Computer-Aided Reasoning for Software

CSE507

# Model Checking II

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# Today

## Last lecture

- Model checking basics

## Today

- Software model checking with SLAM

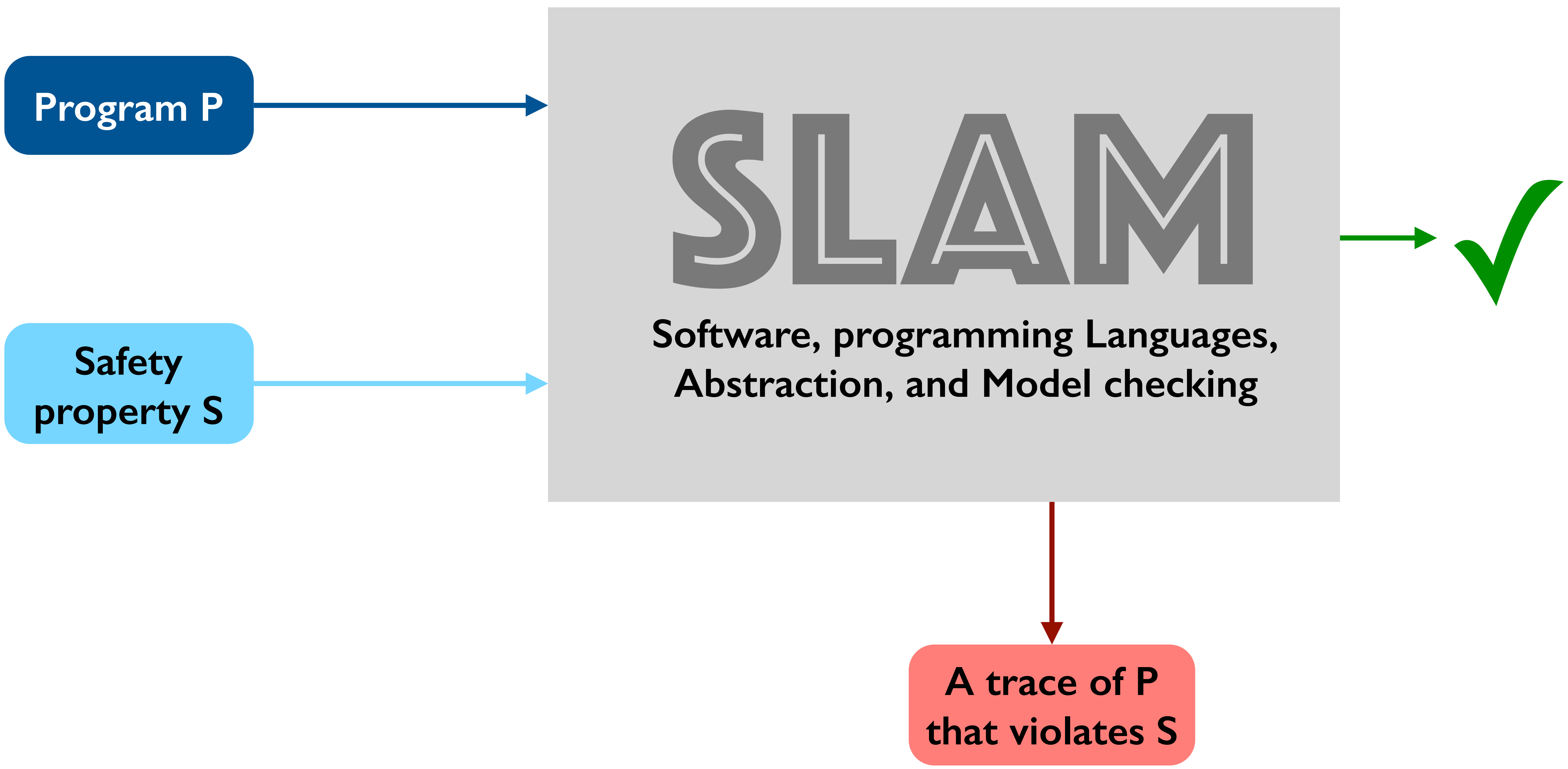
