Counterexample searches in Spot

Clément Gillard

LRDE
EPITA Research and Development Laboratory

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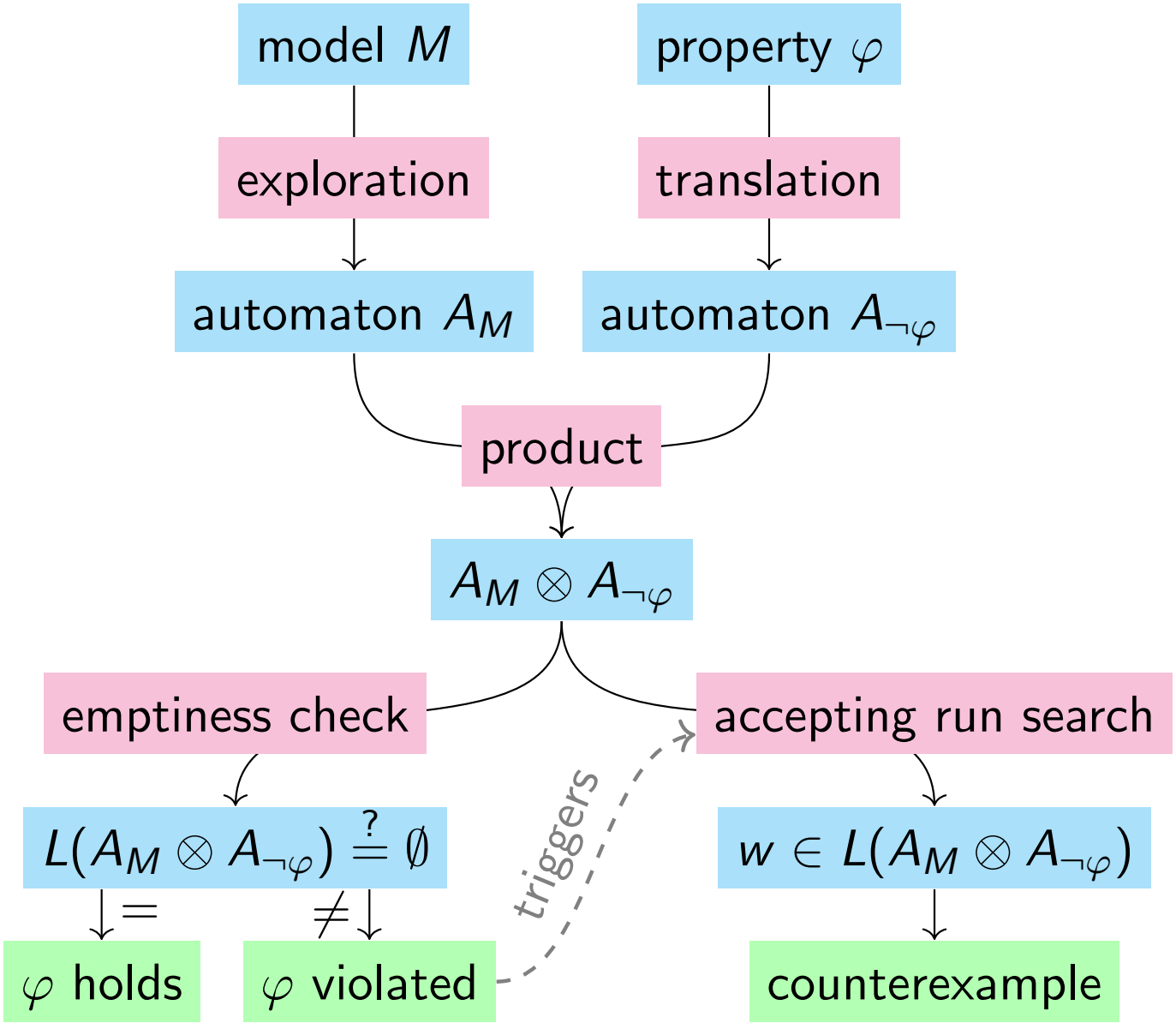
ω-automata Model Checking 101

$$
\begin{aligned}
& M \models \varphi \\
\iff \quad & L\left(A_M\right) \subseteq L\left(A_\varphi\right) \\
\iff \quad & L\left(A_M\right) \cap L\left(\overline{A_\varphi}\right) = \emptyset \\
\iff \quad & L\left(A_M\right) \cap L\left(A_{\neg\varphi}\right) = \emptyset \\
\iff \quad & L\left(A_M \otimes A_{\neg\varphi}\right) = \emptyset
\end{aligned}
$$

The Model Checking Toolchain



ω-automata Equivalence

$$
\begin{aligned}
& A_1 \equiv A_2 \\
\iff \quad & L(A_1) = L(A_2) \\
\iff \quad & L(A_1) \subseteq L(A_2) && \text{and} && L(A_1) \supseteq L(A_2) \\
\iff \quad & L(A_1) \cap L\left(\overline{A_2}\right) = \emptyset && \text{and} && L\left(\overline{A_1}\right) \cap L(A_2) = \emptyset \\
\iff \quad & L\left(A_1 \otimes \overline{A_2}\right) = \emptyset && \text{and} && L\left(\overline{A_1} \otimes A_2\right) = \emptyset
\end{aligned}
$$

A counterexample helps us debug.

