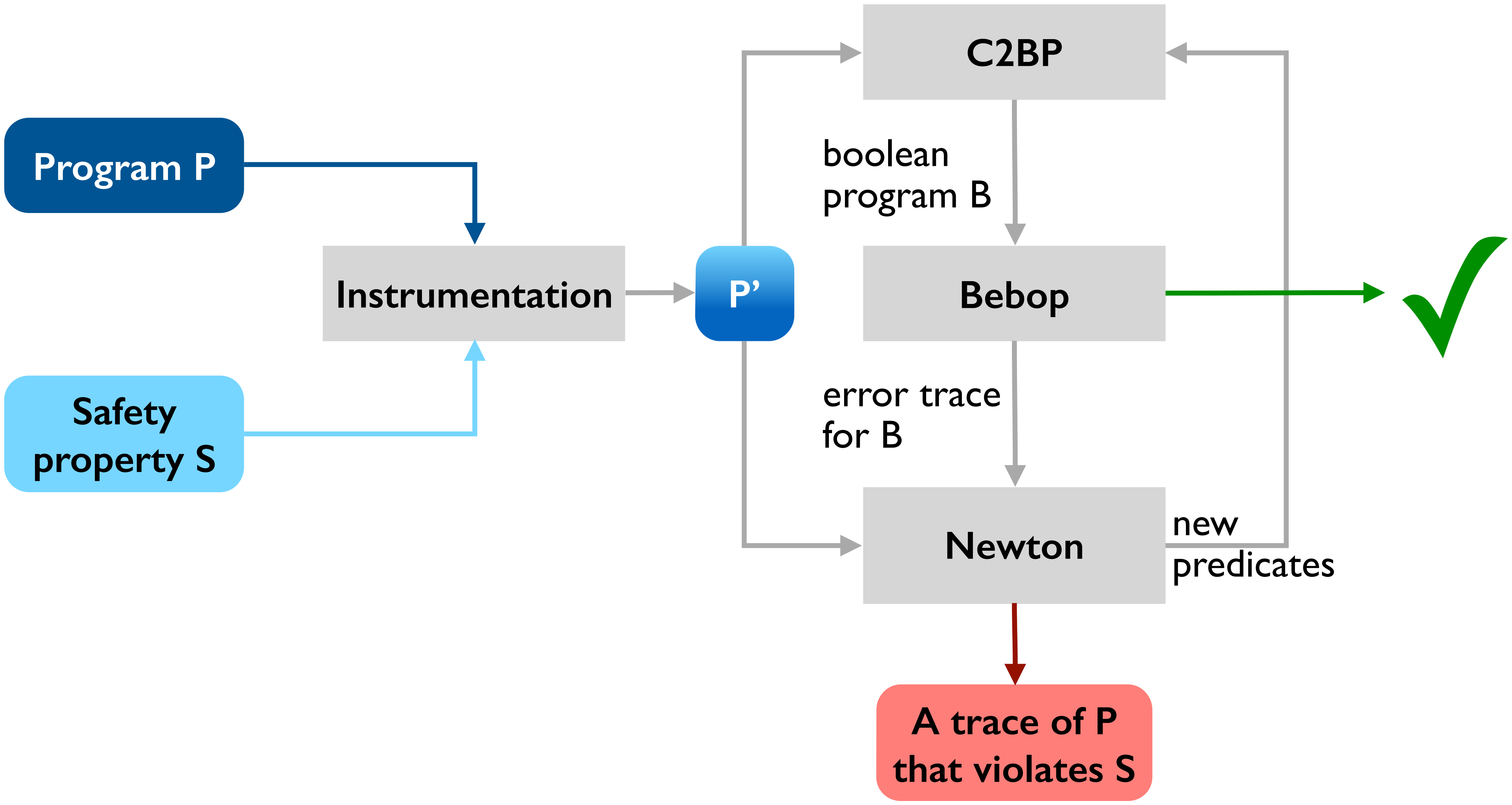
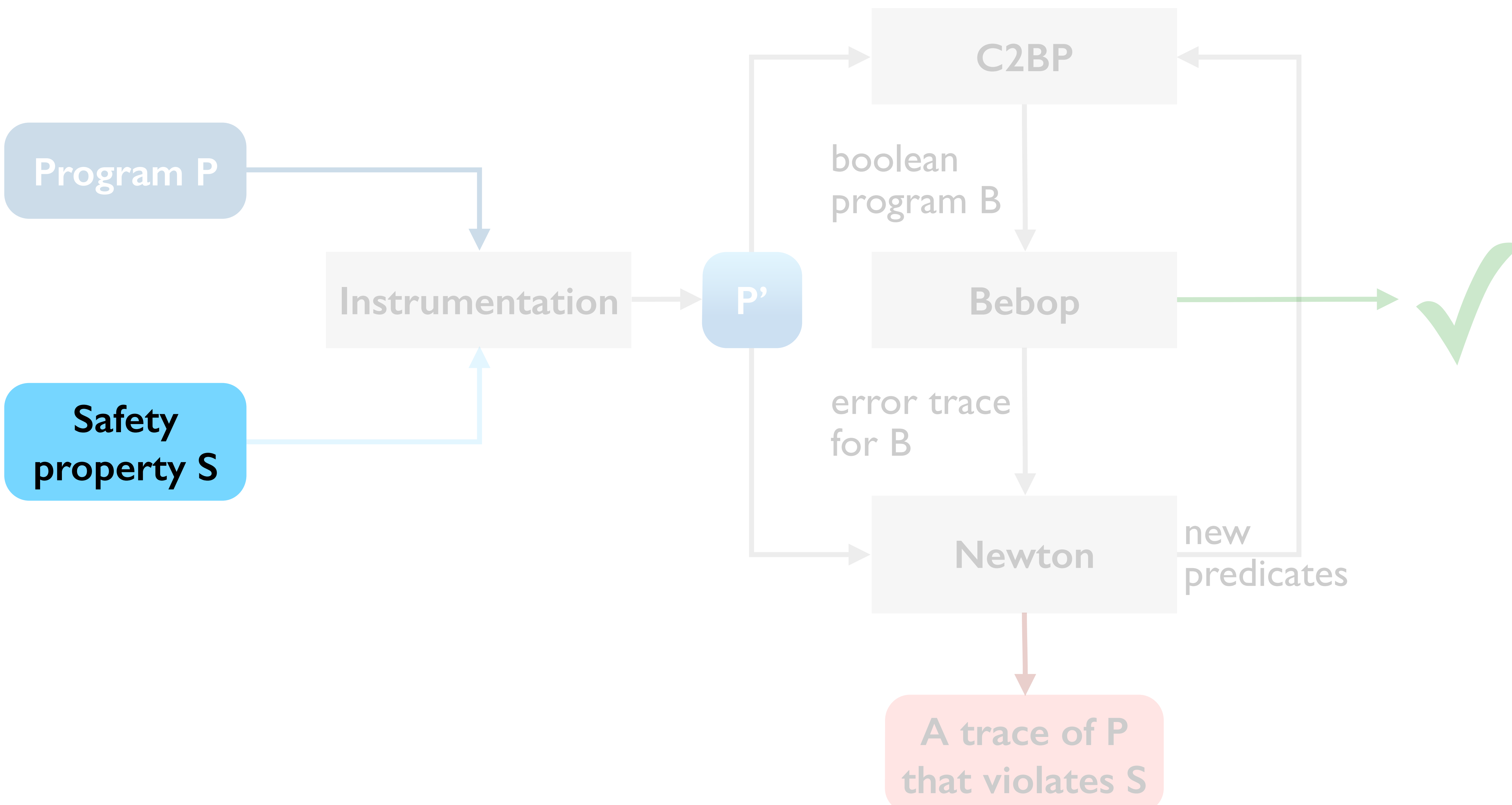