## Reminders

- Homework 3 is due on today at 11pm
- Homework 4 is out

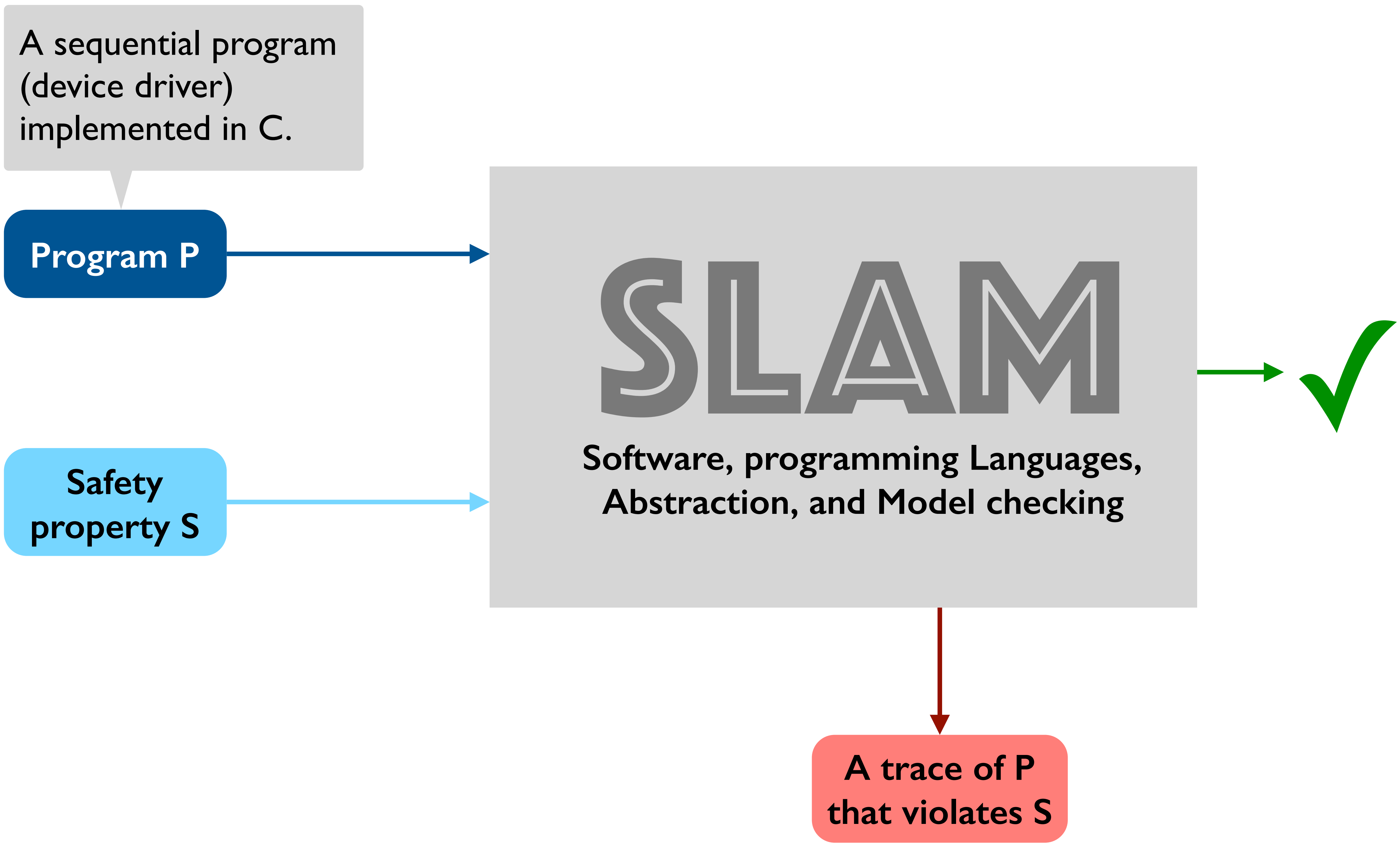
topics

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

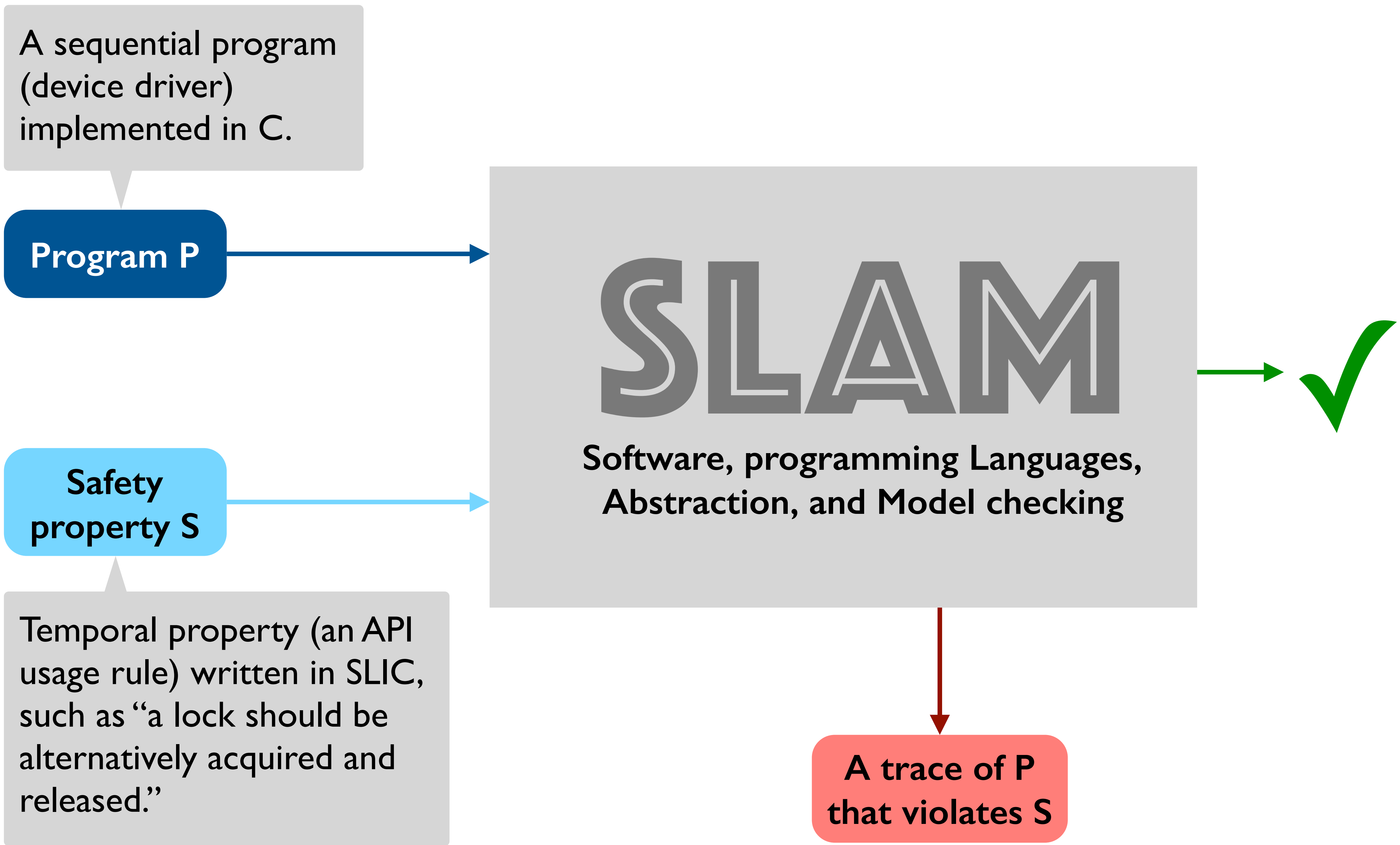
