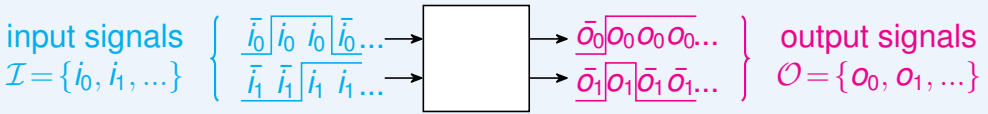
CIAA'25

Engineering an LTL$_f$ synthesis tool

Alexandre Duret-Lutz Shufang Zhu Nir Piterman
Giuseppe De Giacomo Moshe Y. Vardi

Reactive Synthesis in a Nutshell

A **reactive controller** produces output as a reaction to its input



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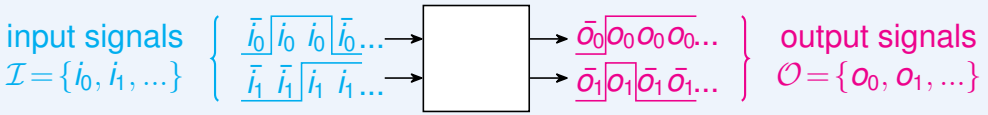


The reactive synthesis problems

Given a specification relating input signals and output signals over time:

Realizability: decide if a controller exists;

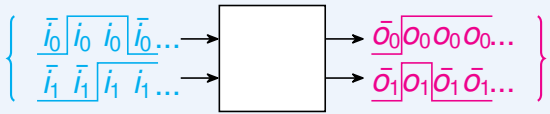
Synthesis: construct it (e.g., as an And-Inverter Graph).

our focus

Reactive Synthesis in a Nutshell

A **reactive controller** produces output as a reaction to its input

input signals $\mathcal{I} = \{i_0, i_1, ...\}$



output signals $\mathcal{O} = \{o_0, o_1, ...\}$

The reactive synthesis problems

Given a specification relating input signals and output signals over time:

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Semantics for an LTL$_f$ specification

Any execution of the controller, seen as an infinite word such as "$\bar{i_0}\bar{i_1}\bar{o_0}\bar{o_1}$; $i_0\bar{i_1}o_0o_1$; $i_0i_1o_0\bar{o_1}$; ...", must have a finite prefix satisfying the specification.

Text-Book Approach

1. LTL$_f$ specification φ

$(i_0 \wedge \mathsf{G} i_1) \leftrightarrow (o_0 \wedge \mathsf{X}^! \mathsf{X}^! o_1)$

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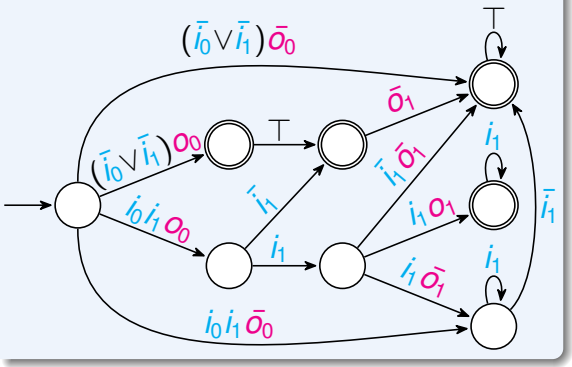

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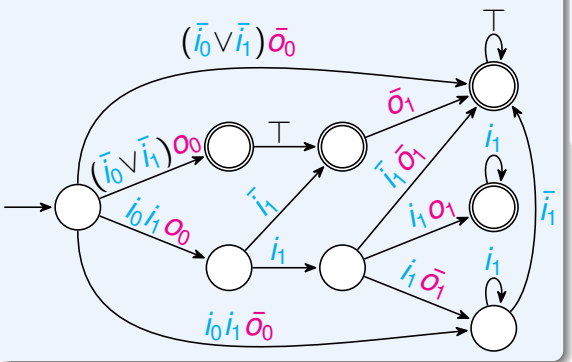
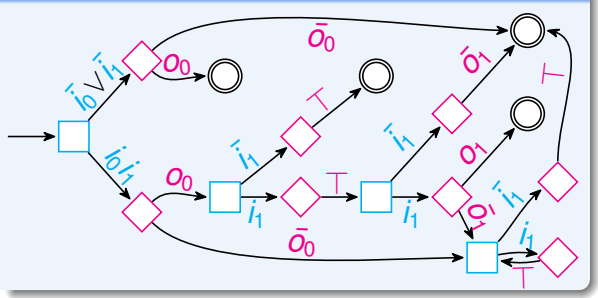


3. Make it a Reachability Game



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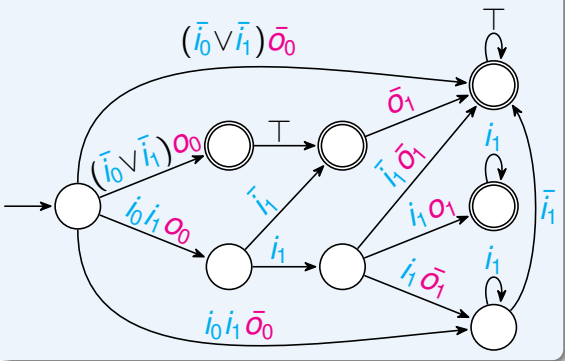

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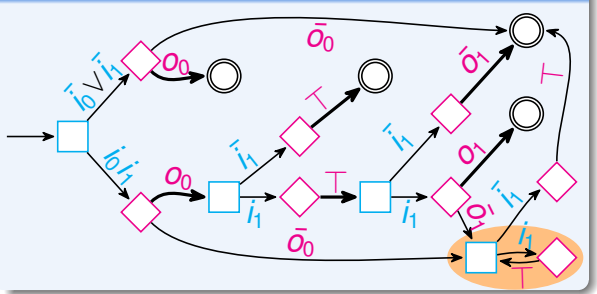