The SLAM process: specifying safety properties



Specification Language for Interface Checking

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A finite state language for stating rules for API usage

- Temporal safety properties expressed as *safety automata* that monitor program's execution behavior at the level of function calls and returns.
- Familiar C syntax.

Specification Language for Interface Checking

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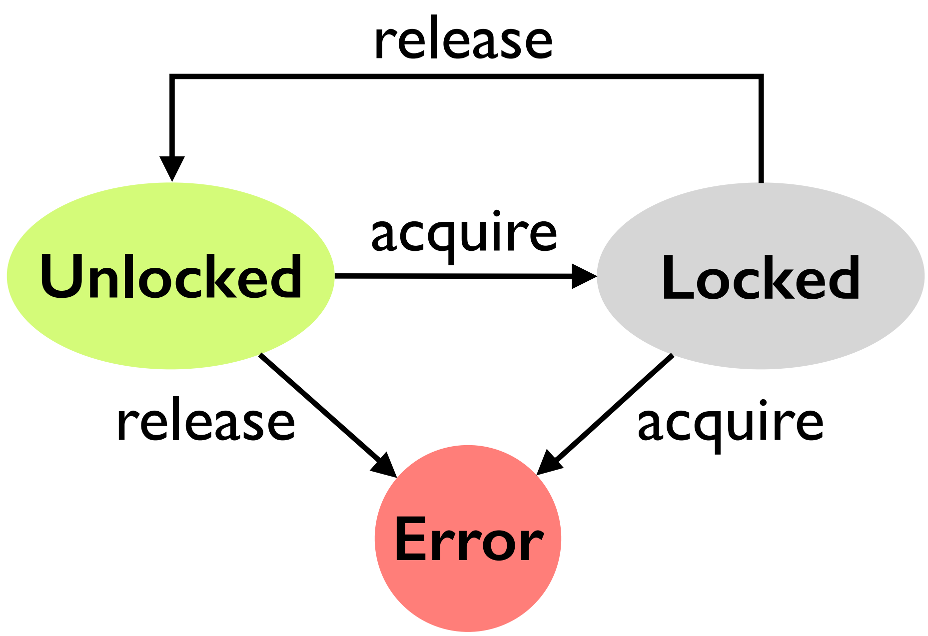
- Familiar C syntax.

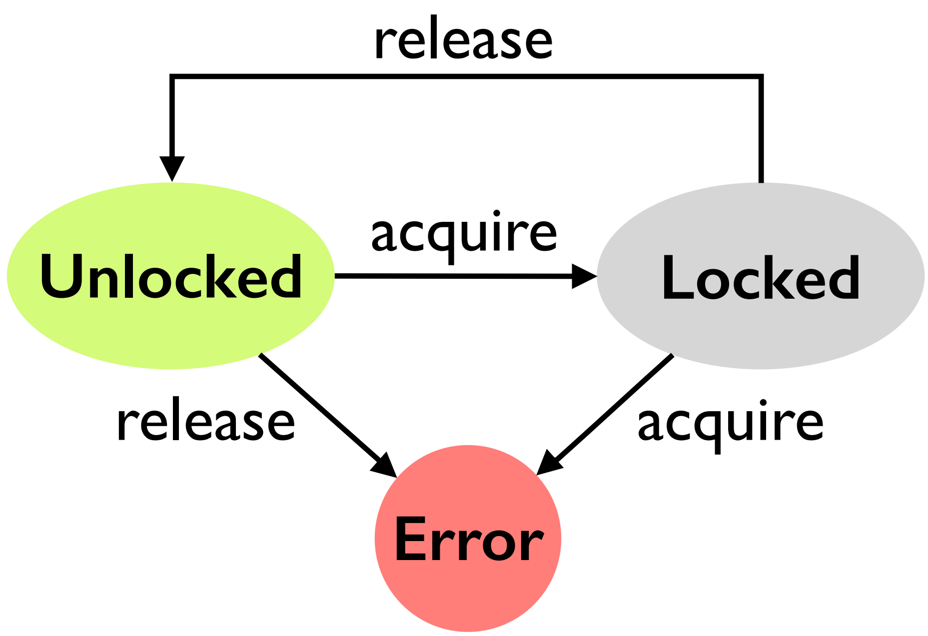
Suitable for control-dominated properties

- E.g., ordering of function calls with associated constraints on data values at the API boundary.