# Overview of SLAM



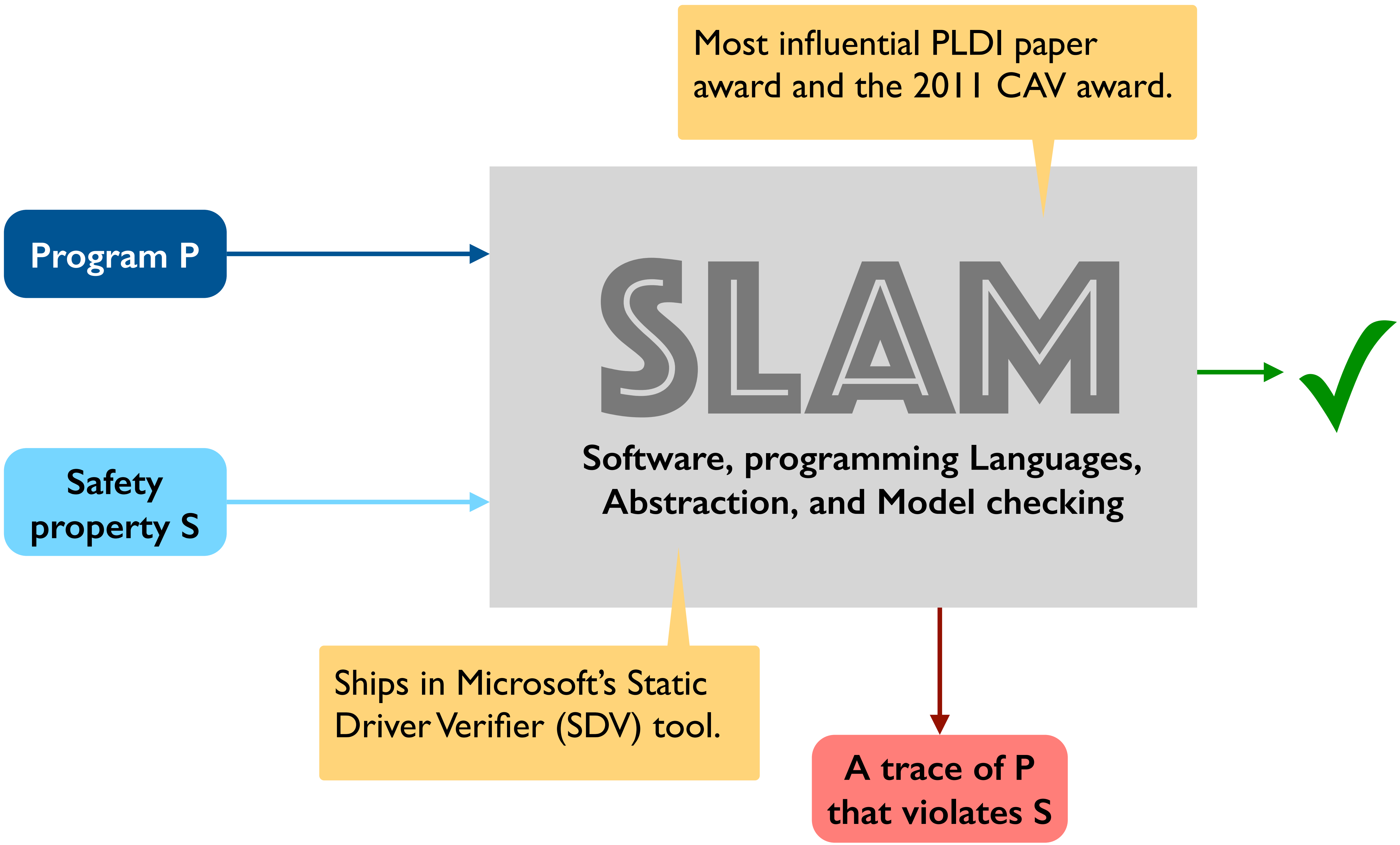
# Overview of SLAM



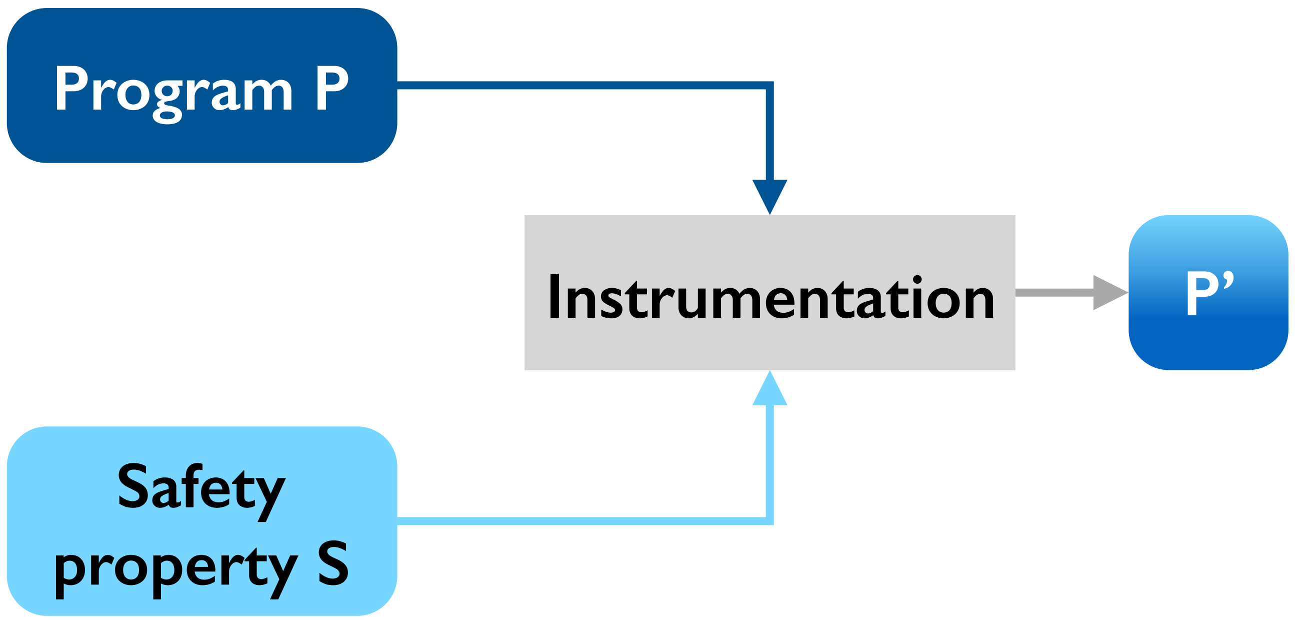
# Overview of SLAM



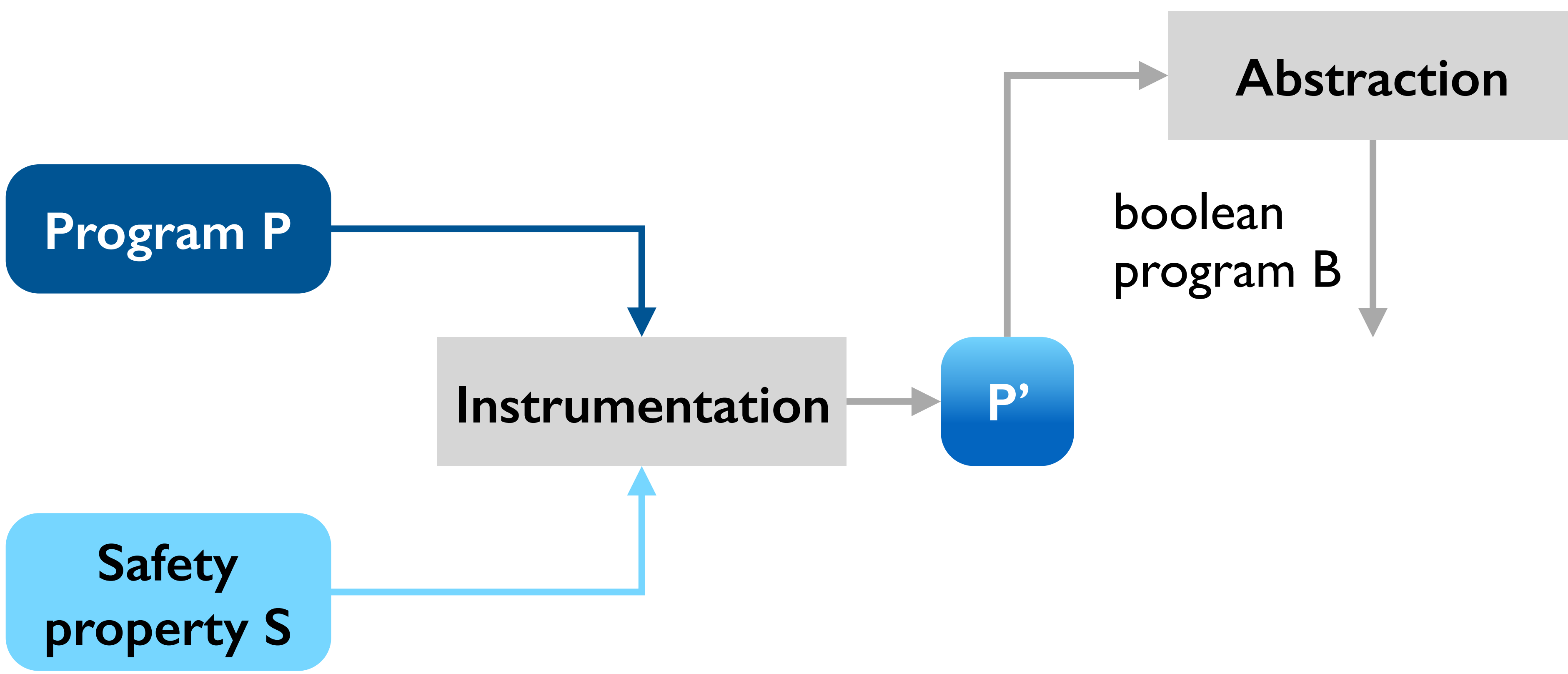
# Overview of SLAM



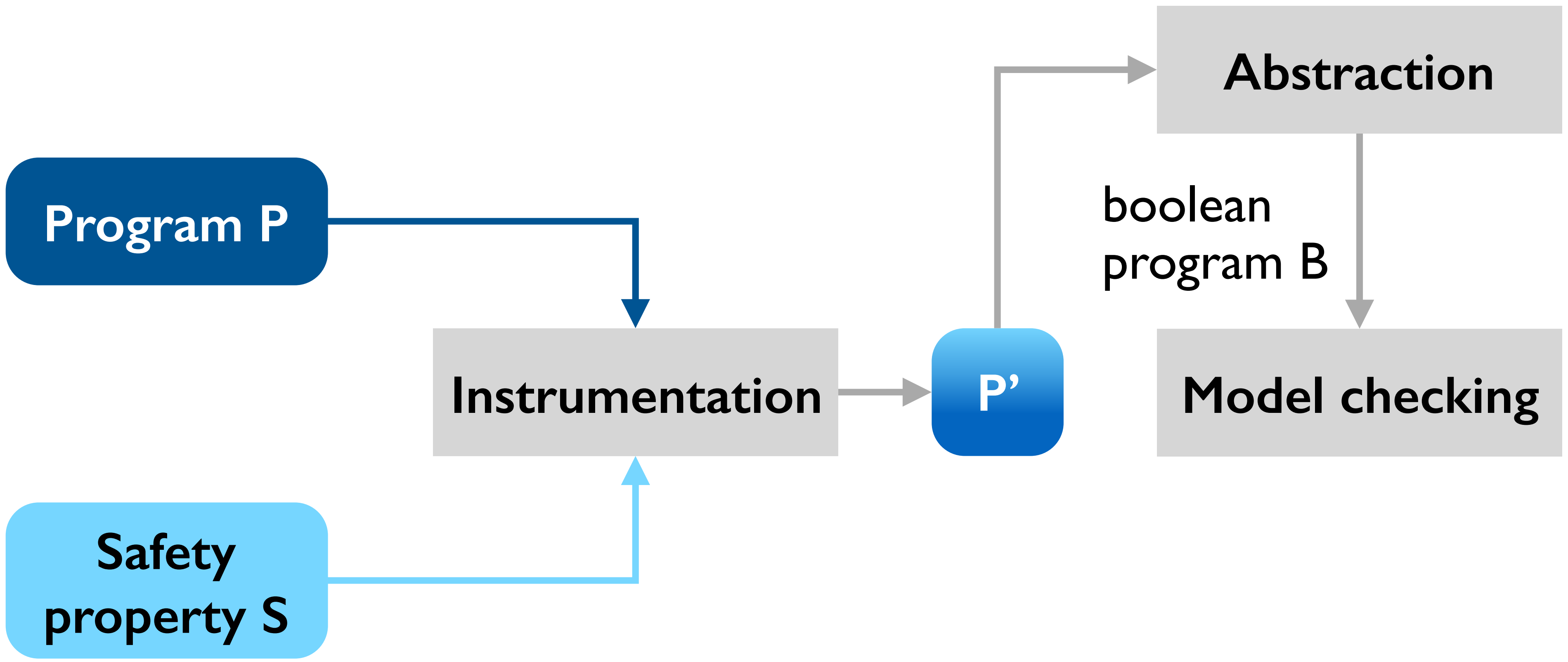