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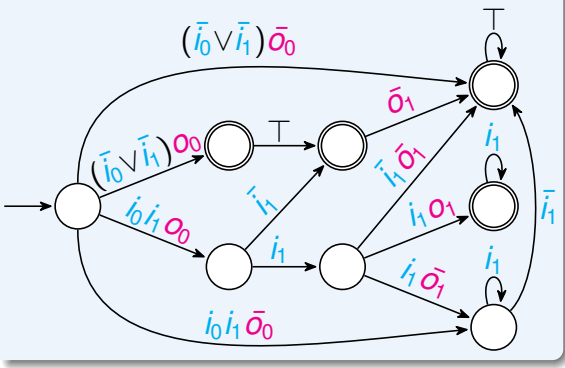

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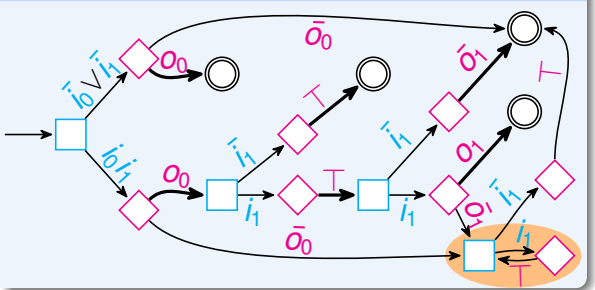

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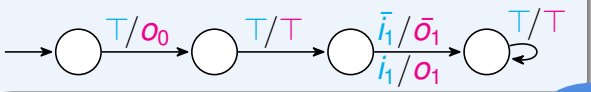

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2-EXPTIME

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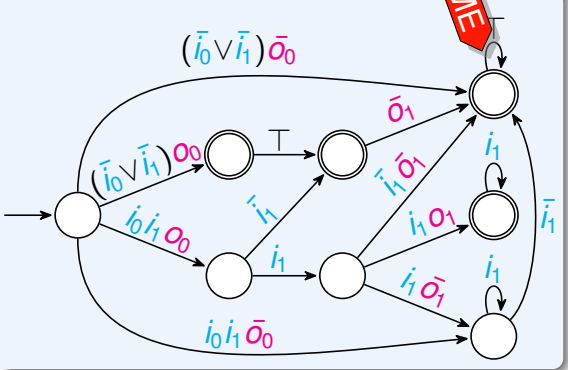

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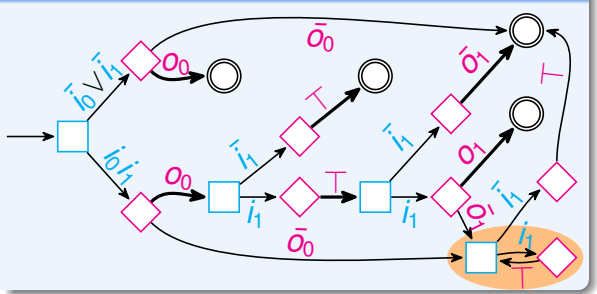

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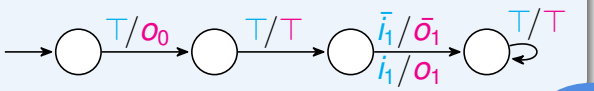

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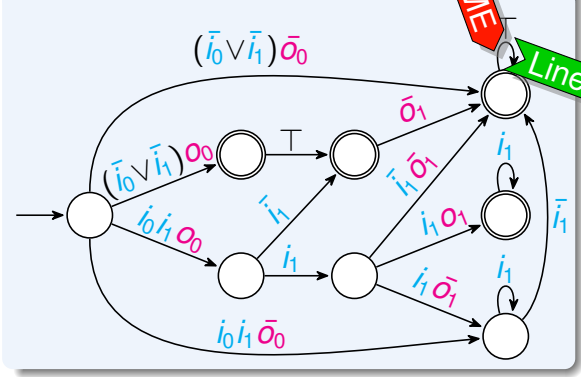

2-EXPTIME

Linear

Linear

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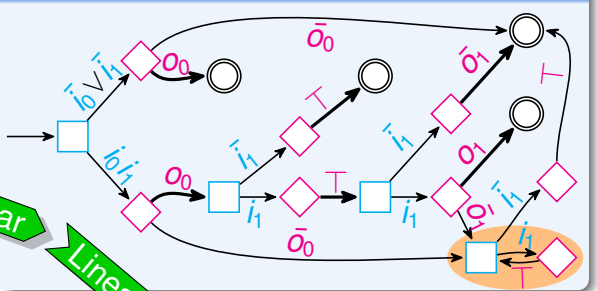

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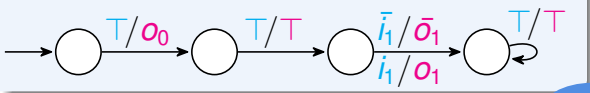

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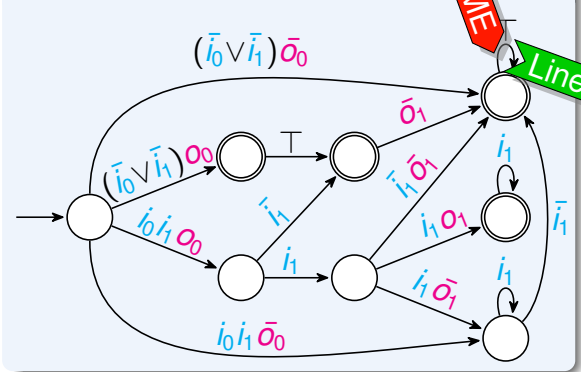

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Doubly exponential in $|\varphi|$, independently of $|\Sigma|$

