From Non-preemptive to Preemptive Scheduling using Synchronization Synthesis

Roopsha Samanta

IST Austria

Joint work with Pavol Černý, Edmund M. Clarke, Tom Henzinger, Arjun Radhakrishna, Leonid Ryzhyk and Thorsten Tarrach

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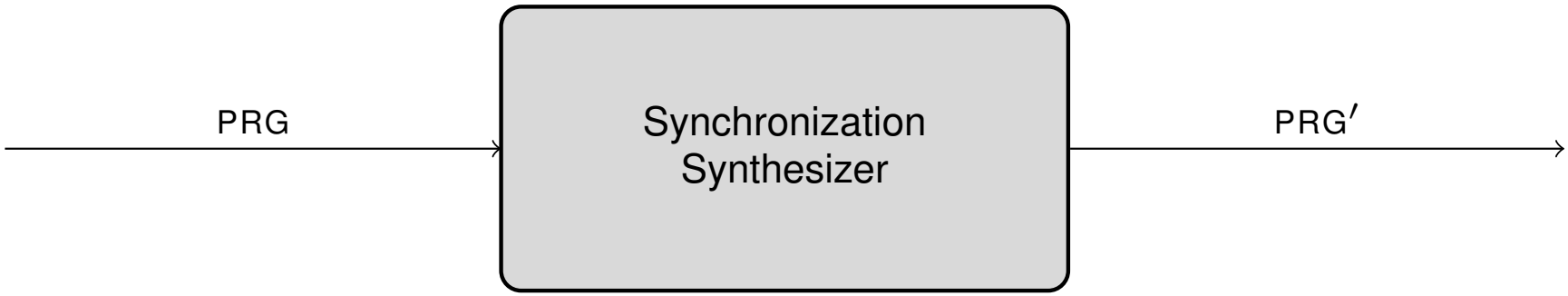
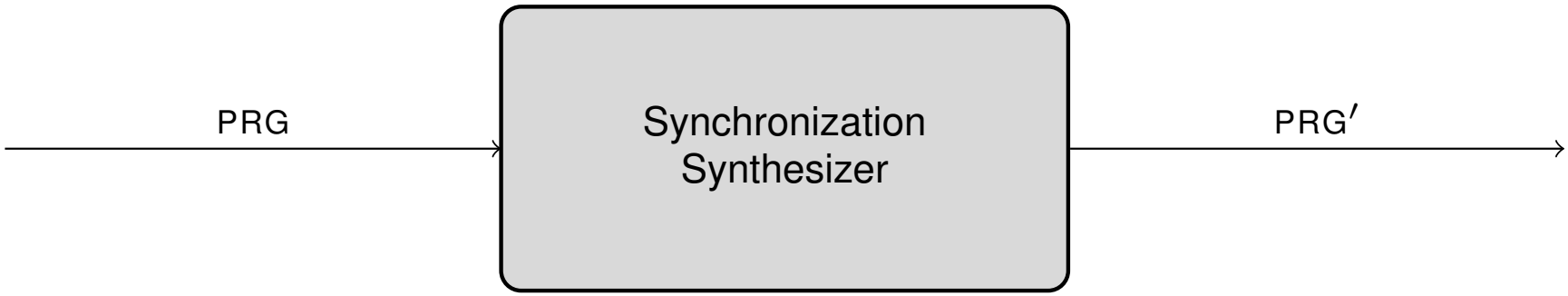
- Non-preemptive scheduler
- Preemptive scheduler

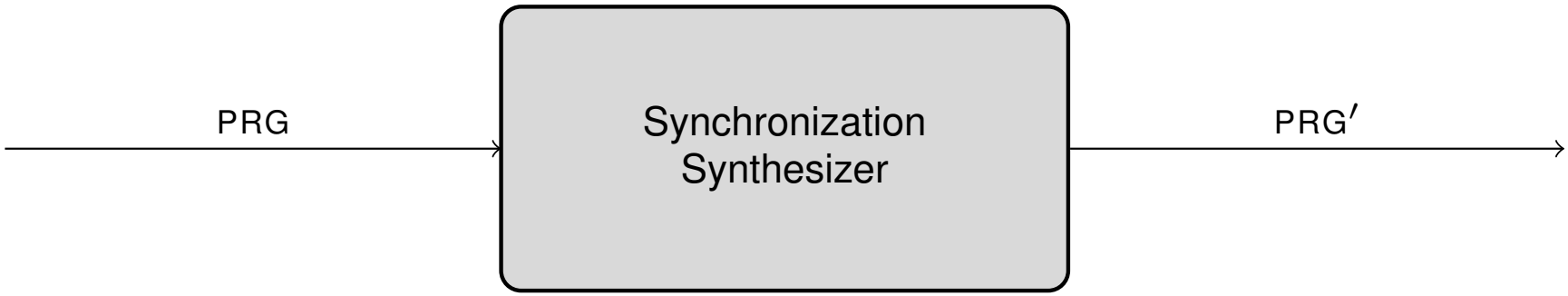
- Non-preemptive scheduler
  - Thread descheduled only if it yields control or terminates
- Preemptive scheduler
  - Thread can be descheduled at any point