# The SLAM process



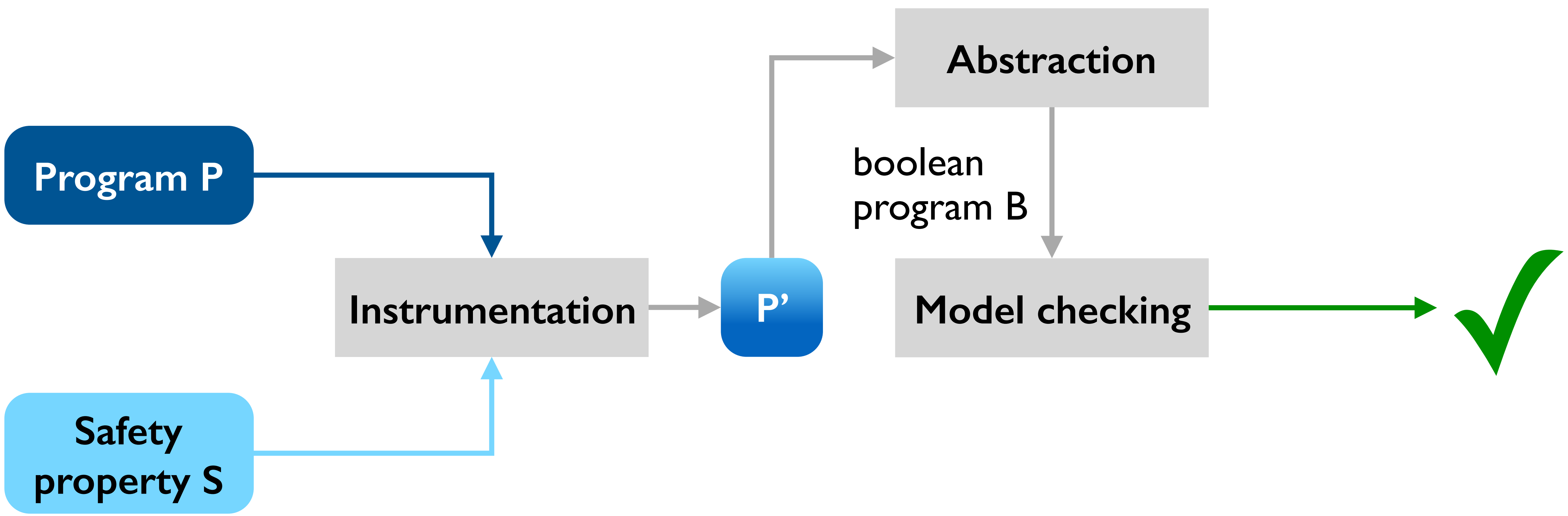
# The SLAM process



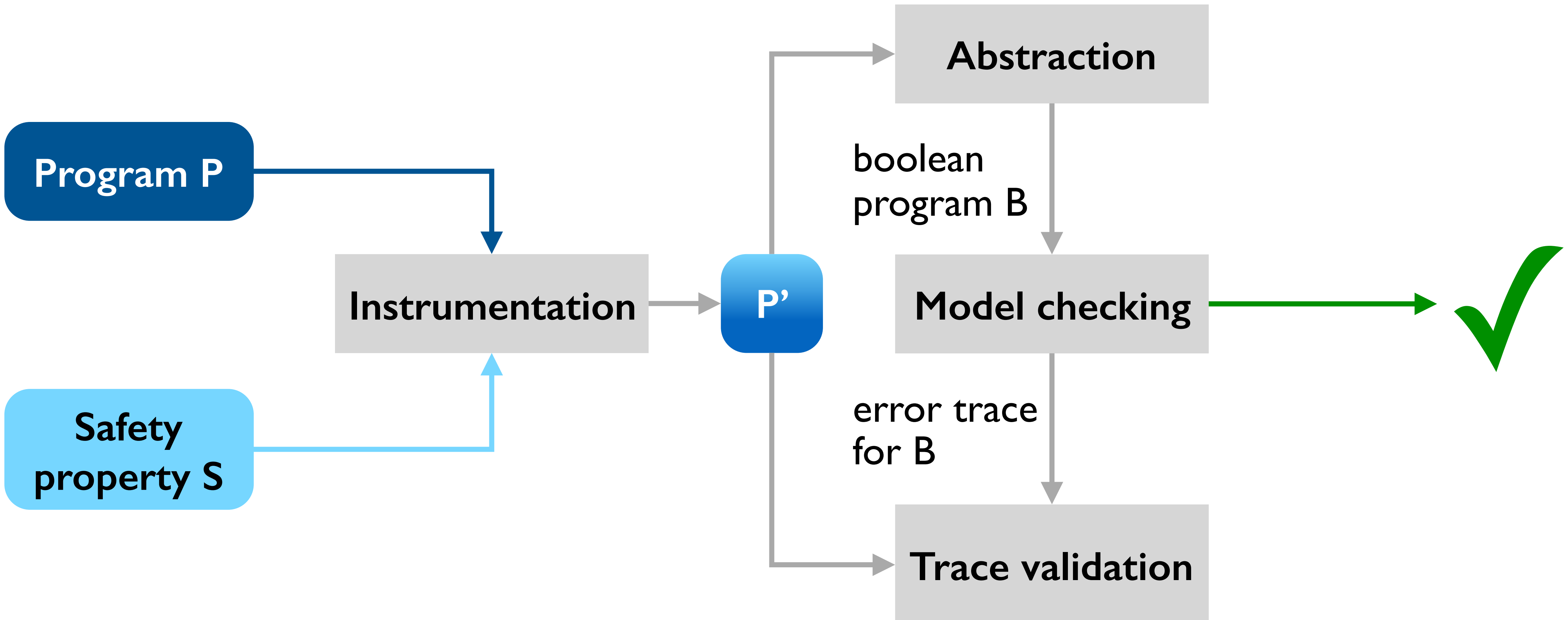
# The SLAM process



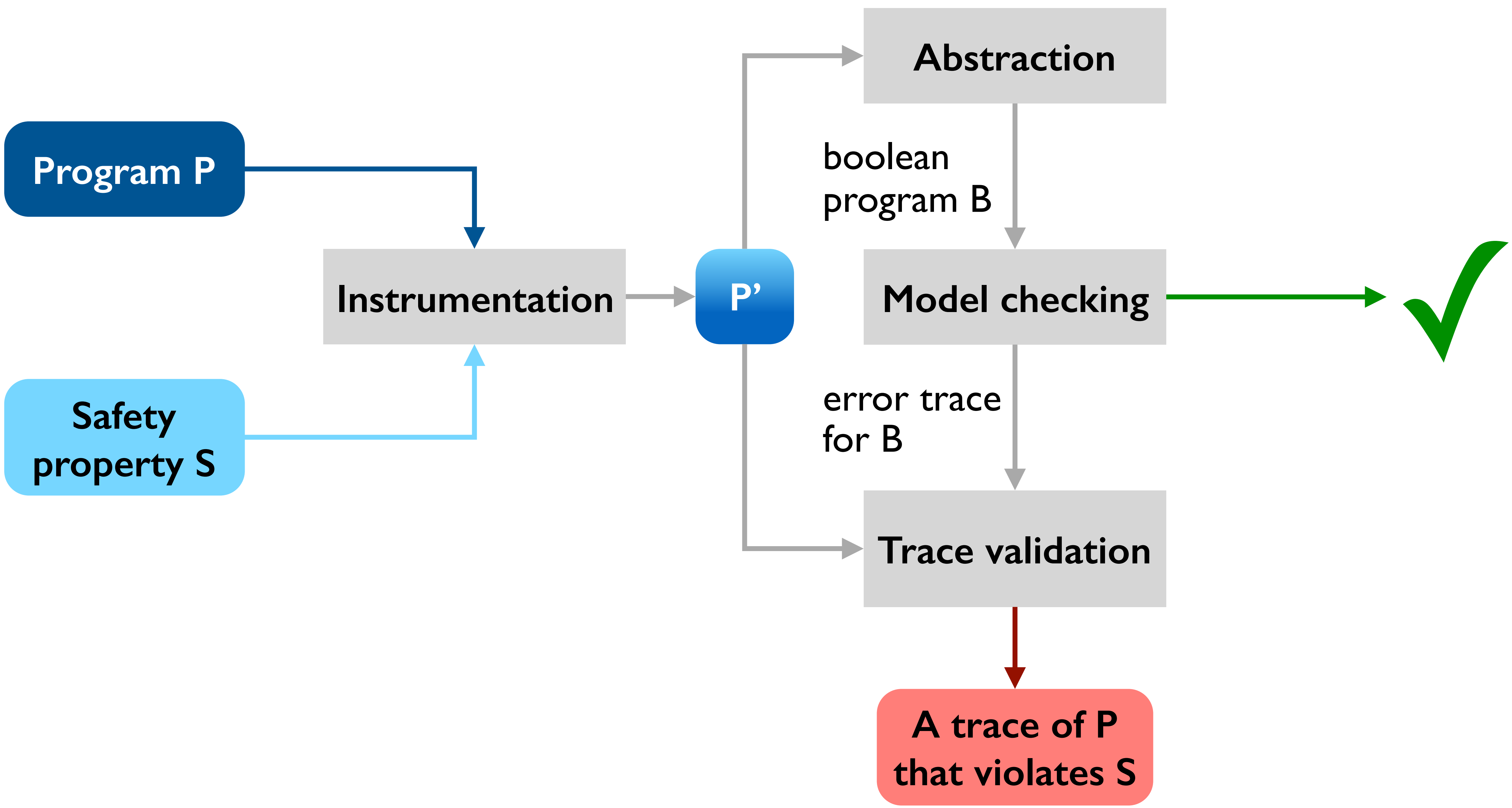
# The SLAM process



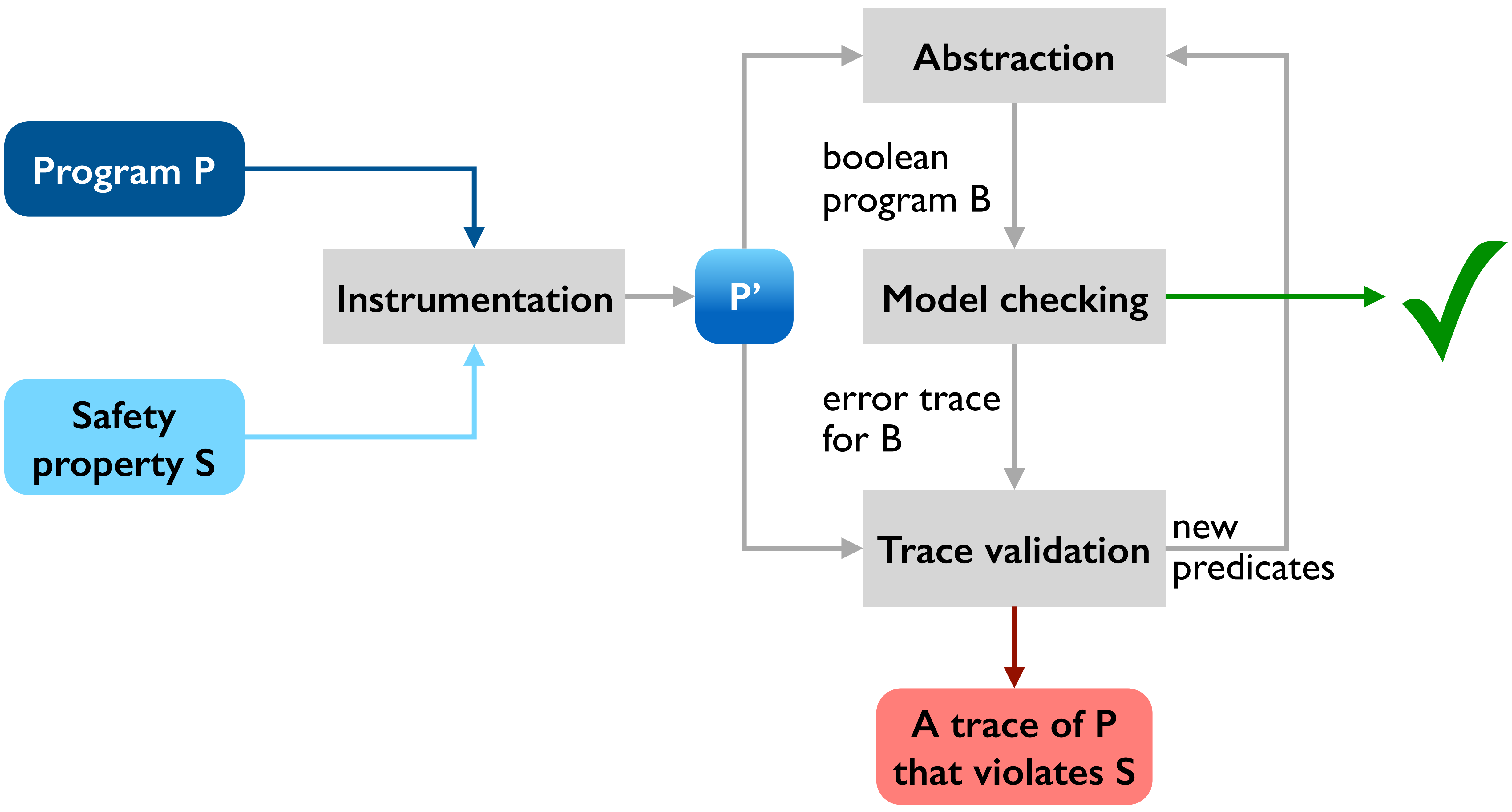