Spot 2

- Duret-Lutz et al., “Spot 2.0 — a framework for LTL and ω-automata manipulation”, ATVA’16 [2]
- C++ library, Python interface
- algorithms and bridges for model checking
- executables for testing and comparing tools: `ltlcross`, `autcross`

Multiple algorithms

Name	Type of automata	Emptiness check	Accepting run search	
Couvreur New:	TGBA			
	– on-the-fly	✔	✔	
	– explicit	✔	✔	
Product EC&CE:	TGBA			
	– on-the-fly	✔ (2017)	✔ (2018)	
	– explicit	✔ (2017)	✔ (2018)	(benches 2019)
Generic EC:	Any			
	– explicit	✔	✔ (2019)	

Counterexample searches in Spot

Generalities on accepting run searches

Papers on efficient counterexample search

- Gastin, Moro, and Zeitoun, “Minimization of counterexamples in SPIN”, SPIN’04 [5]
  ✘ no knowledge search
- Hansen and Kervinen, “Minimal Counterexamples in $O(n \log n)$ Memory and $O(n^2)$ Time”, ACSD’06 [8]
  ✘ no knowledge search
- Gastin and Moro, “Minimal Counterexample Generation for SPIN”, MCS’07 [4]
  ✔✘ path reconstruction... for bitstate hashing
- Hansen and Geldenhuys, “Cheap and Small Counterexamples”, SEFM’08 [7]
  ✘ no knowledge search

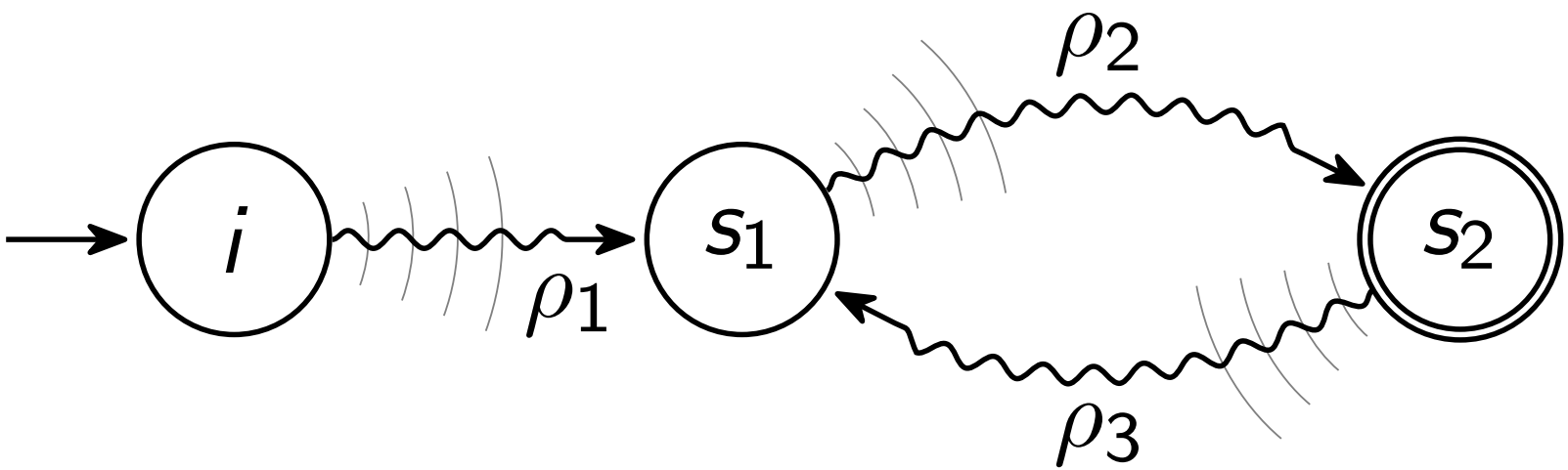
Quote

From “Minimal Counterexample Generation for SPIN” [4]:

“If states are stored in an hash table as usual, one can recover the trace of the counter-example using a BFS algorithm [. . .]. It then suffices to apply this BFS from the initial state i to s_1 to generate ρ_1, then to apply it from s_1 to s_2 to generate ρ_2 and finally to apply it once more from s_2 to s_1 to generate ρ_3.”