PRG
Synchronization Synthesizer
PRG′



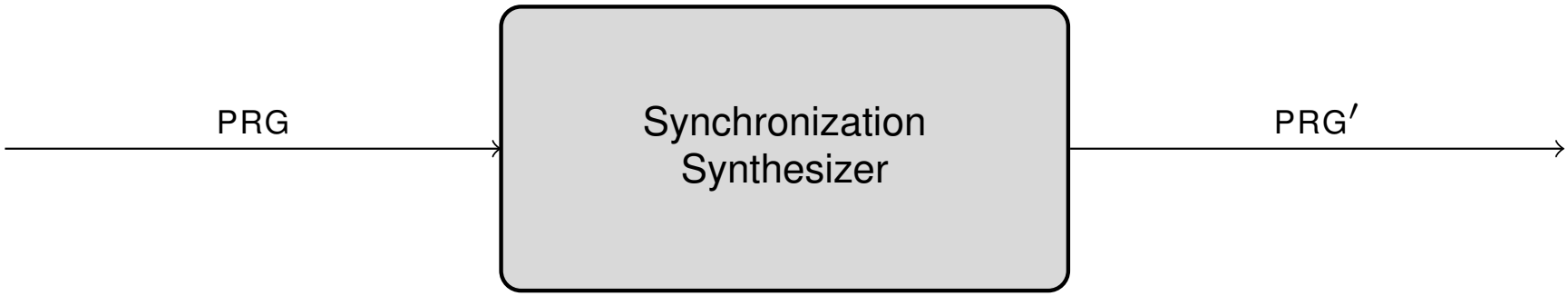
Programmer:

- Writes PRG



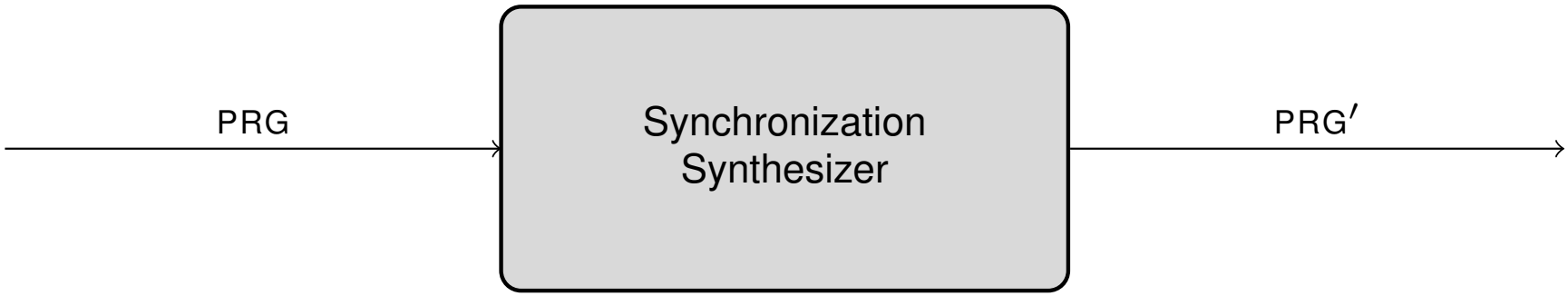
Programmer:

- Writes PRG
- Skips tricky synchronization



Programmer:

- Writes PRG
- Skips tricky synchronization
- Ensures:
  correct under nonpreemptive scheduler



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- Writes PRG
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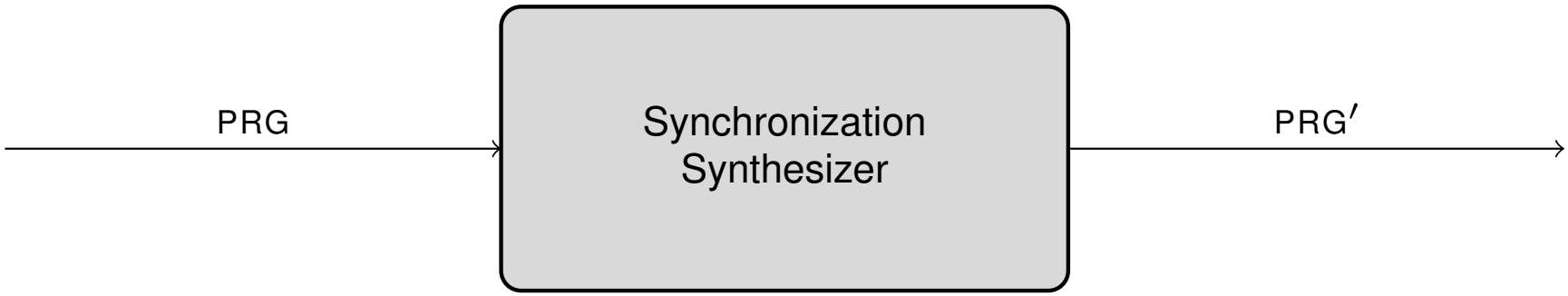
- Ensures:
  correct under nonpreemptive scheduler

Synthesizer:

- Automatically generates PRG′

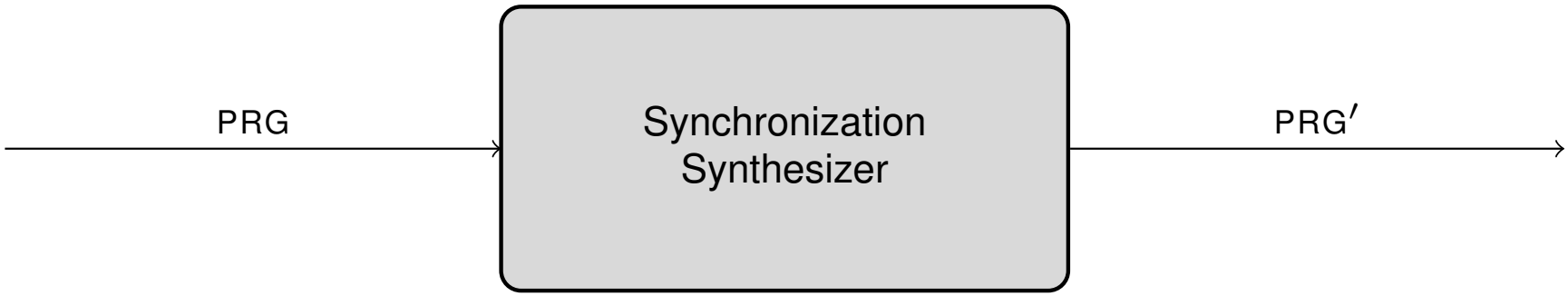


Programmer:

- Writes PRG
- Skips tricky synchronization
- Ensures: correct under nonpreemptive scheduler

Synthesizer:

- Automatically generates PRG′
- Inserts synchronization



Programmer:

- Writes PRG
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- Automatically generates PRG′
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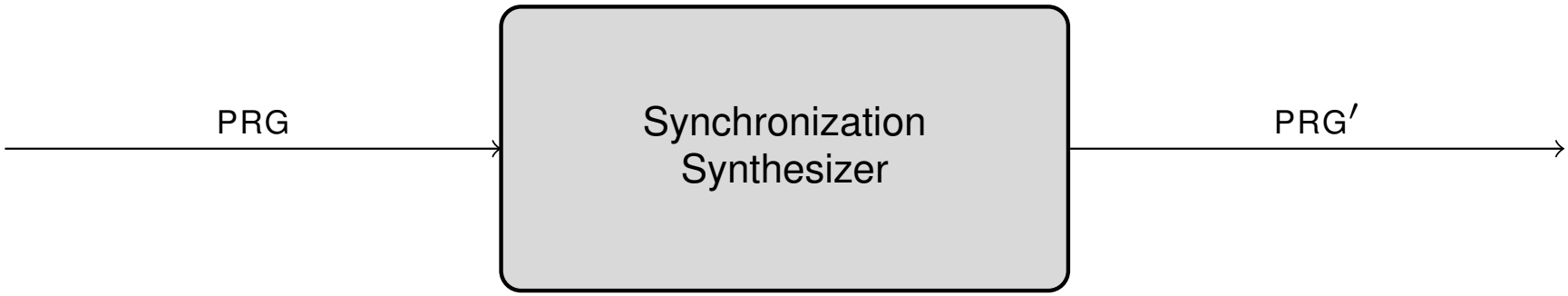

Programmer:

- Writes PRG
- Skips tricky synchronization
- Ensures: correct under nonpreemptive scheduler

Synthesizer:

- Automatically generates PRG′
- Inserts synchronization
- Ensures: correct under preemptive scheduler

$$[\![\text{PRG}']\!]^{\texttt{preempt}} \subseteq [\![\text{PRG}]\!]^{\texttt{nonpreempt}}$$

Preemption-safety

- Why use an implicit specification?
- Why preemption-safety?

- Why use an implicit specification?
  - Hard to write explicit specifications
  - Hard to ensure explicit specification is complete
- Why preemption-safety?

- Why use an implicit specification?
  - Hard to write explicit specifications
  - Hard to ensure explicit specification is complete
- Why preemption-safety?
  - Intuitively appealing
  - Encouraging user study [Sadowski and Yi 2010]
  - Our evaluation: preemption-safety can replace assertions

Target scenario

Module with interfaces

Observations: calls to interfaces

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;

void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

open := 0;

open = 0

```
   void open_dev()
→   if (open==0)
      power_up();
    open := open+1;
    yield;

   void close_dev()
    if (open>0)
      open := open-1;
      if (open==0)
        power_down();
    yield;
```

```
   void open_dev()
→   if (open==0)
      power_up();
    open := open+1;
    yield;

   void close_dev()
    if (open>0)
      open := open-1;
      if (open==0)
        power_down();
    yield;
```

$[\![\mathsf{PRG}]\!]^{\mathtt{nonpreempt}}$:

```
open := 0;
```

open = 0

```
  void open_dev()
→  if (open==0)
     power_up();
    open := open+1;
    yield;

  void close_dev()
    if (open>0)
      open := open-1;
      if (open==0)
        power_down();
    yield;
```

```
  void open_dev()
→  if (open==0)
     power_up();
    open := open+1;
    yield;

  void close_dev()
    if (open>0)
      open := open-1;
      if (open==0)
        power_down();
    yield;
```