# The SLAM process



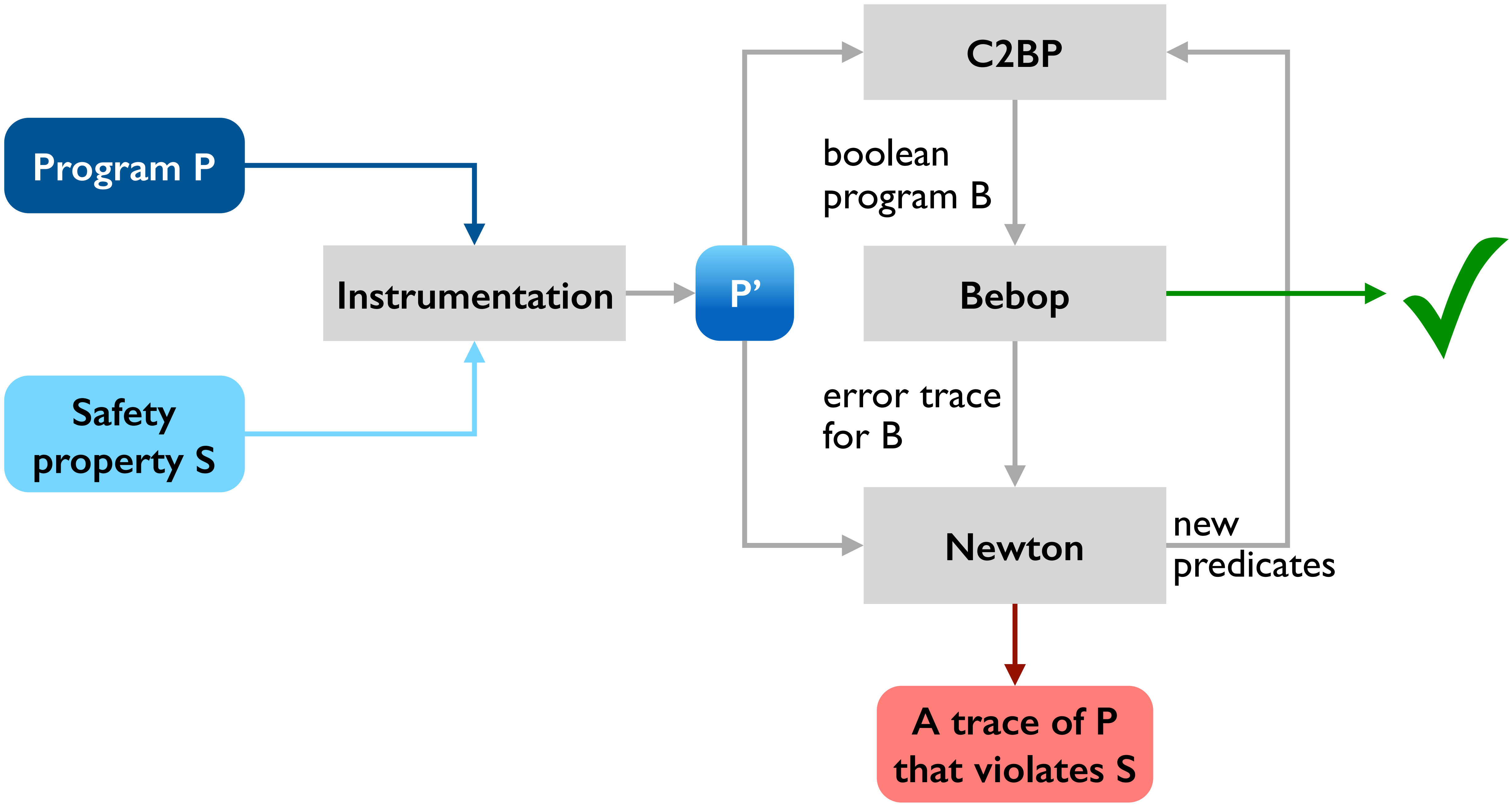
# The SLAM process



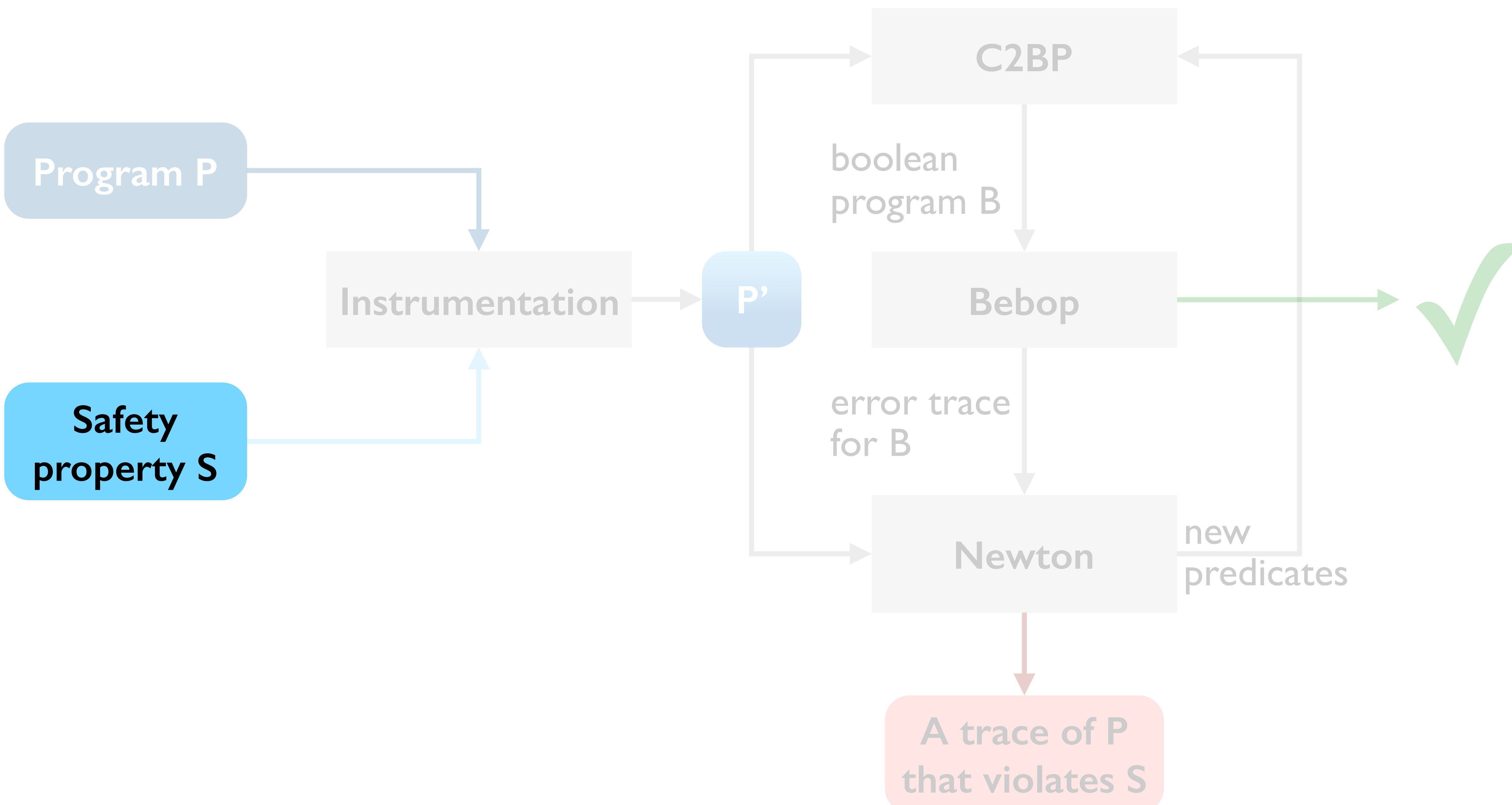
# The SLAM process



# The SLAM process



# The SLAM process: specifying safety properties



# Specification Language for Interface Checking