A locking protocol in SLIC



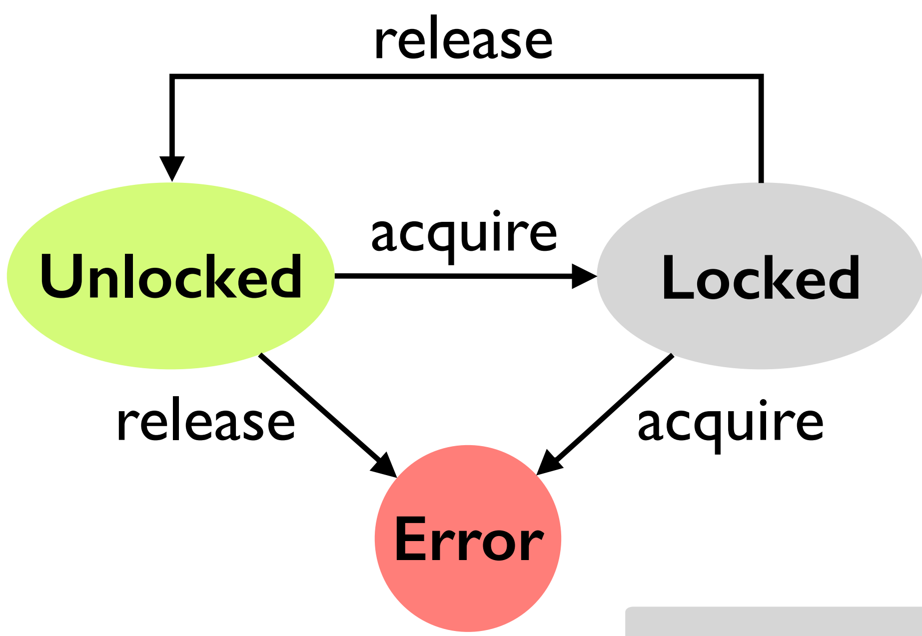
A locking protocol in SLIC




```
state {
  enum {Locked, Unlocked}
   state = Unlocked;
}
```

The global *state structure* defines a static set of *state variables*.

A locking protocol in SLIC



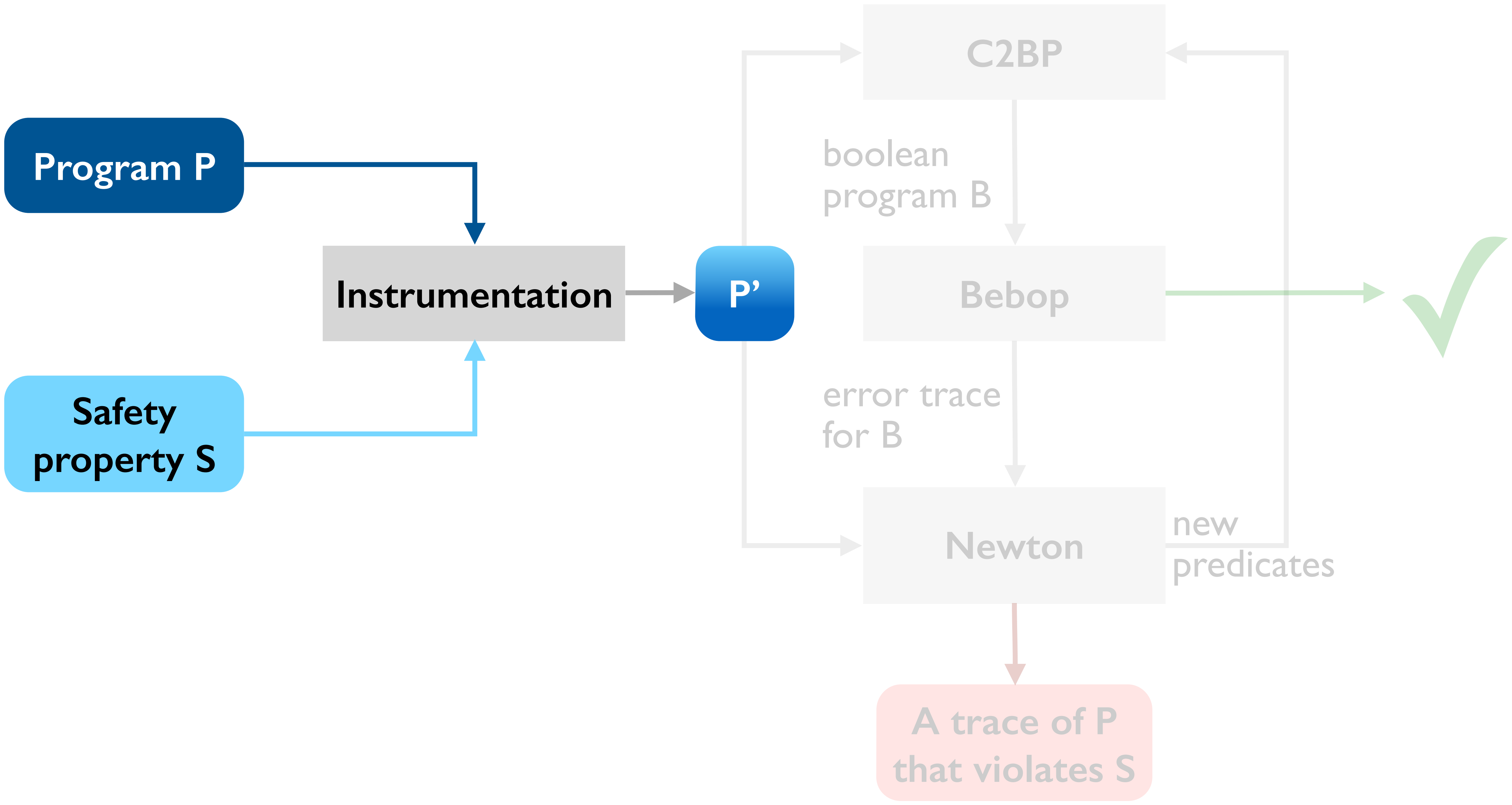
Transfer functions define events and event handlers that describe state transitions on events.

```
state {
  enum {Locked, Unlocked}
   state = Unlocked;
}

KeAcquireSpinLock.return {
  if (state == Locked)
    abort;
  else
    state = Locked;
}

KeReleaseSpinLock.return {
  if (state == Unlocked)
    abort;
  else
    state = Unlocked;
}
```