$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

```
                                    open := 0;

power_up()      void open_dev()                 void open_dev()
                 if (open==0)          →         if (open==0)
              →    power_up();                     power_up();
                 open := open+1;                 open := open+1;
                 yield;                          yield;

                void close_dev()                void close_dev()
open = 0         if (open>0)                     if (open>0)
                   open := open-1;                 open := open-1;
                   if (open==0)                    if (open==0)
                     power_down();                   power_down();
                 yield;                          yield;
```

$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

```
                                  open := 0;
```

power_up()

open = 1

```
void open_dev()                    void open_dev()
 if (open==0)                       if (open==0)
  power_up();                        power_up();
→ open := open+1;                   open := open+1;
 yield;                             yield;

void close_dev()                   void close_dev()
 if (open>0)                        if (open>0)
  open := open-1;                    open := open-1;
  if (open==0)                       if (open==0)
   power_down();                      power_down();
 yield;                             yield;
```

$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

```
                                  open := 0;

power_up()      void open_dev()          void open_dev()
                 if (open==0)      →      if (open==0)
                   power_up();             power_up();
                 open := open+1;          open := open+1;
              →  yield;                   yield;

                void close_dev()         void close_dev()
open = 1         if (open>0)              if (open>0)
                   open := open-1;          open := open-1;
                   if (open==0)             if (open==0)
                     power_down();            power_down();
                 yield;                   yield;
```

$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

```
                                  open := 0;

power_up()      void open_dev()                 void open_dev()
                 if (open==0)          →         if (open==0)
                   power_up();                     power_up();
                 open := open+1;                 open := open+1;
                 yield;                          yield;

                void close_dev()                void close_dev()
open = 1    →    if (open>0)                     if (open>0)
                   open := open-1;                 open := open-1;
                   if (open==0)                    if (open==0)
                     power_down();                   power_down();
                 yield;                          yield;
```

$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

```
                                open := 0;
```

power_up()

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;
```

→

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;
```

open = 2

```
void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

→

```
void close_dev()
 if (open>0)
   open := open-1;
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$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

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                                    open := 0;
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power_up()

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void open_dev()
 if (open==0)
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 open := open+1;
 yield;
```

→

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;
```

open = 2

→

```
void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

```
void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
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$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

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 yield;
```

→

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;

void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

open = 2

$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

```
                                open := 0;
```

power_up()

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;
```

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;
```

open = 1

→

```
void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

→

```
void close_dev()
 if (open>0)
   open := open-1;
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 yield;
```

$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

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                                  open := 0;
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void open_dev()
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open = 1

→

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void open_dev()
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void close_dev()
 if (open>0)
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$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

```
                                  open := 0;

power_up()      void open_dev()          void open_dev()
                 if (open==0)             if (open==0)
                   power_up();              power_up();
                 open := open+1;          open := open+1;
                 yield;                   yield;

                void close_dev()         void close_dev()
                 if (open>0)              if (open>0)
open = 1           open := open-1;          open := open-1;
                   if (open==0)             if (open==0)
                     power_down();            power_down();
              →    yield;                   yield;
```

$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

```
                                    open := 0;

power_up()  →  void open_dev()          void open_dev()
                 if (open==0)             if (open==0)
                   power_up();              power_up();
               open := open+1;          open := open+1;
               yield;                   yield;

               void close_dev()         void close_dev()
open = 1        if (open>0)        →     if (open>0)
                  open := open-1;          open := open-1;
                  if (open==0)             if (open==0)
                    power_down();            power_down();
               yield;                   yield;
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$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

```
                                open := 0;
```

power_up() →

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;
```

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;
```

open = 0

```
void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

→

```
void close_dev()
 if (open>0)
   open := open-1;
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power_up() →

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void open_dev()
 if (open==0)
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void open_dev()
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 yield;
```

open = 0

```
void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

→

```
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   open := open-1;
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$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

```
                                  open := 0;
```

power_up()
power_down() →

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;
```

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;
```

open = 0

```
void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

→

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void close_dev()
 if (open>0)
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$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

```
                                    open := 0;
```

power_up()
power_down()

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
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```
void open_dev()
 if (open==0)
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 yield;
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```
void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

open = 0

→

```
void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

```
open := 0;
```

power_up()
power_down()
power_up()

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;

void close_dev()
 if (open>0)
   open := open-1;
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void open_dev()
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   open := open-1;
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     power_down();
 yield;
```

$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

```
                    open := 0;
```

```
power_up()
power_down()
power_up()
power_down()
```

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;

void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;

void close_dev()
 if (open>0)
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```

$[\![\text{PRG}]\!]^{\texttt{nonpreempt}}$:

```
                    open := 0;
```

```
power_up()
power_down()
power_up()
power_down()
    :
```

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;

void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

```
void open_dev()
 if (open==0)
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 open := open+1;
 yield;

void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

open := 0;

open = 0

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;

void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

→

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;

void close_dev()
 if (open>0)
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     power_down();
 yield;
```

$[\![\text{PRG}]\!]^{\texttt{preempt}}$:

```
                    open := 0;

      void open_dev()          void open_dev()
  →    if (open==0)        →    if (open==0)
        power_up();              power_up();
       open := open+1;          open := open+1;
       yield;                   yield;

      void close_dev()         void close_dev()
       if (open>0)              if (open>0)
open = 0 open := open-1;         open := open-1;
        if (open==0)             if (open==0)
          power_down();            power_down();
       yield;                   yield;
```

$[\![\text{PRG}]\!]^{\texttt{preempt}}$:

```
open := 0;
```

```
void open_dev()
 if (open==0)
→  power_up();
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 yield;

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 if (open>0)
  open := open-1;
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   power_down();
 yield;
```

```
void open_dev()
→ if (open==0)
  power_up();
 open := open+1;
 yield;

void close_dev()
 if (open>0)
  open := open-1;
  if (open==0)
   power_down();
 yield;
```

`open = 0`

$[\![\text{PRG}]\!]^{\text{preempt}}$:

```
                         open := 0;

power_up()       void open_dev()          void open_dev()
                  if (open==0)             if (open==0)
             →     power_up();        →     power_up();
                  open := open+1;          open := open+1;
                  yield;                   yield;

                 void close_dev()         void close_dev()
                  if (open>0)              if (open>0)
open = 0           open := open-1;          open := open-1;
                   if (open==0)             if (open==0)
                     power_down();            power_down();
                  yield;                   yield;
```

$[\![\text{PRG}]\!]^{\texttt{preempt}}$:

```
                                  open := 0;
```

power_up()

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;

void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

→

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;

void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

open = 1

$[\![\text{PRG}]\!]^{\texttt{preempt}}$:

```
                                  open := 0;

power_up()      void open_dev()          void open_dev()
                 if (open==0)             if (open==0)
                   power_up();      →       power_up();
                 open := open+1;          open := open+1;
              →  yield;                   yield;

                void close_dev()         void close_dev()
                 if (open>0)              if (open>0)
 open = 1          open := open-1;          open := open-1;
                   if (open==0)             if (open==0)
                     power_down();            power_down();
                 yield;                   yield;
```

$[\![\text{PRG}]\!]^{\texttt{preempt}}$:

```
                                  open := 0;

power_up()      void open_dev()          void open_dev()
power_up()       if (open==0)             if (open==0)
                   power_up();      →       power_up();
                 open := open+1;          open := open+1;
                 yield;                   yield;

                void close_dev()         void close_dev()
             →   if (open>0)              if (open>0)
 open = 1          open := open-1;          open := open-1;
                   if (open==0)             if (open==0)
                     power_down();            power_down();
                 yield;                   yield;
```

$[\![\text{PRG}]\!]^{\texttt{preempt}}$:

```
                                  open := 0;
```

power_up()
power_up()

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;
```

→

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;
```

open = 2

```
void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

→

```
void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

$[\![\text{PRG}]\!]^{\texttt{preempt}}$:

```
                                  open := 0;

power_up()      void open_dev()          void open_dev()
power_up()       if (open==0)             if (open==0)
                   power_up();              power_up();
                 open := open+1;          open := open+1;
                 yield;              →    yield;

                void close_dev()         void close_dev()
            →    if (open>0)              if (open>0)
 open = 2         open := open-1;          open := open-1;
                  if (open==0)             if (open==0)
                    power_down();            power_down();
                 yield;                   yield;
```

$[\![\text{PRG}]\!]^{\texttt{preempt}}$:

```
open := 0;
```

```
power_up()
power_up()
   ⋮
```

```
void open_dev()
 if (open==0)
  power_up();
 open := open+1;
 yield;

void close_dev()
→ if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

```
void open_dev()
 if (open==0)
  power_up();
 open := open+1;
 yield;

void close_dev()
→ if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```

$[\![\text{PRG}]\!]^{\texttt{preempt}}$:

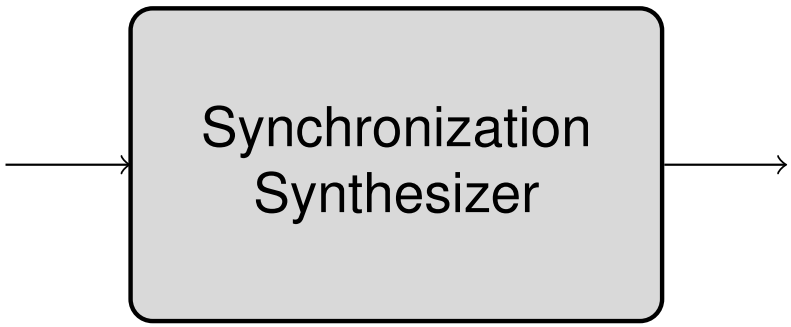
```
                                  open := 0;

power_up()          void open_dev()          void open_dev()
power_up()           if (open==0)             if (open==0)
    ⋮                  power_up();              power_up();
                     open := open+1;          open := open+1;
    ∉                yield;                   yield;

[[PRG]]^nonpreempt   void close_dev()         void close_dev()
              →       if (open>0)        →     if (open>0)
                        open := open-1;          open := open-1;
                        if (open==0)             if (open==0)
                          power_down();            power_down();
                      yield;                   yield;
```

```
void open_dev()
 if (open==0)
   power_up();
 open := open+1;
 yield;

void close_dev()
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
 yield;
```