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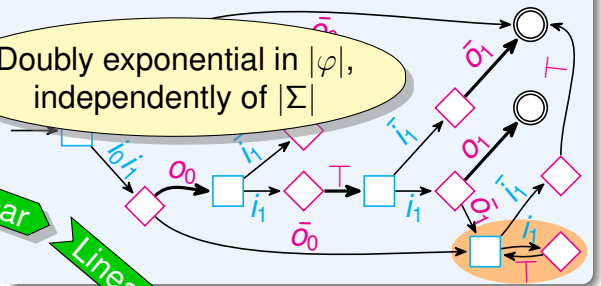

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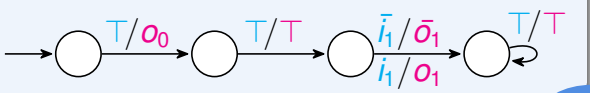

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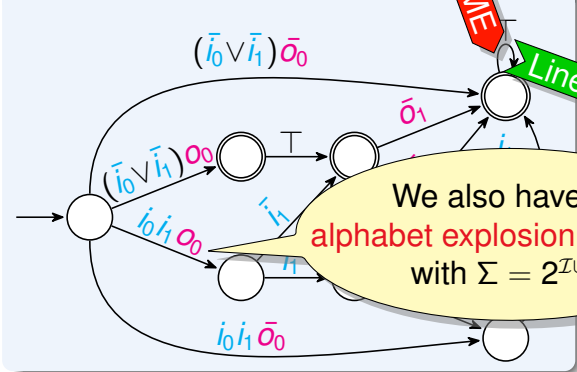

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We also have an alphabet explosion problem, with $\Sigma = 2^{\mathcal{I} \cup \mathcal{O}}$

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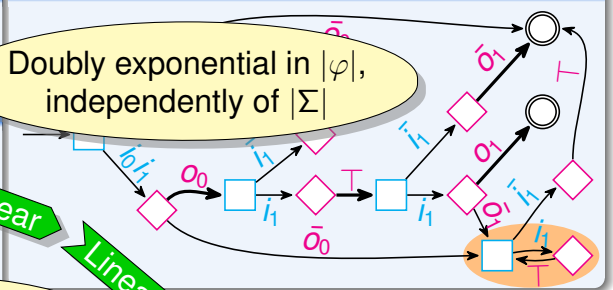

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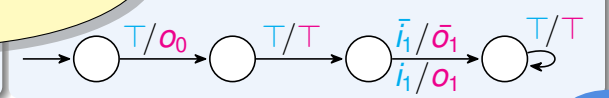
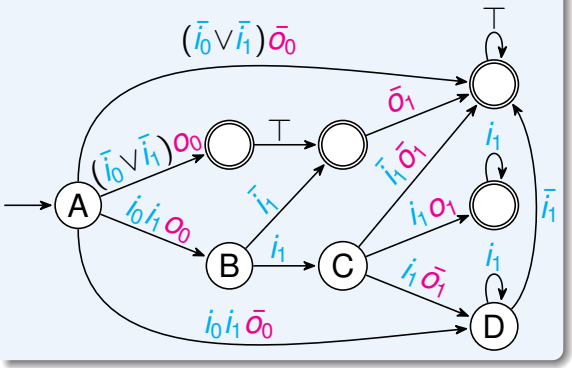


Stopping the DFA Construction on Final States

The goal is to reach final states: we do not care about what follows.

Overkill



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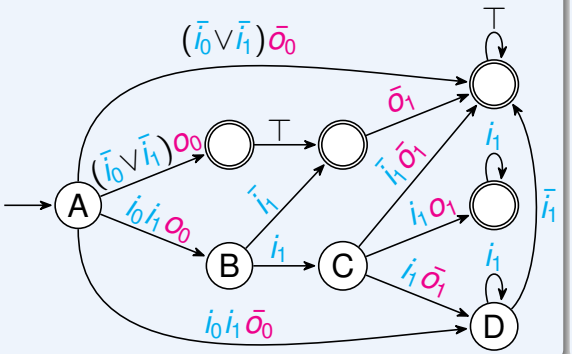
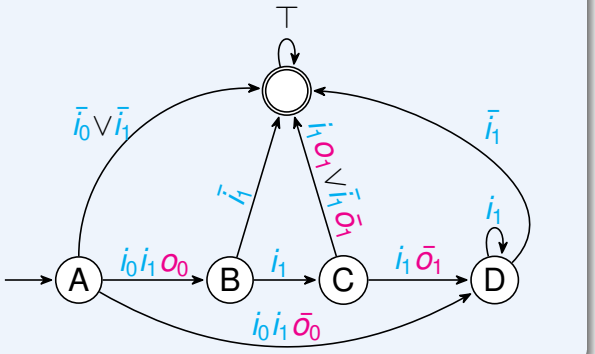
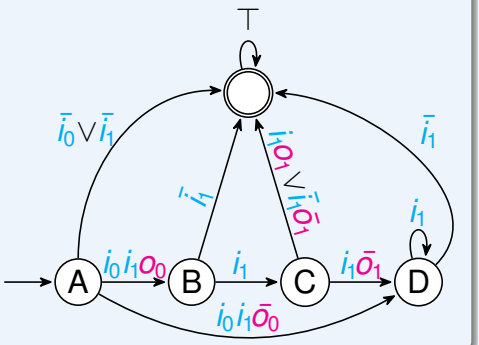


Better



Fighting Alphabet Explosion with MTBDDs

Explicit representation



Semi-symbolic representation: MTBDD

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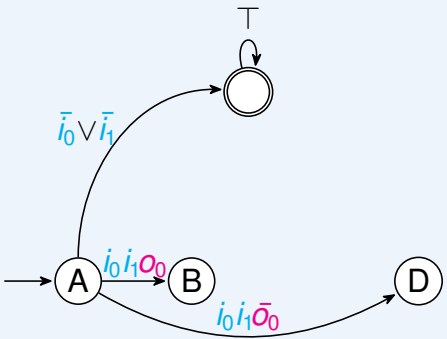