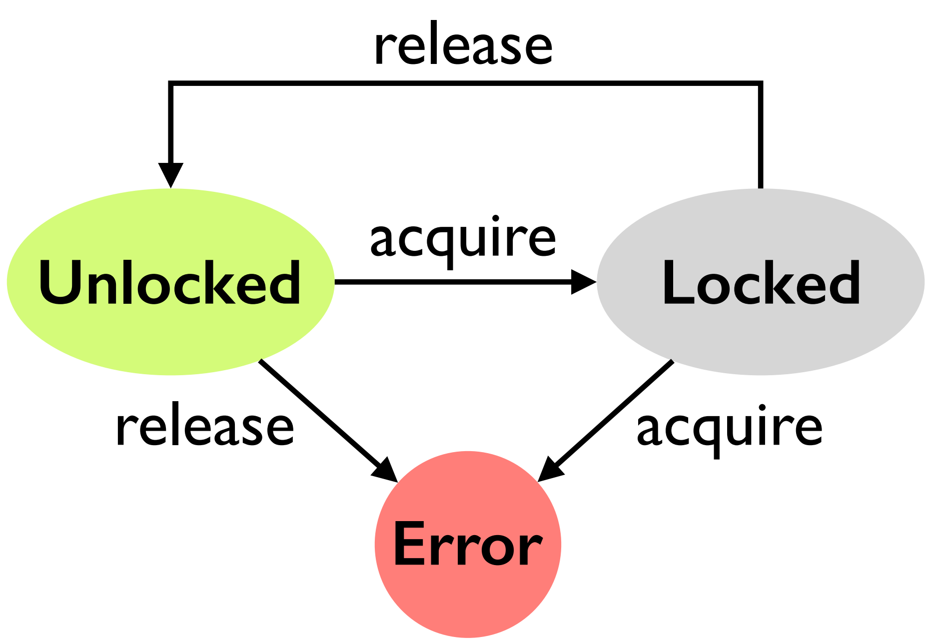
**A finite state language for stating rules for API usage**

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

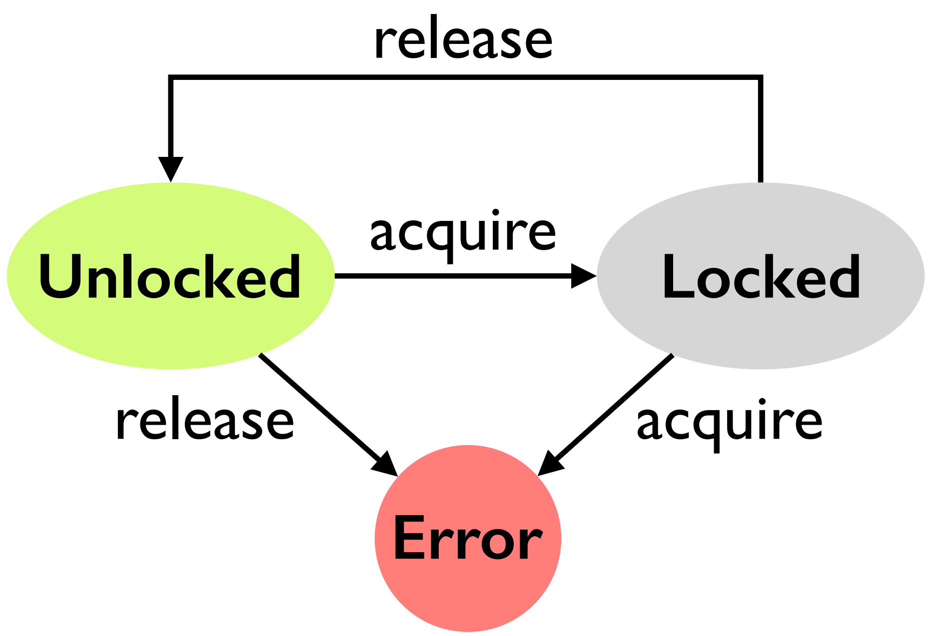
**Suitable for control-dominated properties**