The SLAM process: instrumentation



Instrumentation by example: 2 steps

```
state {
  enum {Locked, Unlocked}
   state = Unlocked;
}

KeAcquireSpinLock.return {
  if (state == Locked)
    abort;
  else
    state = Locked;
}

KeReleaseSpinLock.return {
  if (state == Unlocked)
    abort;
  else
    state = Unlocked;
}
```

Safety property S

```
void example() {
  do {
   KeAcquireSpinLock();

   nOld = nPackets;

   if (request) {
     request = request->next;
     KeReleaseSpinLock();
     nPackets++;
   }
  } while (nPackets != nOld);

  KeReleaseSpinLock();
}
```

Simplified code for a PCI device driver.

Program P

Step 1: translate the SLIC spec S to C

```
state {
  enum {Locked, Unlocked}
   state = Unlocked;
}

KeAcquireSpinLock.return {
  if (state == Locked)
    abort;
  else
    state = Locked;
}

KeReleaseSpinLock.return {
  if (state == Unlocked)
    abort;
  else
    state = Unlocked;
}
```

Safety property S

```
enum {Locked=0, Unlocked=1}
   state = Unlocked;

void slic_abort() {
  SLIC_ERROR: ;
}

void KeAcquireSpinLock_return {
  if (state == Locked)
    slic_abort();
  else
    state = Locked;
}

void KeReleaseSpinLock_return {
  if (state == Unlocked)
    slic_abort();
  else
    state = Unlocked;
}
```

Distinguished error label.

Step 2: insert calls to SLIC functions into P

```
void example() {
  do {
   KeAcquireSpinLock();

   nOld = nPackets;

   if (request) {
     request = request->next;
     KeReleaseSpinLock();
     nPackets++;
   }
  } while (nPackets != nOld);

  KeReleaseSpinLock();
}
```

Program P

```
void example() {
  do {
   KeAcquireSpinLock();
   KeAcquireSpinLock_return();

   nOld = nPackets;

   if (request) {
     request = request->next;
     KeReleaseSpinLock();
     KeReleaseSpinLock_return();
     nPackets++;
   }
  } while (nPackets != nOld);

  KeReleaseSpinLock();
  KeReleaseSpinLock_return();
}
```

Program P’