```
void open_dev()
lock
 if (open==0)
   power_up();
 open := open+1;
unlock
 yield;

void close_dev()
lock
 if (open>0)
   open := open-1;
   if (open==0)
     power_down();
unlock
 yield;
```

$$[\![\text{PRG}']\!]^{\text{preempt}} \subseteq [\![\text{PRG}]\!]^{\text{nonpreempt}}$$

Abstraction

Data-oblivious abstraction

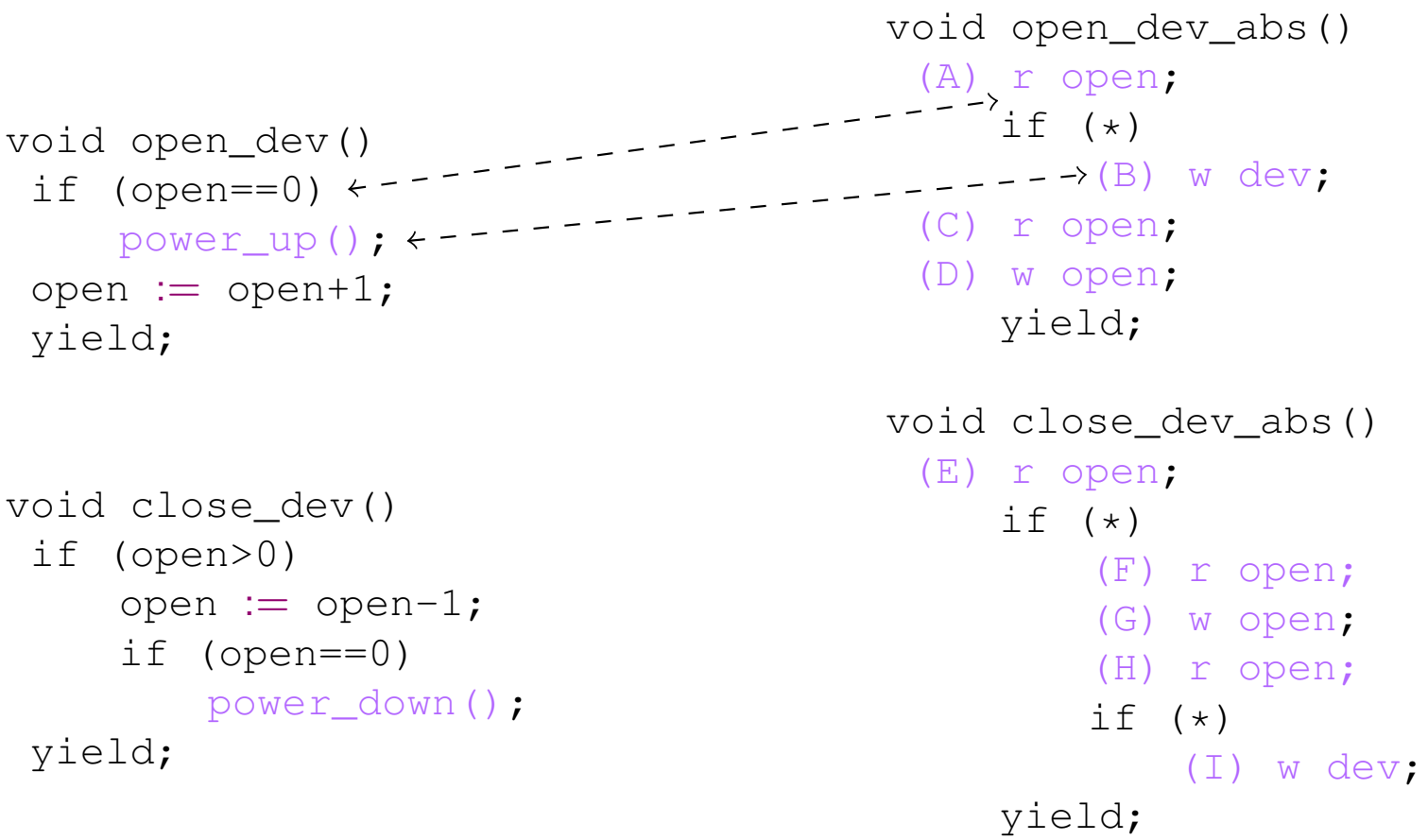
```
void open_dev()
 if (open==0)
     power_up();
 open := open+1;
 yield;
```

```
void close_dev()
 if (open>0)
     open := open-1;
     if (open==0)
         power_down();
 yield;
```

```
void open_dev_abs()
 (A) r open;
     if (*)
         (B) w dev;
 (C) r open;
 (D) w open;
     yield;
```