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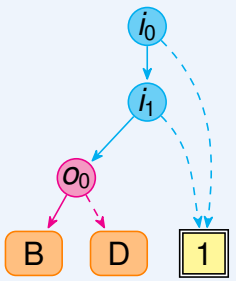

MTBDD representing outgoing edges of (A) (unique for a given variable order)

true BDD node as accepting sink

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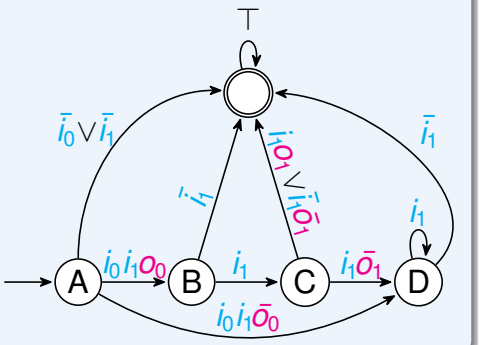
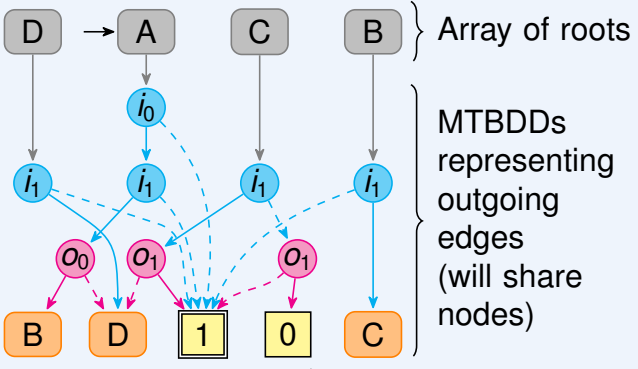


Semi-symbolic representation: **MTDFA**



LTL_f Synthesis with MTDFA

What Other Tools Have Tried

MTDFA Constructions:

- Transform $\mathrm{LTL}_f \rightarrow$ FOL, then use Mona for FOL $\rightarrow$ MTDFA.
- Use Mona's MTDFA library to translate LTL_f to MTDFA by composition.

Game Solving: convert MTDFA to BDD, and solve symbolically.

Also exist on-the-fly approaches that do not go through MTDFAs.

What we Suggest

1. Direct translation from LTL_f to MTBDD, building the MTDFA one state at a time.
2. Solving the game on the MTDFA directly.
3. Doing those on-the-fly.

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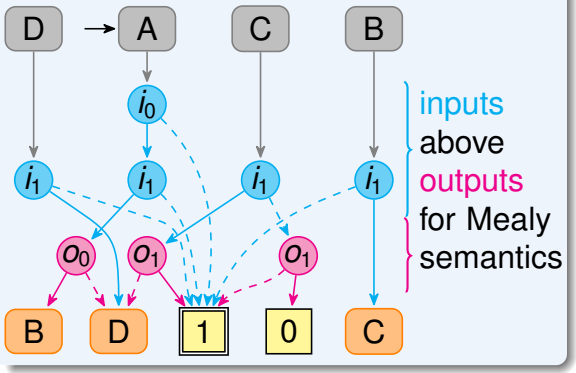
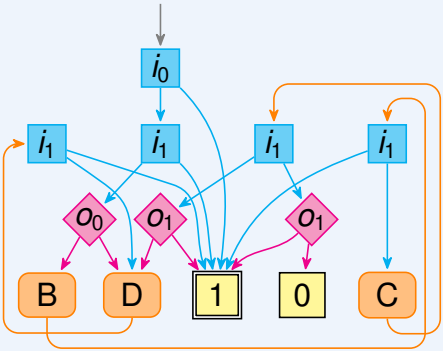
Seeing the MTDFA as a Game Arena

Turn input/output nodes into universal/existential vertices.
Order input/output variables according to the desired semantics (Moore/Mealy).

The MTDFA



The Game Interpretation



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Actually stores reversed edges.

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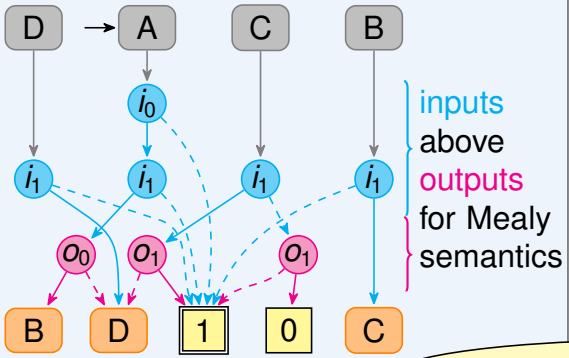

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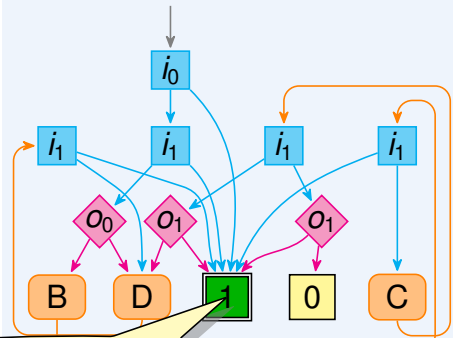

Solve by backpropagation from 1.