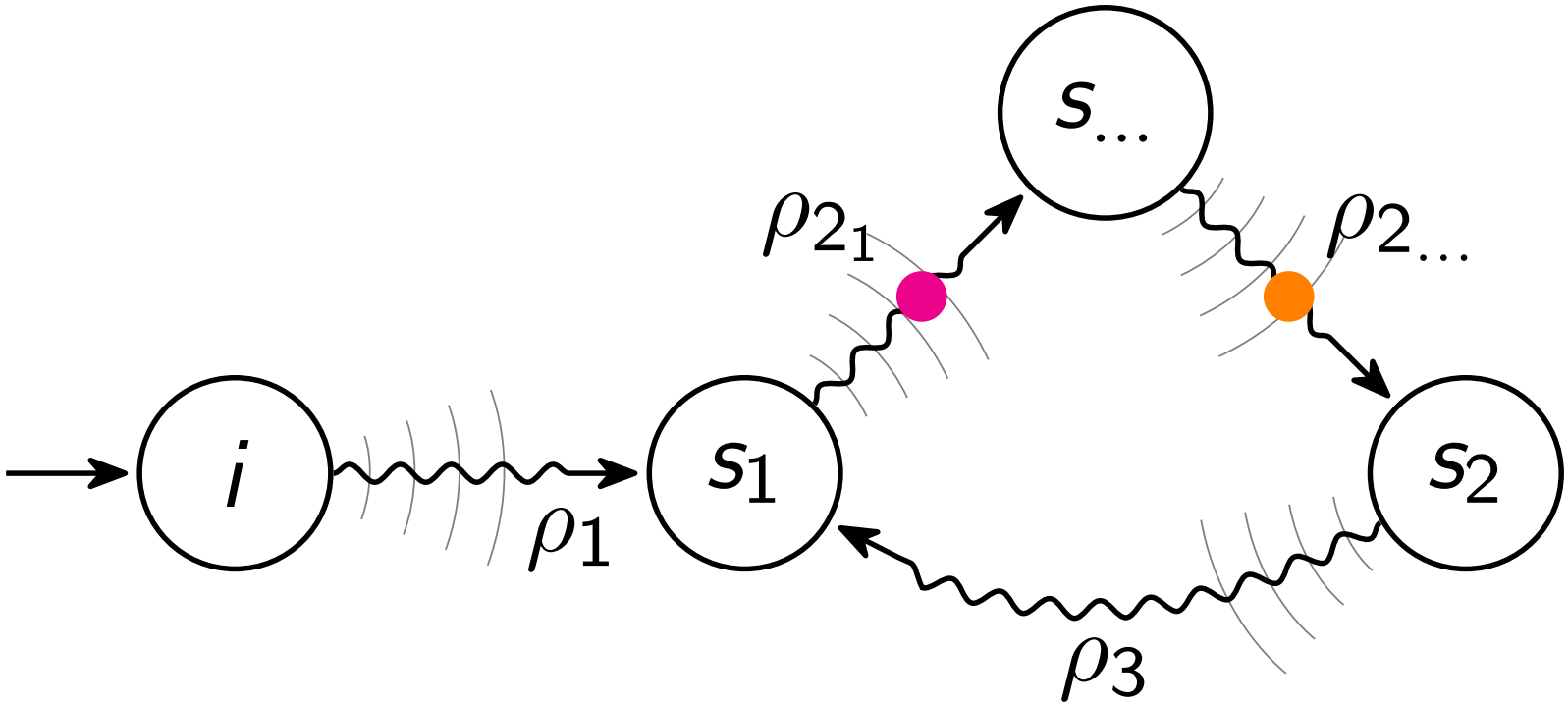
Gastin and Moro

From BA to TGBA



From BA to TGBA

$$Inf(\bullet) \wedge Inf(\bullet)\ldots$$

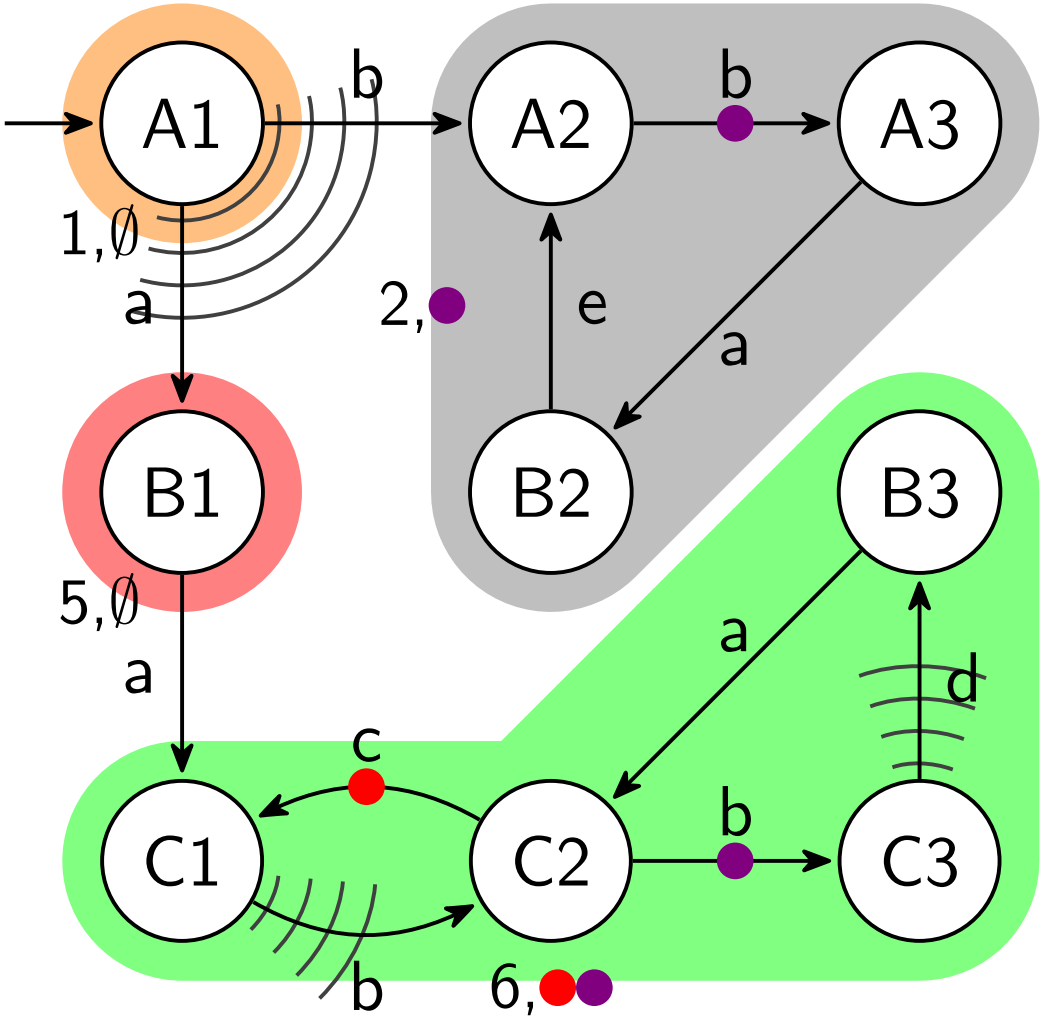


Product accepting run search

The Product Emptiness Check

- Gillard, Two-automaton emptiness check in Spot, 2017 [6]
- Algorithm by Couvreur, “On-the-fly Verification of Temporal Logic”, FM’99 [1]
- Removes a limitation of building the product by simulating it with custom data structures
- Generalised Büchi acceptance condition only