P satisfies S iff SLIC_ERROR is unreachable in P’

```
void example() {
  do {
   KeAcquireSpinLock();
   KeAcquireSpinLock_return();

   nOld = nPackets;

   if (request) {
     request = request->next;
     KeReleaseSpinLock();
     KeReleaseSpinLock_return();
     nPackets++;
   }
  } while (nPackets != nOld);

  KeReleaseSpinLock();
  KeReleaseSpinLock_return();
}
```

```
enum {Locked=0, Unlocked=1}
   state = Unlocked;

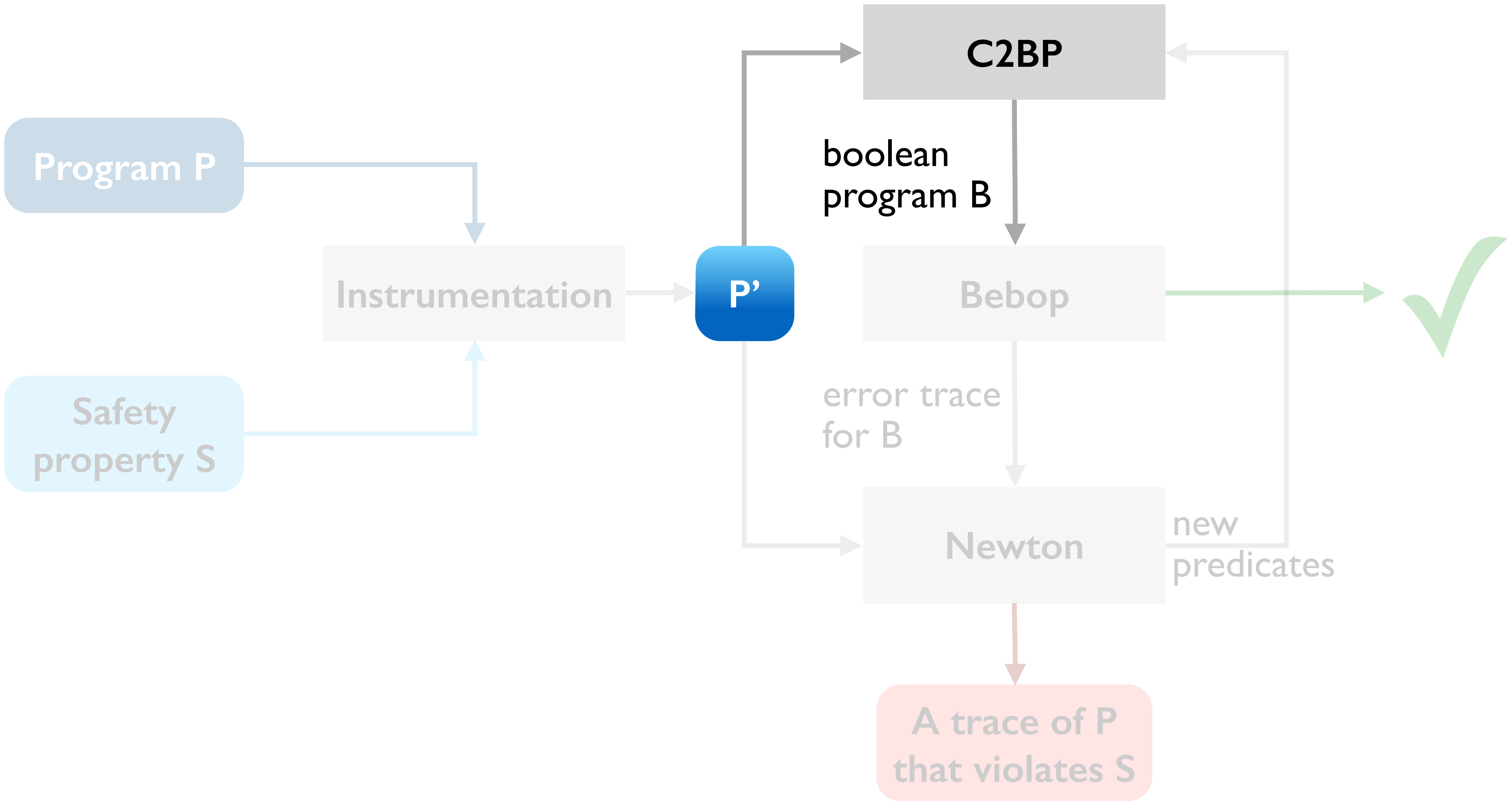

void slic_abort() {
  SLIC_ERROR: ;
}

void KeAcquireSpinLock_return {
  if (state == Locked)
    slic_abort();
  else
    state = Locked;
}

void KeReleaseSpinLock_return {
  if (state == Unlocked)
    slic_abort();
  else
    state = Unlocked;
}
```

Program P’

The SLAM process: predicate abstraction



Predicate abstraction of C Programs

Predicate abstraction of C Programs

Given a program P and a finite set E of predicates, C2BP creates a *boolean program* B that is a sound over-approximation of P.

- B has the same control-flow structure as P, but only |E| boolean variables.
- For any path p feasible in P, there is a corresponding feasible path in B.

Predicate abstraction of C Programs

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- B has the same control-flow structure as P, but only |E| boolean variables.
- For any path p feasible in P, there is a corresponding feasible path in B.

Suitable abstraction for checking control-dominated properties (such as SLIC rules).

- Models control flow in P precisely.
- Models only a few predicates about data relevant to each rule being checked (so limits state explosion).

Predicate abstraction by example: 5+ steps

```
void example() {
  do {
   KeAcquireSpinLock();
   KeAcquireSpinLock_return();

   nOld = nPackets;

   if (request) {
     request = request->next;
     KeReleaseSpinLock();
     KeReleaseSpinLock_return();
     nPackets++;
   }
  } while (nPackets != nOld);

  KeReleaseSpinLock();
  KeReleaseSpinLock_return();
}
```

```
enum {Locked=0, Unlocked=1}
   state = Unlocked;

void slic_abort() {
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void KeAcquireSpinLock_return {
  if (state == Locked)
    slic_abort();
  else
    state = Locked; }

void KeReleaseSpinLock_return {
  if (state == Unlocked)
    slic_abort();
  else
    state = Unlocked; }
```

Program P'

Step 1: extract initial predicates from SLIC rules

```
void example() {
  do {
   KeAcquireSpinLock();
   KeAcquireSpinLock_return();

   nOld = nPackets;

   if (request) {
     request = request->next;
     KeReleaseSpinLock();
     KeReleaseSpinLock_return();
     nPackets++;
   }
  } while (nPackets != nOld);

  KeReleaseSpinLock();
  KeReleaseSpinLock_return();
}
```

```
enum {Locked=0, Unlocked=1}
   state = Unlocked;

void slic_abort() {
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void KeAcquireSpinLock_return {
  if (state == Locked)
    slic_abort();
  else
    state = Locked; }

void KeReleaseSpinLock_return {
  if (state == Unlocked)
    slic_abort();
  else
    state = Unlocked; }
```

Program P'

```
(state == Locked)
(state == Unlocked)
```

Step 2: introduce boolean variables for E

```
void example() {
  do {
   KeAcquireSpinLock();
   KeAcquireSpinLock_return();

   nOld = nPackets;

   if (request) {
     request = request->next;
     KeReleaseSpinLock();
     KeReleaseSpinLock_return();
     nPackets++;
   }
  } while (nPackets != nOld);

  KeReleaseSpinLock();
  KeReleaseSpinLock_return();
}
```

```
b(state==Locked), b(state==Unlocked) := F, T;

void slic_abort() {
  SLIC_ERROR: ; }

void KeAcquireSpinLock_return {
  if b(state==Locked)
    slic_abort();
  else
    state = Locked;
}

void KeReleaseSpinLock_return {
  if b(state==Unlocked)
    slic_abort();
  else
    state = Unlocked; }
```

```
(state == Locked)
(state == Unlocked)
```