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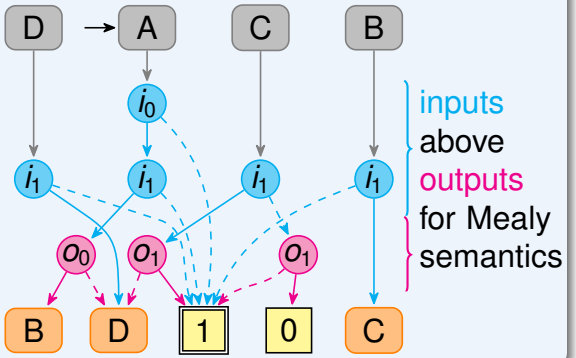

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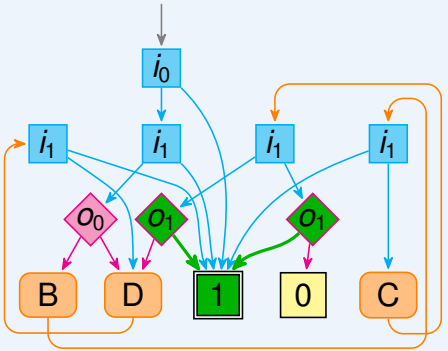

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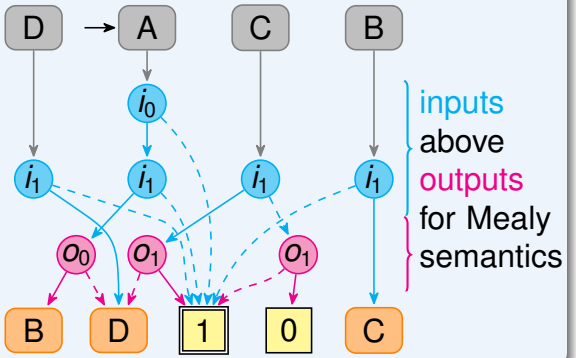

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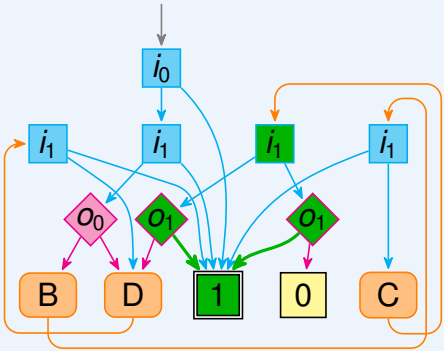

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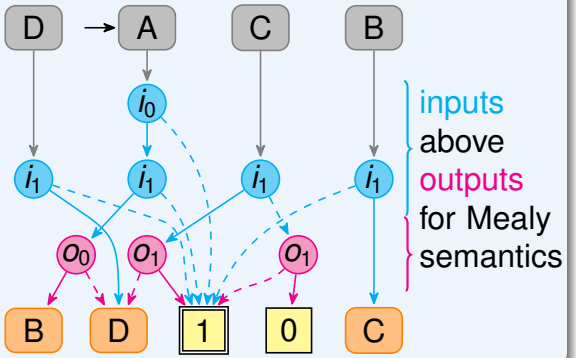

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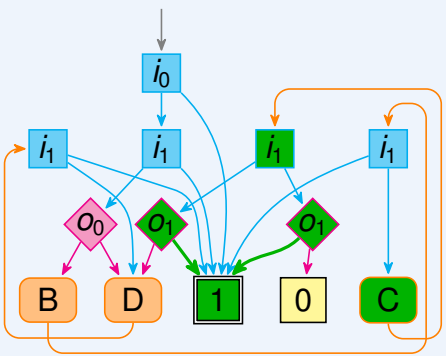

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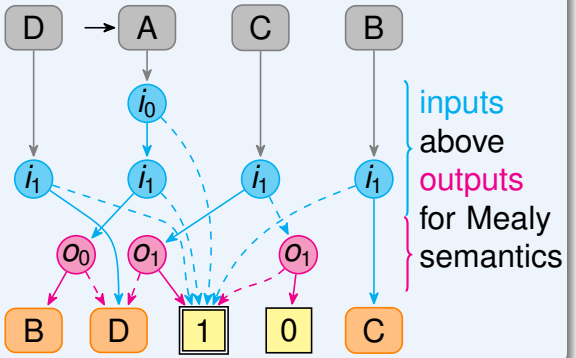

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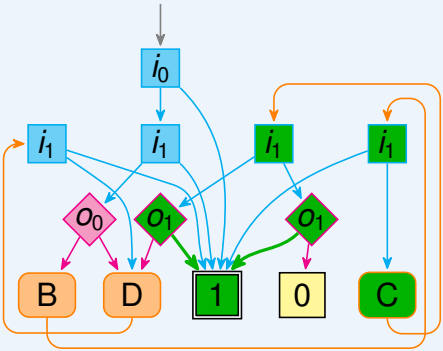
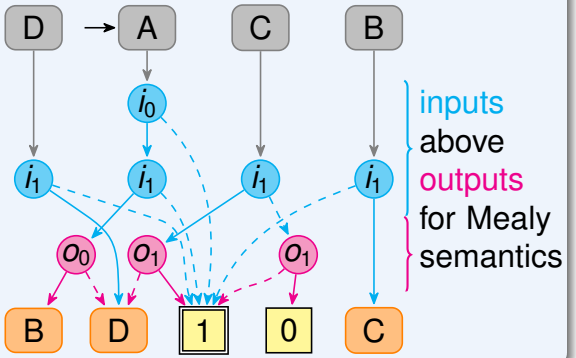


Seeing the MTDFA as a Game Arena

Turn input/output nodes into universal/existential vertices.
Order input/output variables according to the desired semantics (

Actually stores reversed edges.