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

# A locking protocol in SLIC



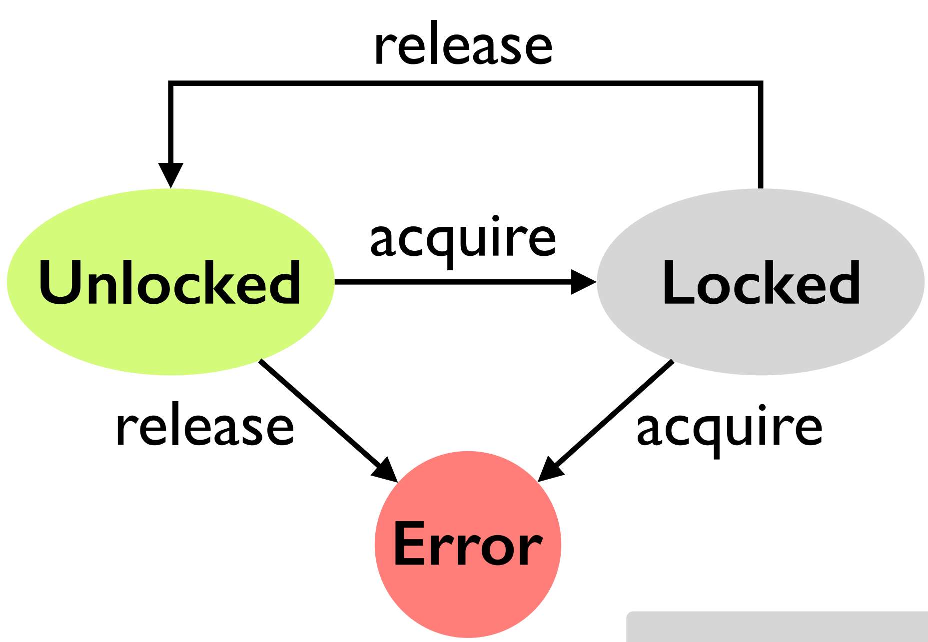
# A locking protocol in SLIC




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

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

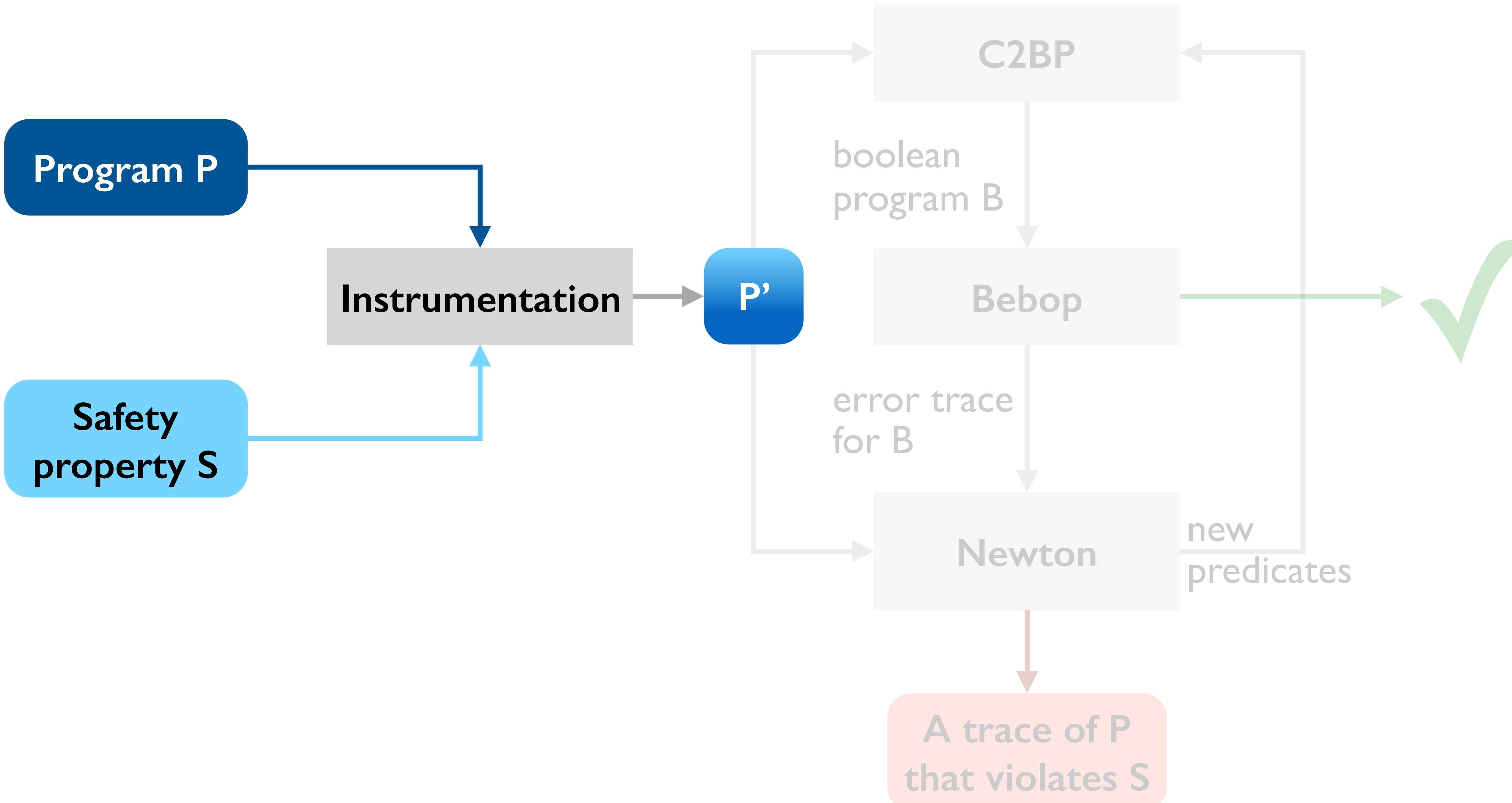
# A locking protocol in SLIC




*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'

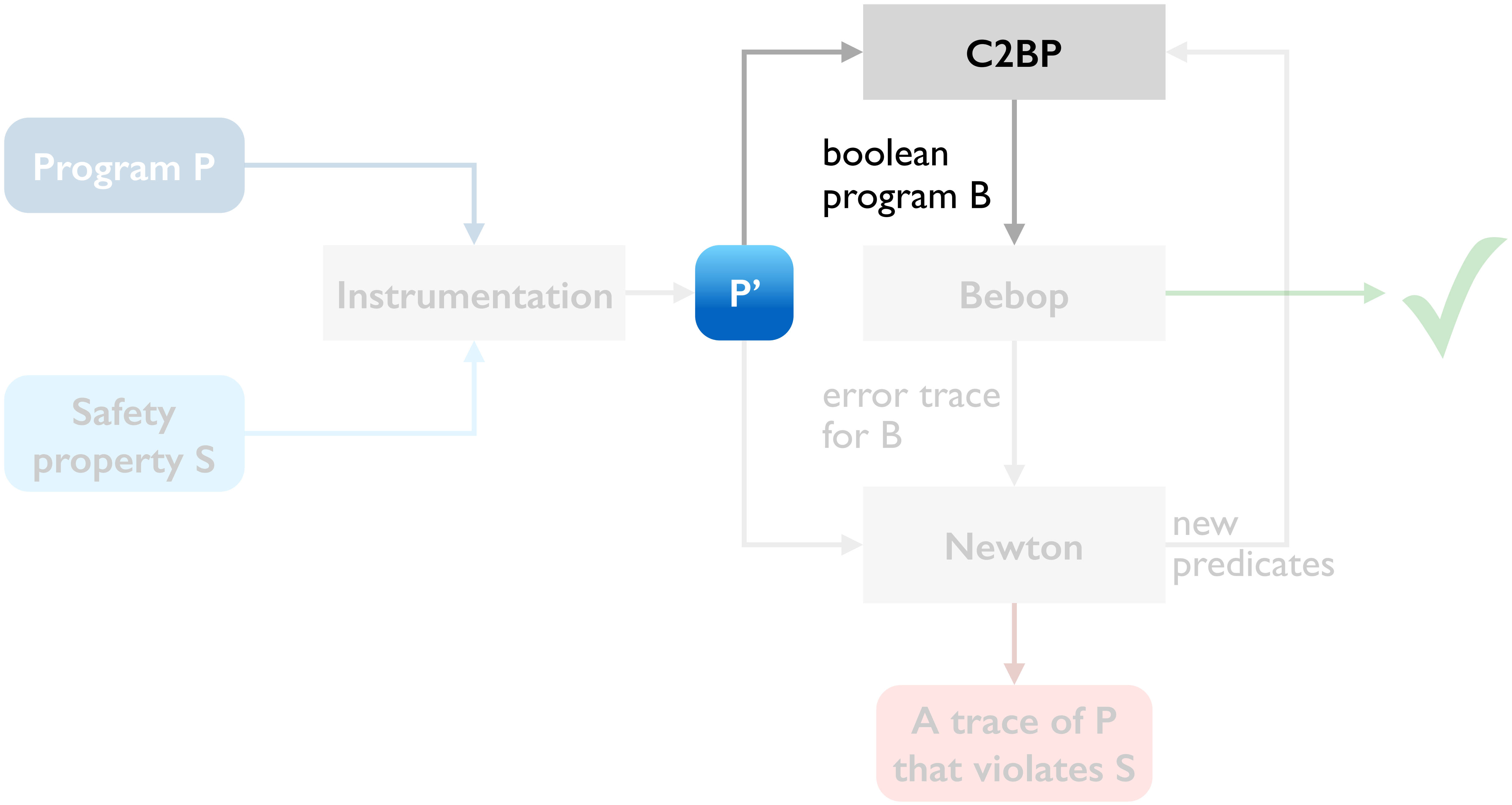
# P satisfies S iff SLIC_ERROR is unreachable in P'

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

   nOld = nPackets;