Step 3: skip statements with no effect on E

```
void example() {
  do {
   skip;
   KeAcquireSpinLock_return();

   skip;

   if (request) {
     skip;
     skip;
     KeReleaseSpinLock_return();
     skip;
   }
  } while (nPackets != nOld);

  skip;
  KeReleaseSpinLock_return();
}
```

```
b(state==Locked), b(state==Unlocked) := F, T;

void slic_abort() {
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void KeAcquireSpinLock_return {
  if b(state==Locked)
    slic_abort();
  else
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  if b(state==Unlocked)
    slic_abort();
  else
    state = Unlocked; }
```

```
(state == Locked)
(state == Unlocked)
```

Step 4: encode the effects of assignments on E

```
void example() {
  do {
   skip;
   KeAcquireSpinLock_return();

   skip;

   if (request) {
     skip;
     skip;
     KeReleaseSpinLock_return();
     skip;
   }
  } while (nPackets != nOld);

  skip;
  KeReleaseSpinLock_return();
}
```

```
b(state==Locked), b(state==Unlocked) := F, T;

void slic_abort() {
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void KeAcquireSpinLock_return {
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  else
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void KeReleaseSpinLock_return {
  if b(state==Unlocked)
    slic_abort();
  else
    b(state==Locked),
    b(state==Unlocked) := F, T; }
```

```
(state == Locked)
(state == Unlocked)
```

Step 5: use non-determinism for conditions

```
void example() {
  do {
   skip;
   KeAcquireSpinLock_return();

   skip;

   if (*) {
     skip;
     skip;
     KeReleaseSpinLock_return();
     skip;
   }
  } while (*);

  skip;
  KeReleaseSpinLock_return();
}
```

```
b(state==Locked), b(state==Unlocked) := F, T;

void slic_abort() {
  SLIC_ERROR: ; }

void KeAcquireSpinLock_return {
  if b(state==Locked)
    slic_abort();
  else
    b(state==Locked),
    b(state==Unlocked) := T, F; }

void KeReleaseSpinLock_return {
  if b(state==Unlocked)
    slic_abort();
  else
    b(state==Locked),
    b(state==Unlocked) := F, T; }
```

```
(state == Locked)
(state == Unlocked)
```

Step 5: use non-determinism for conditions

```
void example() {
  do {
   skip;
   KeAcquireSpinLock_return();

   skip;

   if (*) {
     skip;
     skip;
     KeReleaseSpinL
     skip;
   }
  } while (*);

  skip;
  KeReleaseSpinLock_return();
}
```

```
b(state==Locked)

void
  SLIC_ERROR: ; }

();

void

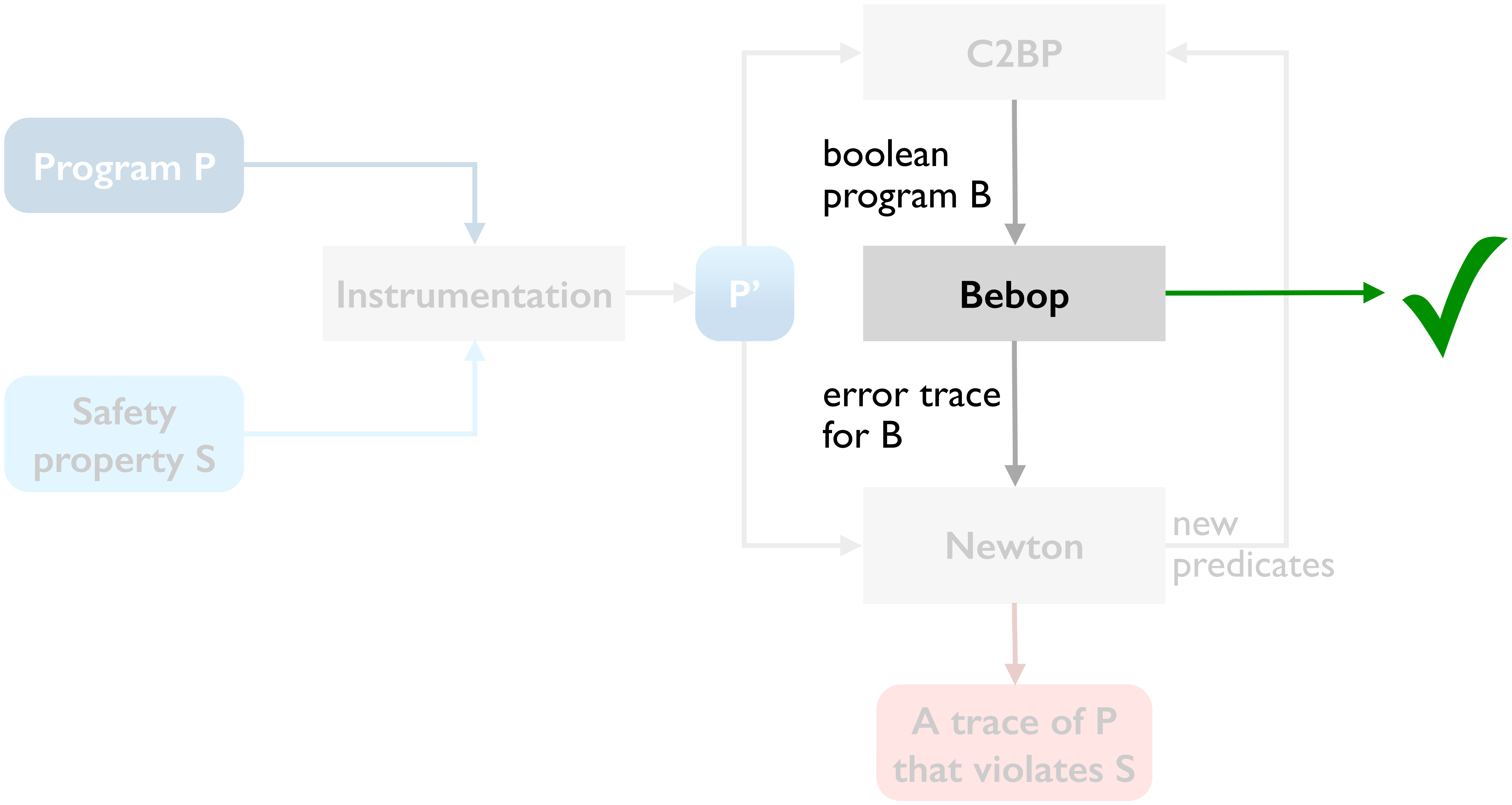
    slic_abort();

    b
    b
```