The MTDFA



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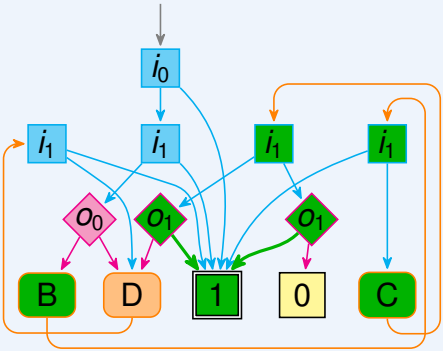

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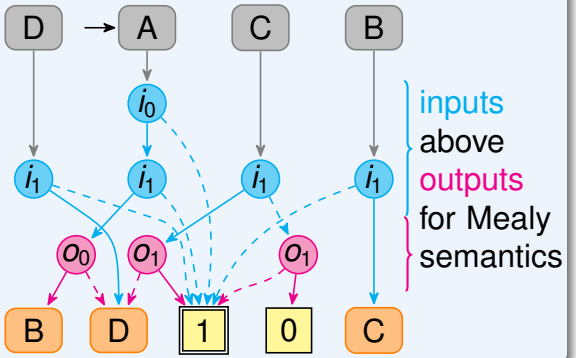

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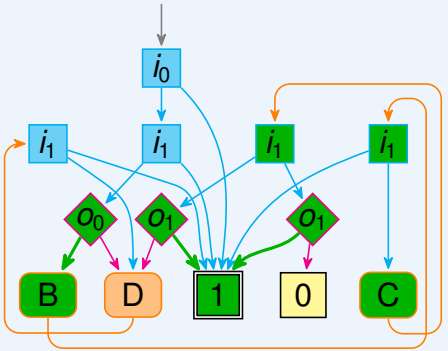

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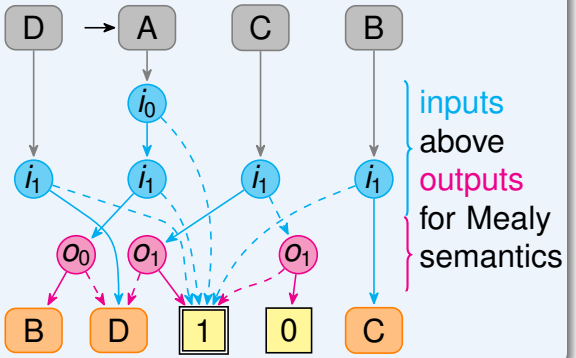

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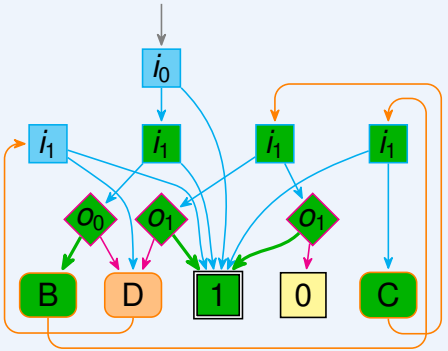
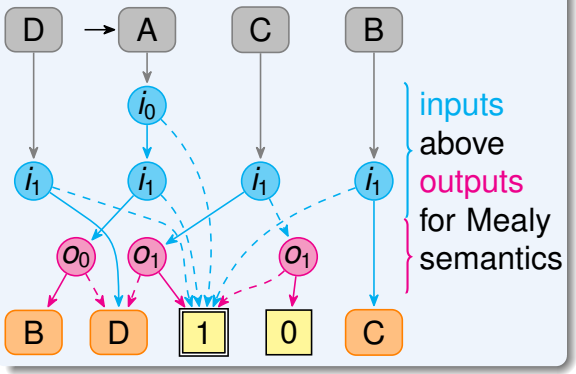


Seeing the MTDFA as a Game Arena

Turn input/output nodes into universal/existential vertices.
Order input/output variables according to the desired semantics (Moore/Mealy).

The MTDFA



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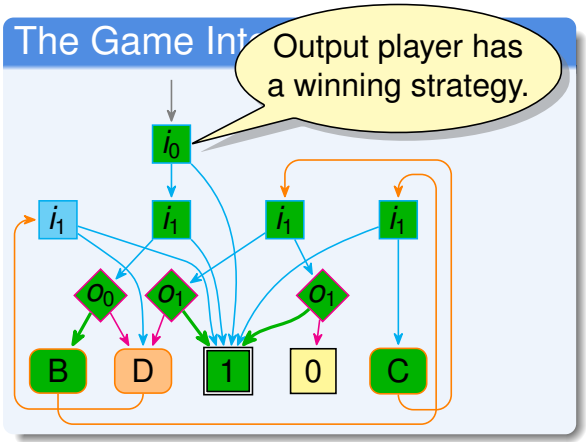


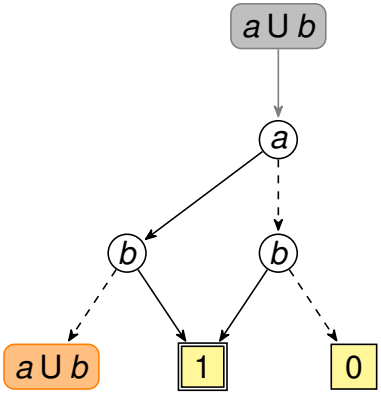
LTL_f Synthesis with MTDFA

What we Suggest

1. Direct translation from LTL_f to MTBDD, building the MTDFA one state at a time. up next!
2. Solving the game on the MTDFA directly. ✓
3. Doing those on-the-fly.