The Product Accepting Run Search



$Inf(\bullet) \wedge Inf(\bullet)$

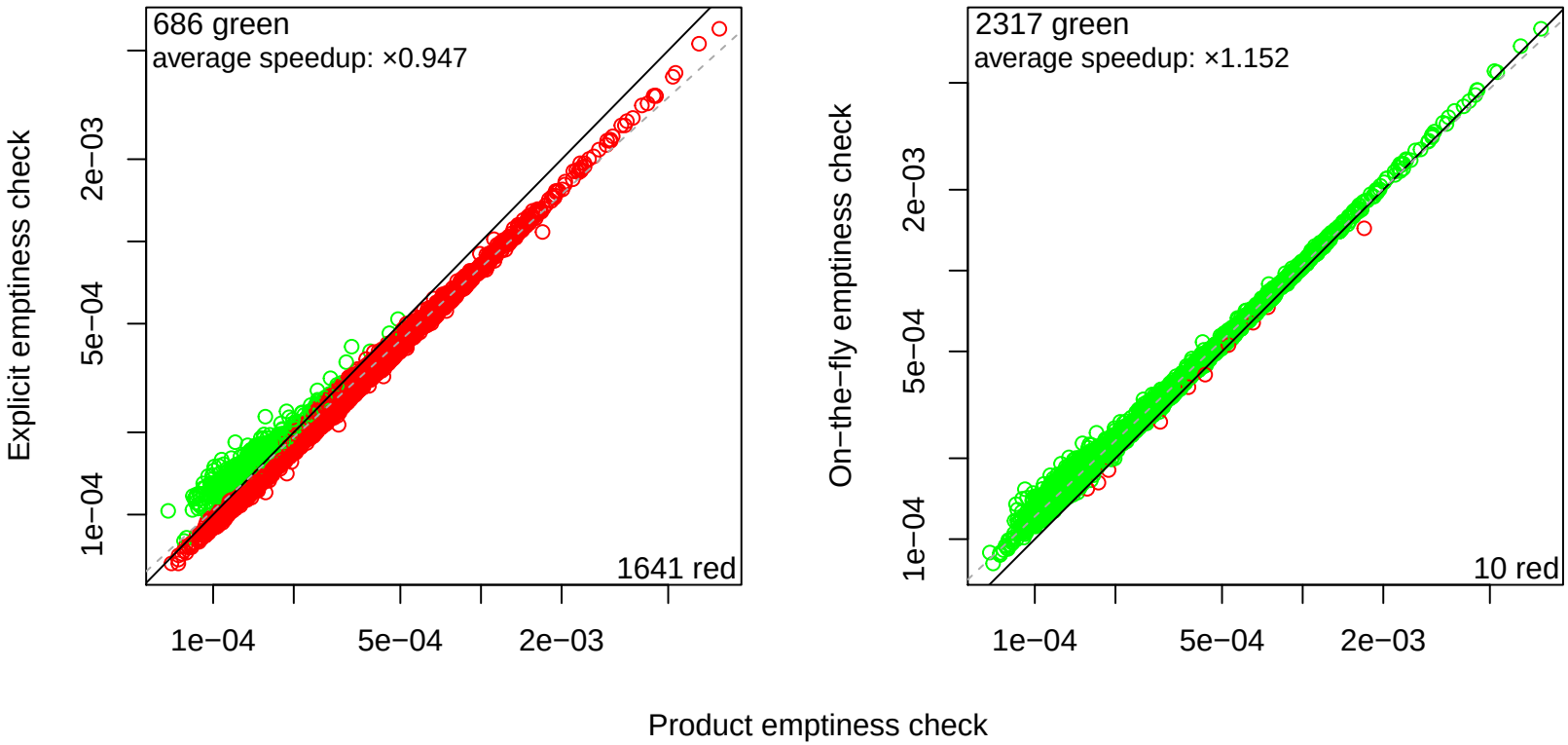
Prefix: A1
B1
C1
Cycle: C2
C1 ●
C2
C3 ●
B3
C2
C1

The Product Accepting Run Search

- Knowledge:
  - map: *state* of $A_1 \times$ *state* of $A_2 \rightarrow$ *order*
  - "*order*" of s_1
  - marks seen in the accepting SCC
- Implementation:
  - Reimplementation of the `bfs_steps` algorithm
  - BFS from i to s_1 $\rightarrow \rho_1$
  - repeated BFSs to cross off marks, until s_2 is reached $\rightarrow \rho_2$
  - BFS from s_2 to s_1 $\rightarrow \rho_3$