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

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

Program P'

```
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;
}
```

# The SLAM process:  predicate abstraction



# 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.

**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() {
  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'

# 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() {
  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'

```
(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: encode the effects of assignments on 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
    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 4: 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() {
  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;
     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

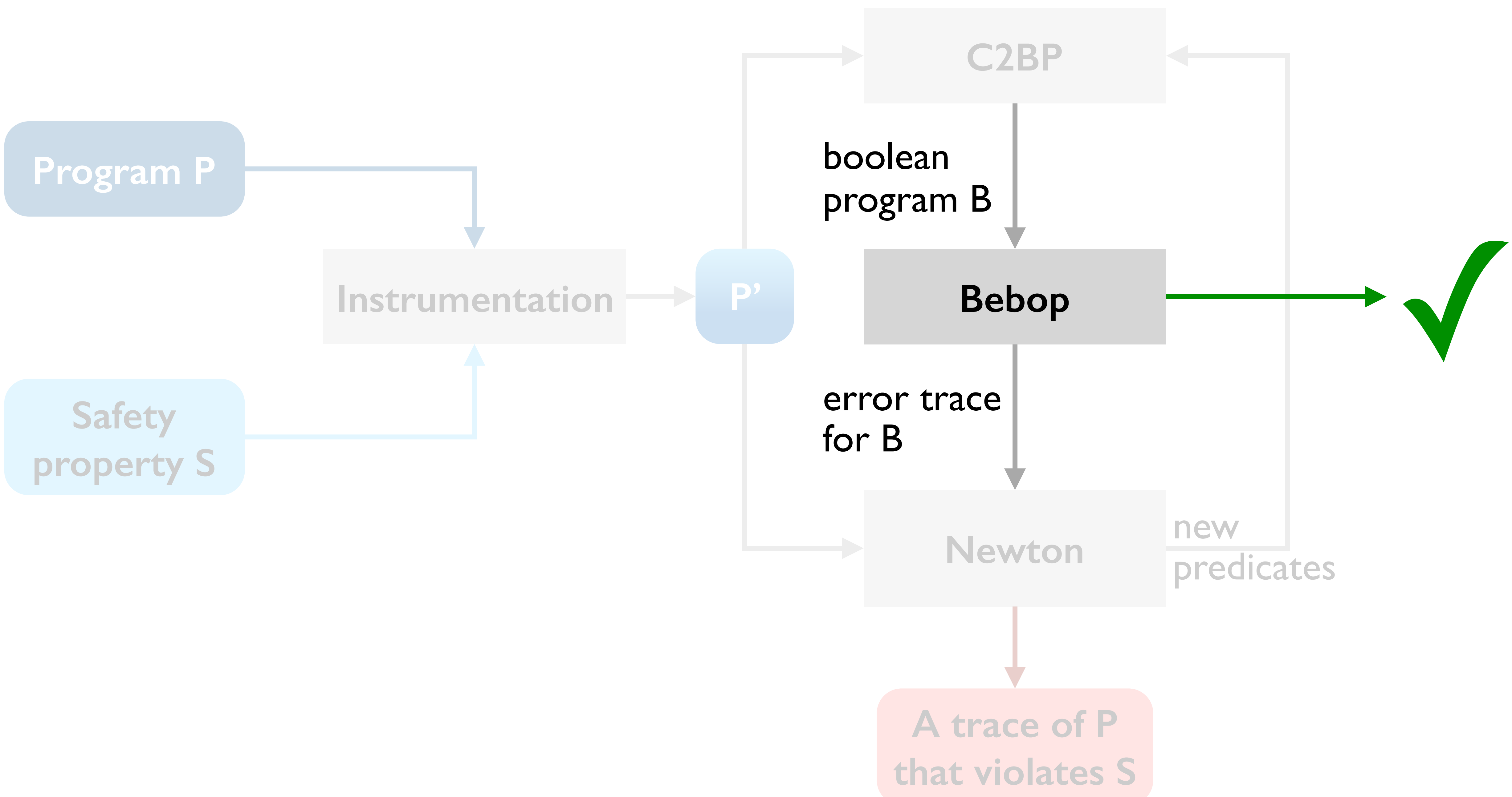
```
void example() {
  do {
   skip;
   KeAcquireSpinLock_return();

   skip;

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

  skip;
  KeReleaseSpinLock_return();
}
```

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

void slic_abort() {
  SLIC_ERROR: ; }

SpinLock_return {
ed)
();

),
ed) := T, F; }

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

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

**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.

**Performs symbolic reachability analysis using BDDs.**

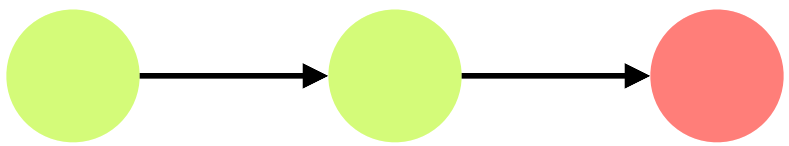
- Adapts the interprocedural dataflow analysis of **Reps,** Horwitz and Sagiv (RHS) to decide the reachability of s in B.
- Uses BDDs to represent the procedure summaries in RHS, which are binary relations between sets of states.

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

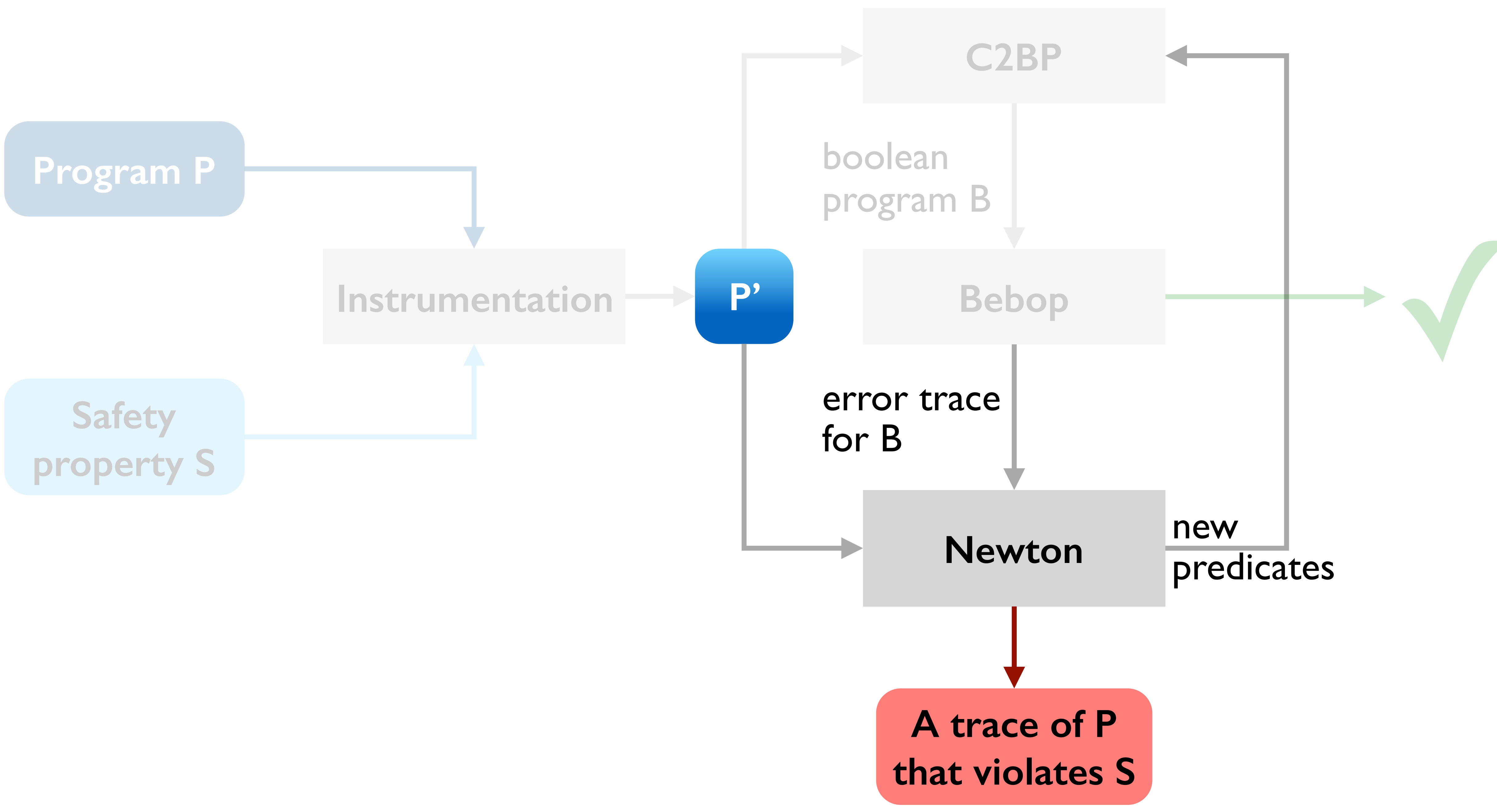
# Model checking of the example program

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



# The SLAM process:  trace validation



# Error trace validation & abstraction refinement

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

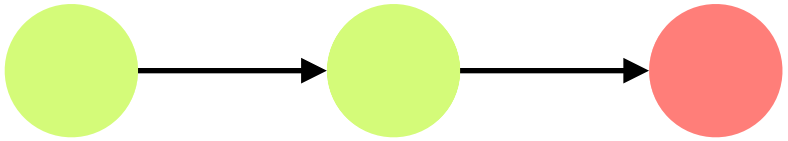
- Uses verification condition generation for feasibility checking.
- If feasible, the error trace corresponds to a real bug.
- If not, returns a small set of predicates that explain why the path is infeasible. Based on greedy minimal unsatisfiable core computation.

**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();
}
```

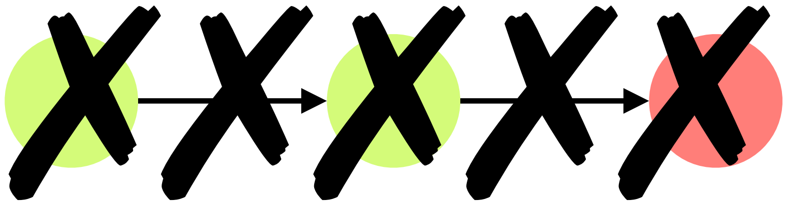
```
enum {Locked=0, Unlocked=1}
   state = Unlocked;

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() {
  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; }
```

```
(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;

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; }
```

```
(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;

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**

- Program synthesis