From LTL_f to MTBDD (not yet MTDFA)

Use LTL_f formulas as terminals.
Assume we know an MTBDD for the successors of $a \,\mathsf{U}\, b$



This is a deterministic representation of the *next normal form* (XNF):

$$a \,\mathsf{U}\, b \equiv b \vee (a \wedge \mathsf{X}^{!}(a \,\mathsf{U}\, b))$$

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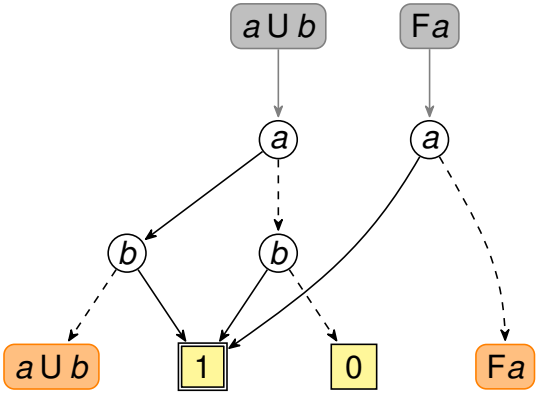

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$$\mathsf{F}a \equiv a \vee \mathsf{X}^{!}\mathsf{F}a$$

From LTL$_f$ to MTBDD (not yet MTDFA)

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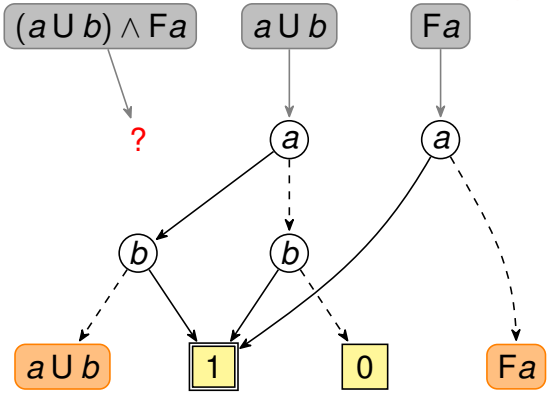

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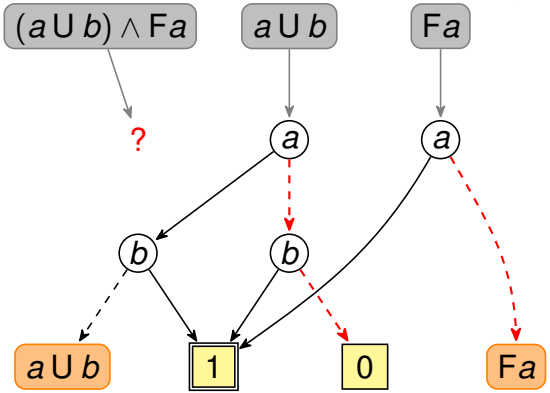

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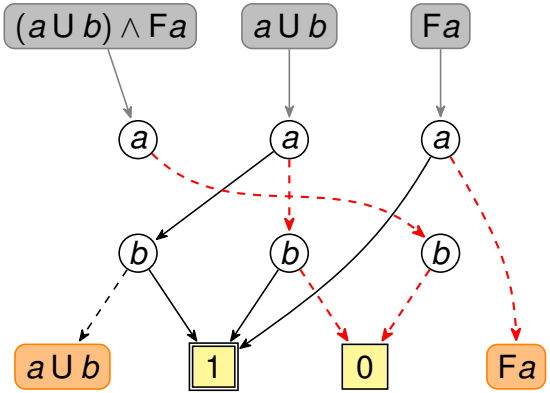

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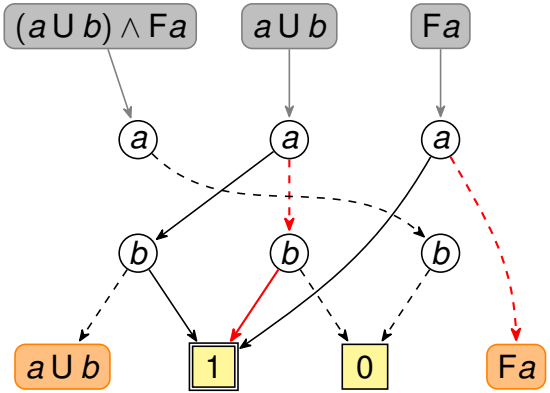

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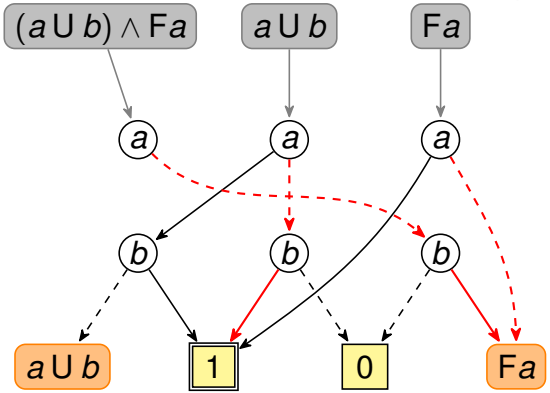

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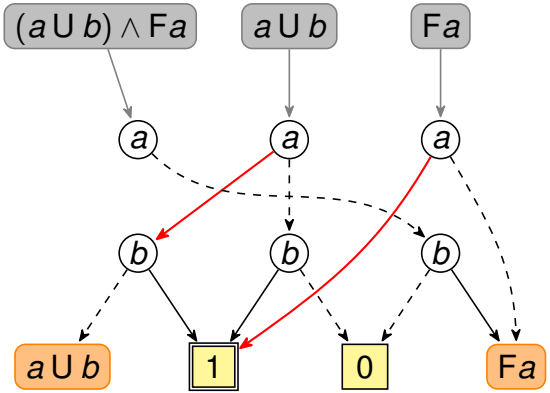

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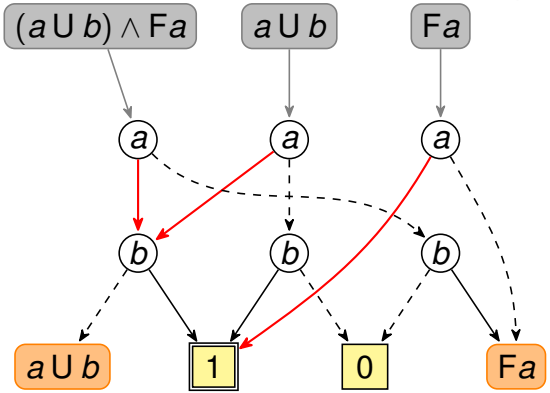