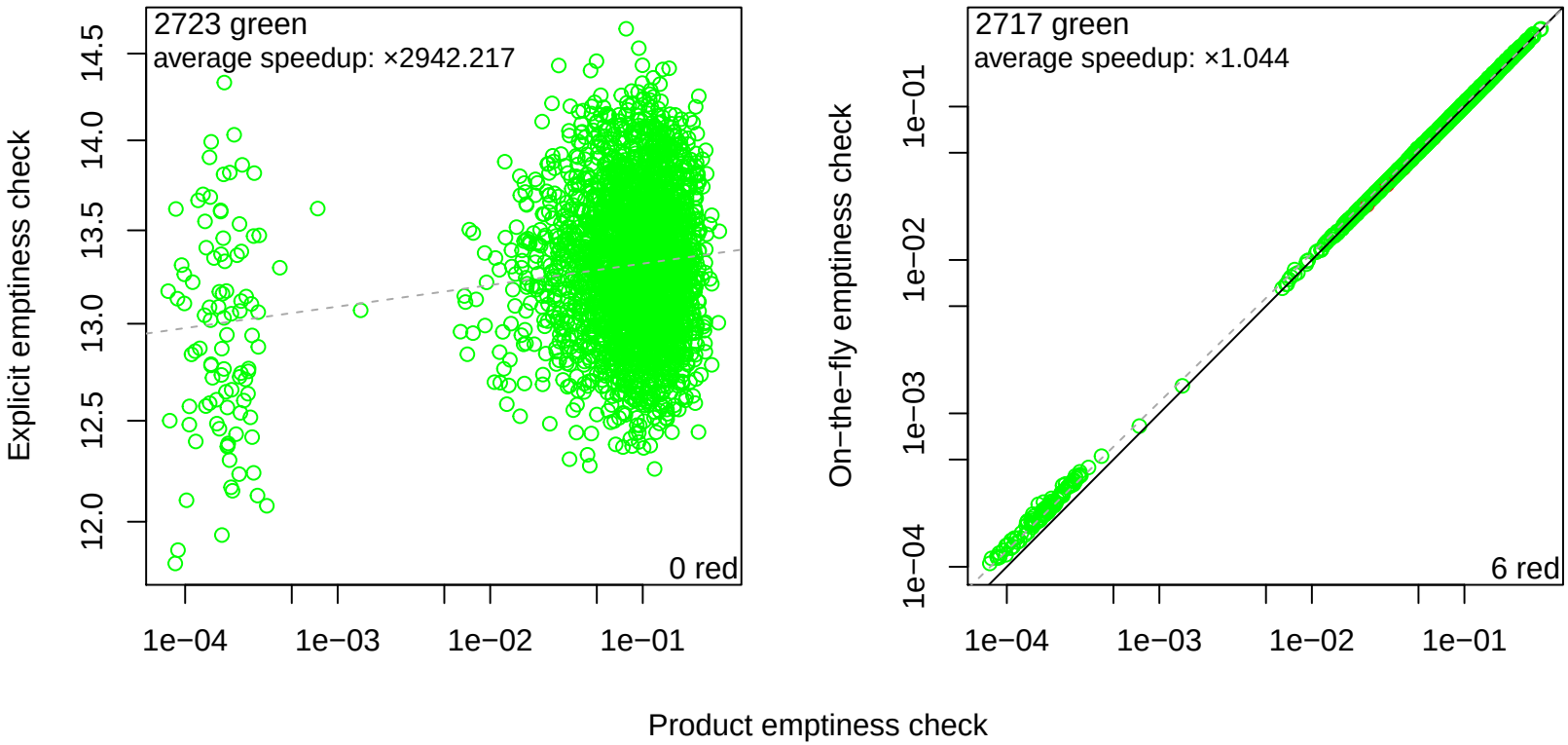
Benches

Time of emptiness check − Empty

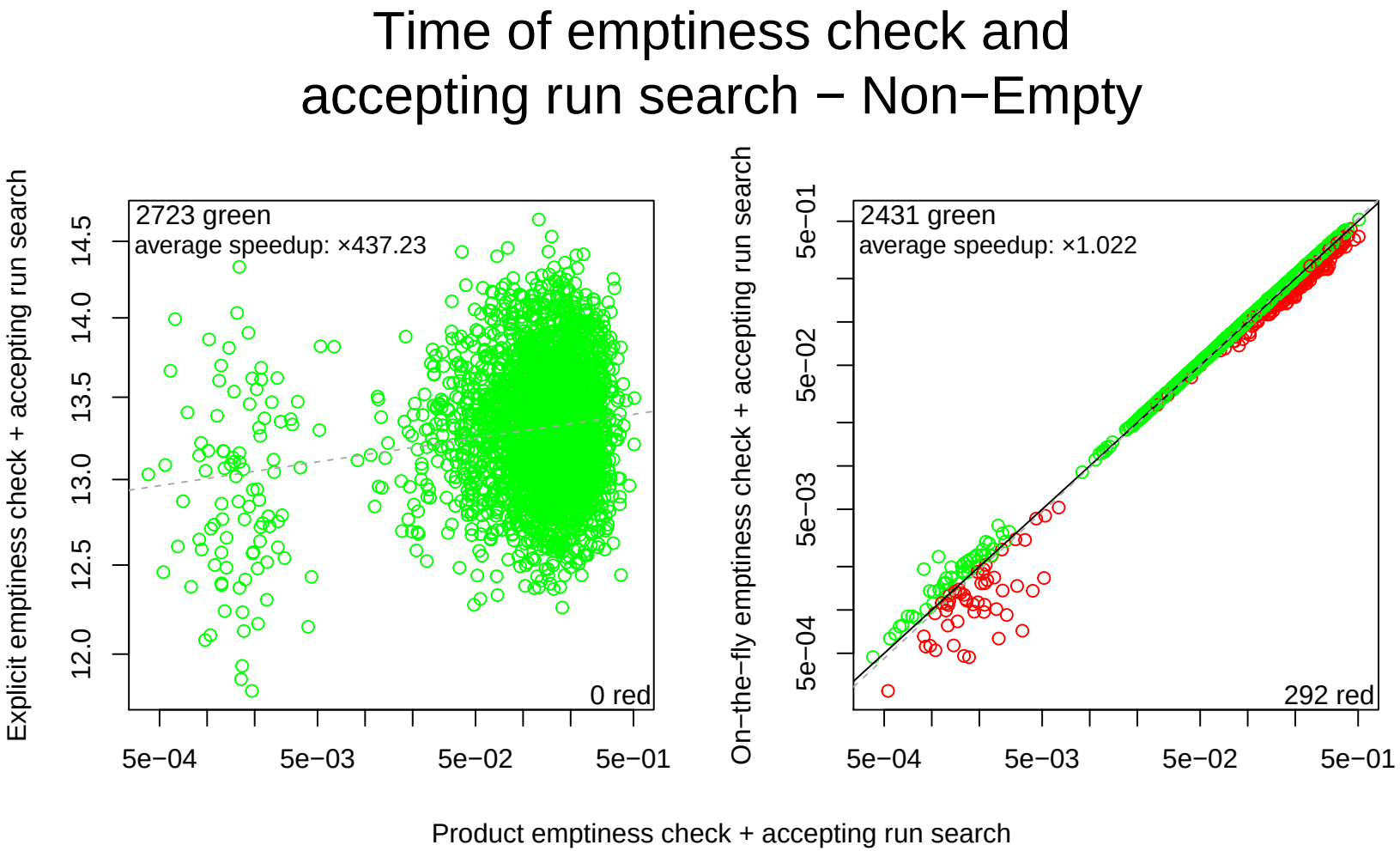


Benches

Time of emptiness check − Non−Empty



Benches

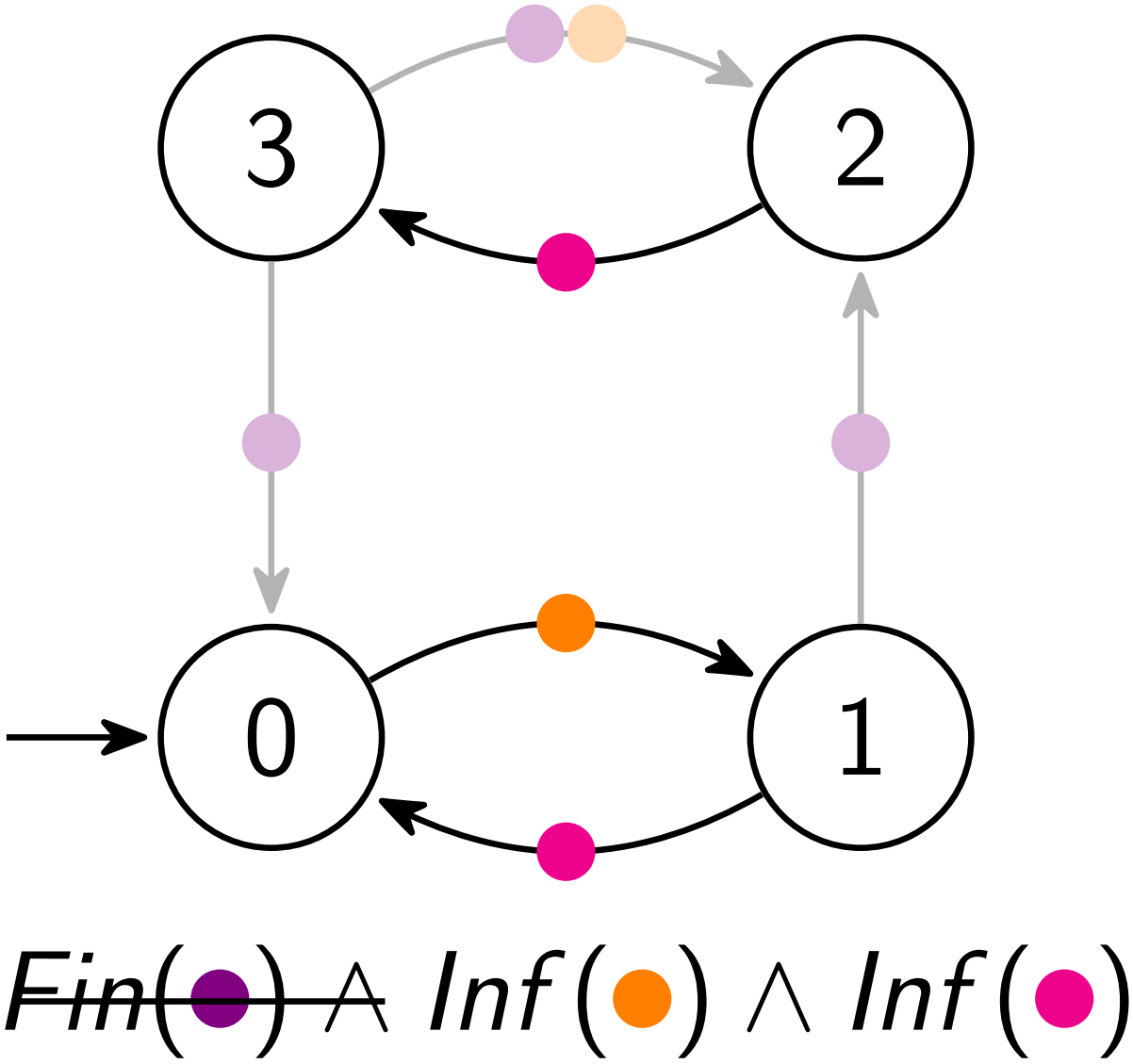

Time of emptiness check and
accepting run search − Non−Empty
Explicit emptiness check + accepting run search
2723 green
average speedup: ×437.23
0 red
12.0
12.5
13.0
13.5
14.0
14.5
5e−04
5e−03
5e−02
5e−01
On−the−fly emptiness check + accepting run search
2431 green
average speedup: ×1.022
292 red
5e−04
5e−03
5e−02
5e−01
Product emptiness check + accepting run search

Generic accepting run search

The Generic Emptiness Check