This is a highly simplified example of predicate abstraction. The process is much more complex in reality. For details, see **Automatic predicate abstraction of C programs**.

```
(state == Locked)
(state == Unlocked)
```

The SLAM process: model checking



Model checking of boolean programs

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Given a boolean program B and a statement s in B, Bebop determines if s is reachable in B.

- Produces a shortest trace in B (if any) leading to S.

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Performs symbolic reachability analysis using BDDs.

- Adapts the interprocedural dataflow analysis of Reps, Horwitz and Sagiv (RHS) to decide the reachability of s in B.
- Uses BDDs to represent the procedure summaries in RHS, which are binary relations between sets of states.

Model checking of boolean programs

Given a boolean program B and a statement s in B, Bebop determines if s is reachable in B.

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- Adapts the interprocedural dataflow analysis of Reps, Horwitz and Sagiv (RHS) to decide the reachability of s in B.
- Uses BDDs to represent the procedure summaries in RHS, which are binary relations between sets of states.

For details, see Bebop: A Symbolic Model Checker for Boolean Programs**.**

Model checking of the example program

```
void example() {
  do {
   skip;
   KeAcquireSpinLock_return();

   skip;

   if (*) {
     skip;
     skip;
     KeReleaseSpinLock_return();
     skip;
   }
  } while (*);

  skip;
  KeReleaseSpinLock_return();
}
```

```
b(state==Locked), b(state==Unlocked) := F, T;

void slic_abort() {
  SLIC_ERROR: ; }

void KeAcquireSpinLock_return {
  if b(state==Locked)
    slic_abort();
  else
    b(state==Locked),
    b(state==Unlocked) := T, F; }

void KeReleaseSpinLock_return {
  if b(state==Unlocked)
    slic_abort();
  else
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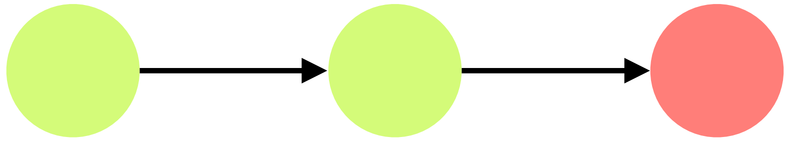
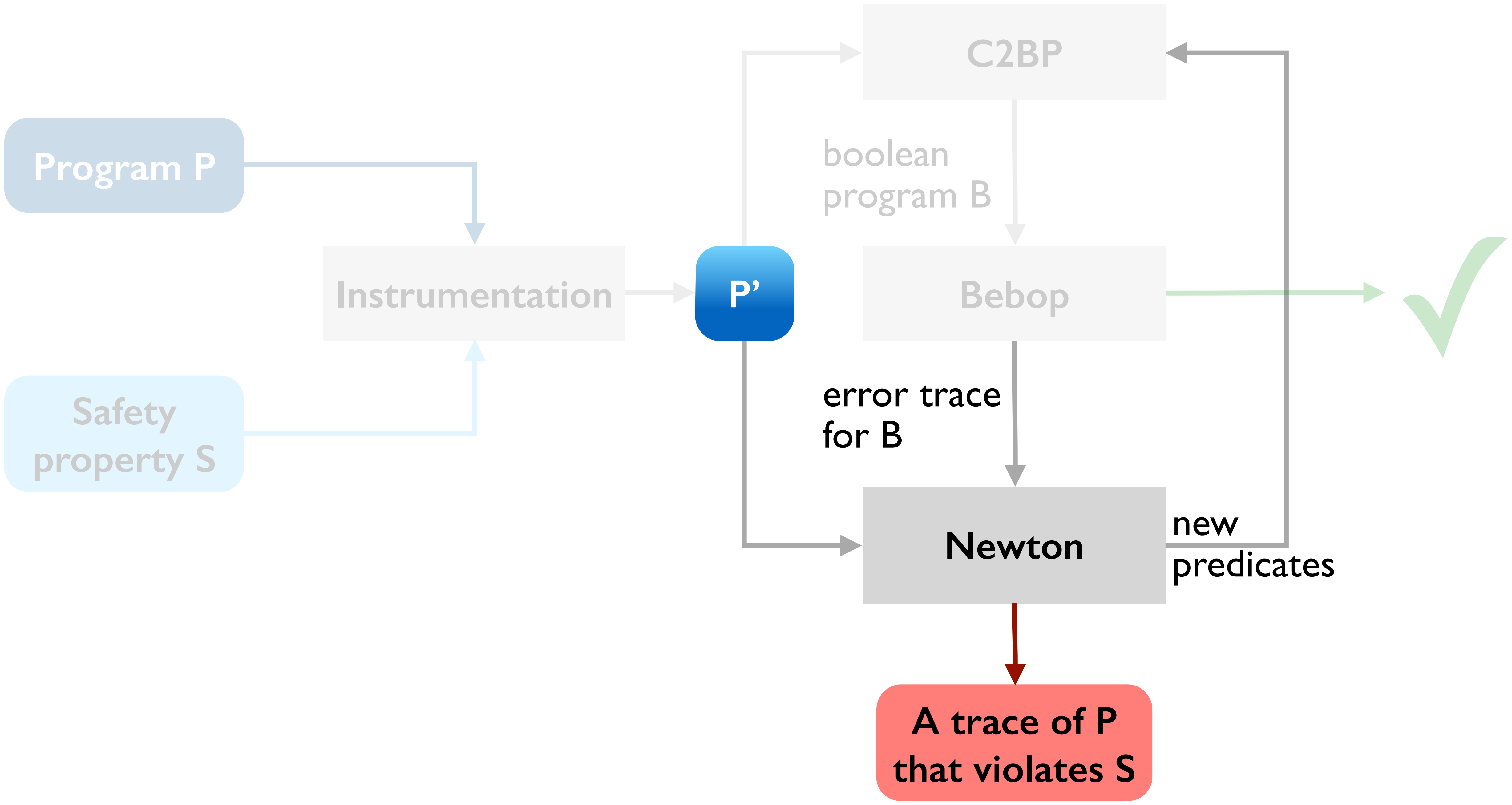
```