```
void close_dev_abs()
 (E) r open;
     if (*)
         (F) r open;
         (G) w open;
         (H) r open;
         if (*)
             (I) w dev;
     yield;
```

Data-oblivious abstraction



The Concrete Case:

Observations:

Calls to interface

The Abstract Case:

Observations:

Read/write memory locations

The Concrete Case:

Observations:
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Trace:
Sequence of observations

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Trace equivalence:
Equality

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Equality modulo $\mathcal{I}$

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Correctness:
Preemption-safety

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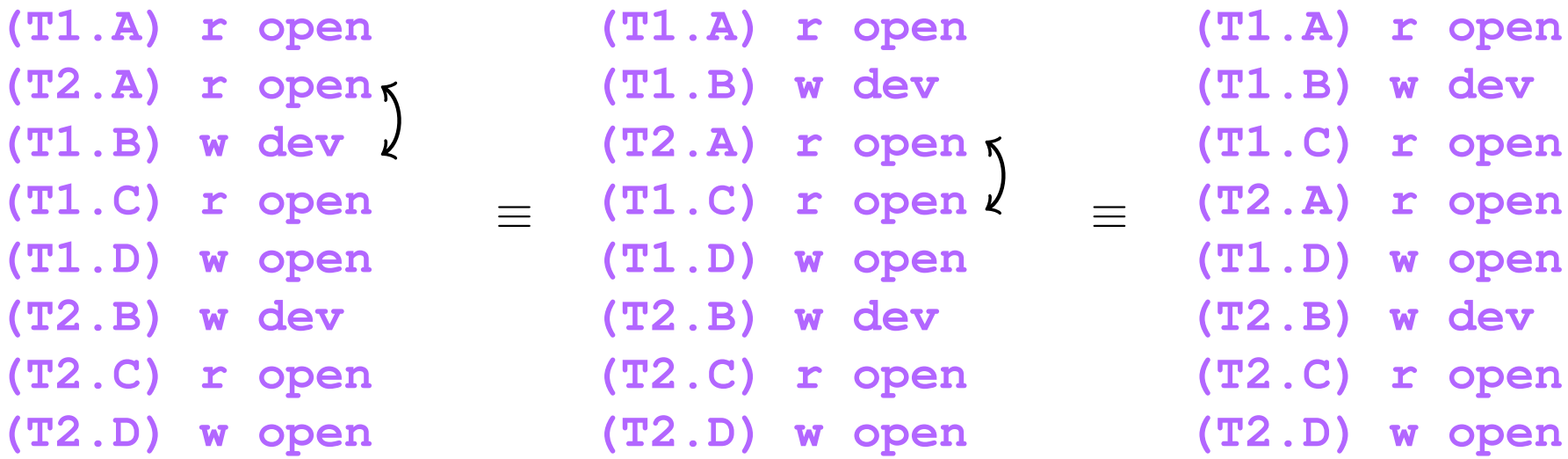

Classical independence relation $\mathcal{I}$:

- Accesses to different locations
- Read accesses to the same location

Soundness of Abstraction

Preemption-safety under abstraction $\Rightarrow$ Preemption safety

(T1.A) r open
(T2.A) r open
(T1.B) w dev
(T1.C) r open
(T1.D) w open
(T2.B) w dev
(T2.C) r open
(T2.D) w open
⋮

$\notin$

$[\![\text{PRG}]\!]^{\text{nonpreempt}}_{\text{ABS}}$

```
void open_dev_abs()
(A) r open;
    if (*)
        (B) w dev;
(C) r open;
(D) w open;
    yield;

void close_dev_abs()
(E) r open;
    if (*)
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        (G) w open;
        (H) r open;
        if (*)
            (I) w dev;
    yield;
```

```
void open_dev_abs()
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    if (*)
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(C) r open;
(D) w open;
    yield;