- New recursive algorithm
- Works with any acceptance condition
- NP-complete
  - Emerson and Lei, “Modalities for Model Checking: Branching Time Logic Strikes Back”, SCP’87 [3]

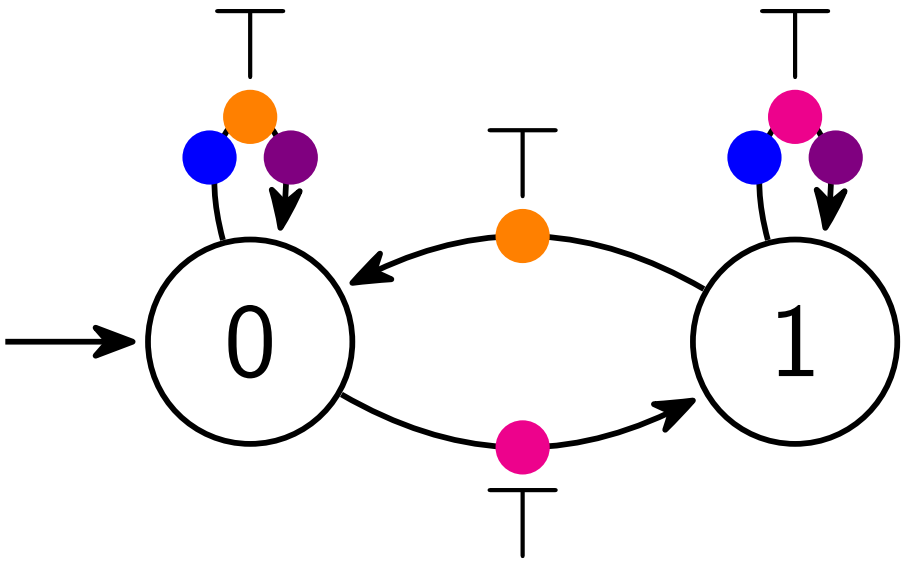
The Generic Emptiness Check



The Generic Accepting Run Search

- Knowledge:
  - states of the accepting SCC
  - marks seen in the accepting SCC
  - cut-out acceptance condition
- Implementation:
  - At the deepest recursion level, in `scc_info`
  - Repeat what was done for the product accepting run search, what has to be cut out has been already, right? ✘ Wrong!
  - We can use `bfs_steps` as is

Example



$$(Fin(\bullet) \vee Fin(\bullet)) \wedge (Fin(\bullet) \vee Fin(\bullet))$$

Conclusion

Conclusion

- Emptiness checks are useful in many ways
- Multiple ways to do them, with tradeoffs on efficiency
- Go together with accepting run searches, which completes their usage
- Different knowledge can be extracted from different algorithms

Conclusion

- Fix the generic accepting run search
  - Custom BFS? More versatile `bfs_steps`?
  - Bench
- Integrate the product emptiness check to Spot
- Better automata for benching

Questions?

Thank you for your attention!

Any imprecision? Would you like me to go into more details?

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