The SLAM process: trace validation



Error trace validation & abstraction refinement

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Given a program P' and a candidate error trace, Newton determines if the trace is feasible.

- Uses verification condition generation for feasibility checking.
- If feasible, the error trace corresponds to a real bug.
- If not, returns a small set of predicates that explain why the path is infeasible. Based on greedy minimal unsatisfiable core computation.

Error trace validation & abstraction refinement

Given a program P' and a candidate error trace, Newton determines if the trace is feasible.

- Uses verification condition generation for feasibility checking.
- If feasible, the error trace corresponds to a real bug.
- If not, returns a small set of predicates that explain why the path is infeasible. Based on greedy minimal unsatisfiable core computation.

For details, see Generating Abstract Explanations of Spurious Counterexamples in C Programs**.**

Validation & refinement for the example

```
void example() {
  do {
   KeAcquireSpinLock();
   KeAcquireSpinLock_return();

   nOld = nPackets;

   if (request) {
     request = request->next;
     KeReleaseSpinLock();
     KeReleaseSpinLock_return();
     nPackets++;
   }
  } while (nPackets != nOld);

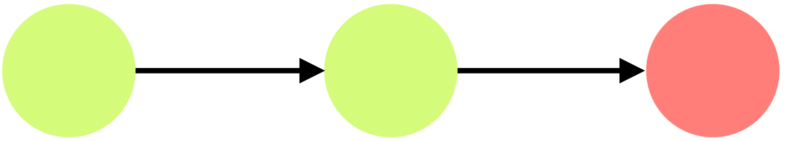
  KeReleaseSpinLock();
  KeReleaseSpinLock_return();
}
```

```
enum {Locked=0, Unlocked=1}
   state = Unlocked;

void slic_abort() {
  SLIC_ERROR: ; }

void KeAcquireSpinLock_return {
  if (state == Locked)
    slic_abort();
  else
    state = Locked; }

void KeReleaseSpinLock_return {
  if (state == Unlocked)
    slic_abort();
  else
    state = Unlocked; }
```



```
(state == Locked)
(state == Unlocked)
```

Validation & refinement for the example

```
void example() {
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   KeAcquireSpinLock();
   KeAcquireSpinLock_return();

   nOld = nPackets;

   if (request) {
     request = request->next;
     KeReleaseSpinLock();
     KeReleaseSpinLock_return();
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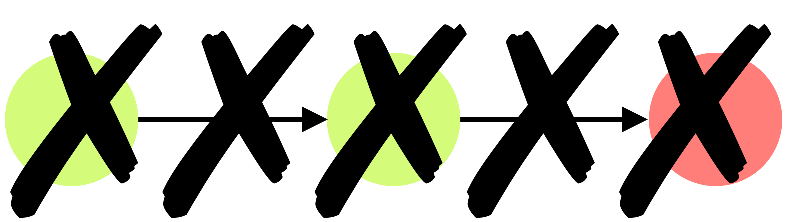
```



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    slic_abort();
  else
    state = Unlocked; }
```

```
(nPackets == nOld)
(state == Locked)
(state == Unlocked)
```

Back to C2BP and Bebop ...

```
void example() {
  do {
   skip;
   KeAcquireSpinLock_return();

   b(nOld==nPackets) := T;

   if (*) {
     skip;
     skip;
     KeReleaseSpinLock_return();
     b(nOld==nPackets) :=
      b(nOld==nPackets) ? F : *;
   }
  } while (!b(nOld==nPackets));

  skip;
  KeReleaseSpinLock_return();
}
```

```
b(state==Locked), b(state==Unlocked) := F, T;

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```

```
(nPackets == nOld)
(state == Locked)
(state == Unlocked)
```

Back to C2BP and Bebop …

```
void example() {
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   if (*) {
     skip;
     skip;
     KeReleaseSpinLock_return();
     b(nOld==nPackets) :=
      b(nOld==nPackets) ? F : *;
   }
  } while (!b(nOld==nPackets));

  skip;
  KeReleaseSpinLock_return();
}
```

✓

```
b(state==Locked), b(state==Unlocked) := F, T;

void slic_abort() {
  SLIC_ERROR: ; }

void KeAcquireSpinLock_return {
  if b(state==Locked)
    slic_abort();
  else
    b(state==Locked),
    b(state==Unlocked) := T, F; }

void KeReleaseSpinLock_return {
  if b(state==Unlocked)
    slic_abort();
  else
    b(state==Locked),
    b(state==Unlocked) := F, T; }
```

Summary

Today

- Software model checking with SLAM
  - Predicate abstraction of C programs
  - Model checking of boolean programs
  - Trace validation and abstraction refinement

Next lecture

- Guest lecture by Zach Tatlock!
- Verifying compiler optimizations with SMT solvers