void close_dev_abs()
(E) r open;
    if (*)
        (F) r open;
        (G) w open;
        (H) r open;
        if (*)
            (I) w dev;
    yield;
```

Brief Note on The Rest

- Abstract semantics to automata

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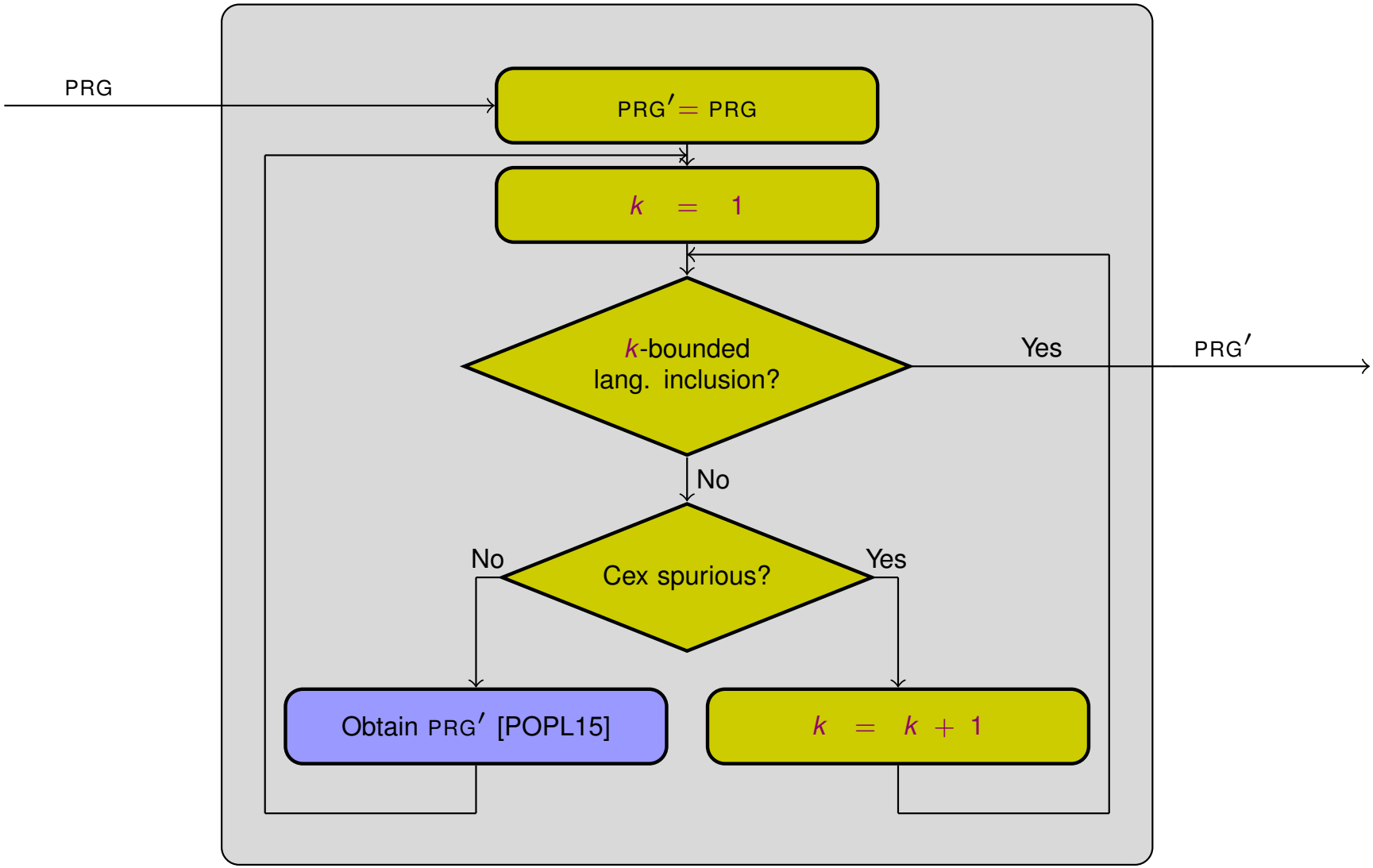
- Reduce preemption-safety to language inclusion modulo $\mathcal{I}$
  - Known to be undecidable [Bertoni et al. 1982]

- Abstract semantics to automata
- Reduce preemption-safety to language inclusion modulo $\mathcal{I}$
  - Known to be undecidable [Bertoni et al. 1982]
- We define k-bounded language inclusion modulo $\mathcal{I}$
  - And develop decision procedure


PRG
PRG′ = PRG
k = 1
k-bounded lang. inclusion?
Yes
PRG′
No
No
Cex spurious?
Yes
Obtain PRG′ [POPL15]
k = k + 1

Evaluation

LISS

- Evaluated on device driver benchmarks
- Implicit vs explicit specification

- Efficacy of abstraction

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LISS

- Evaluated on device driver benchmarks
- Implicit vs explicit specification
  - LISS eliminated all races (except 2)
  - LISS detected and eliminated a race missed by assertion-based approach
- Efficacy of abstraction
  - Highly efficient
  - Very precise

Experiments

Name	#Loc	#Th	#Iter	Max k	Bug(s)	Syn(s)	Ver(s)
ex1.c	18	2	1	1	<1	<1	<1
ex2.c	23	2	1	1	<1	<1	<1
ex3.c	37	2	1	1	<1	<1	<1
ex5.c	42	2	3	1	<1	<1	2
lc-rc.c	35	4	0	1	-	-	<1
dv1394.c	37	2	1	1	<1	<1	<1
em28xx.c	20	2	1	1	<1	<1	<1
f_acm.c	80	3	1	1	<1	<1	<1
i915_irq.c	17	2	1	1	<1	<1	<1
ipath.c	23	2	1	1	<1	<1	<1
iwl3945.c	26	3	1	1	<1	<1	<1
md.c	35	2	1	1	<1	<1	<1
myri10ge.c	60	4	2	1	-	-	<1

Experiments

Name	#Loc	#Th	#Iter	Max k	Bug(s)	Syn(s)	Ver(s)
usb-serial.bug1.c	357	7	2	1	0.4	3.1	3.4
usb-serial.bug2.c	355	7	1	3	0.7	2.1	12.9
usb-serial.bug3.c	352	7	1	4	3.8	1.3	111.1
usb-serial.bug4.c	351	7	1	4	93.9	2.4	123.1
usb-serial.c	357	7	1	4	-	-	103.2
cpmac.bug1.c	1275	5	1	1	1.3	113.4	21.9
cpmac.bug2.c	1275	5	1	1	3.3	68.4	27.8
cpmac.bug3.c	1270	5	1	1	5.4	111.3	8.7
cpmac.bug4.c	1276	5	2	1	2.4	124.8	31.5
cpmac.bug5.c	1275	5	1	1	2.8	112.0	58.0
cpmac.c	1276	5	1	1	-	-	17.4

Conclusion

Contributions:

- Synchronization synthesis for preemption-safety
- LISS can handle realistic device driver code

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Ongoing work: Quality of synthesized solution

- Deadlock-freedom
- Performance