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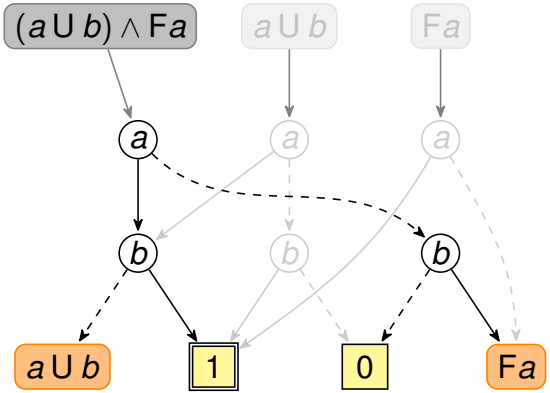
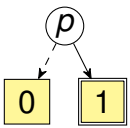


MTBDDs for subformulas are cached (i.e., not thrown away) in case they are needed later during the construction.

From LTL$_f$ to MTBDD: Formal Definition

$\mathrm{tr}(\mathsf{ff}) = 0$

$\mathrm{tr}(\mathsf{tt}) = 1$

$\mathrm{tr}(p) =$ 

for $p \in \mathcal{I} \cup \mathcal{O}$

$\mathrm{tr}(\mathsf{X}\alpha) = \alpha$

$\mathrm{tr}(\mathsf{X}^!\alpha) = \alpha$

$\mathrm{tr}(\neg\alpha) = \neg\mathrm{tr}(\alpha)$

LTL$_f$ operator

MTBDD operator

$\mathrm{tr}(\alpha \odot \beta) = \mathrm{tr}(\alpha) \odot \mathrm{tr}(\beta)$ for any $\odot \in \{\wedge, \vee, \rightarrow, \leftrightarrow, \oplus\}$

previous slide

$\mathrm{tr}(\alpha\ \mathsf{U}\ \beta) = \mathrm{tr}(\beta) \vee (\mathrm{tr}(\alpha) \wedge \alpha\ \mathsf{U}\ \beta)$

$\mathrm{tr}(\alpha\ \mathsf{R}\ \beta) = \mathrm{tr}(\beta) \wedge (\mathrm{tr}(\alpha) \vee \alpha\ \mathsf{R}\ \beta)$

$\mathrm{tr}(\mathsf{F}\alpha) = \mathrm{tr}(\alpha) \vee \mathsf{F}\alpha$

$\mathrm{tr}(\mathsf{G}\alpha) = \mathrm{tr}(\alpha) \wedge \mathsf{G}\alpha$

With the convention that $\alpha \wedge \beta = \alpha \wedge \beta$, $\alpha \vee \beta = \alpha \vee \beta$, ...

From LTL$_f$ to MTDFA: Build States One at a Time

To translate $(a \,\mathsf{U}\, b) \wedge \mathsf{F}a$:

1. Compute successors of the initial state: $\mathrm{tr}((a \,\mathsf{U}\, b) \wedge \mathsf{F}a)$.

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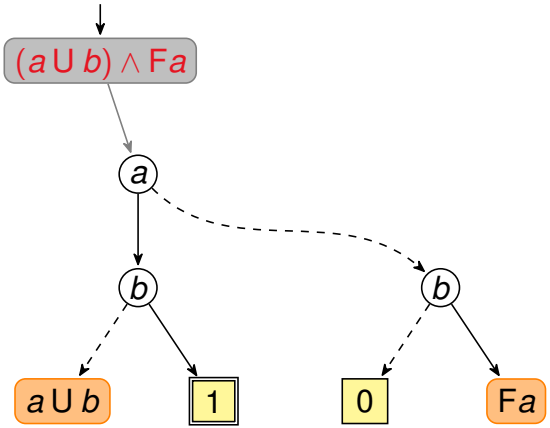

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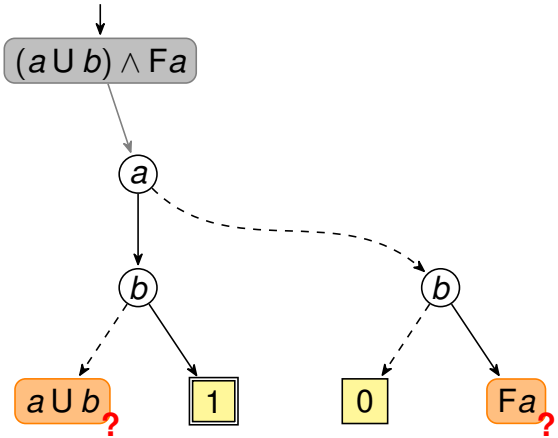

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1. Compute successors of the initial state: $\mathrm{tr}((a \,\mathsf{U}\, b) \wedge \mathsf{F}a)$.
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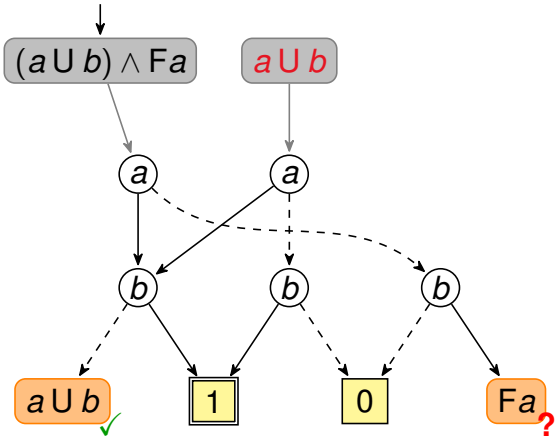

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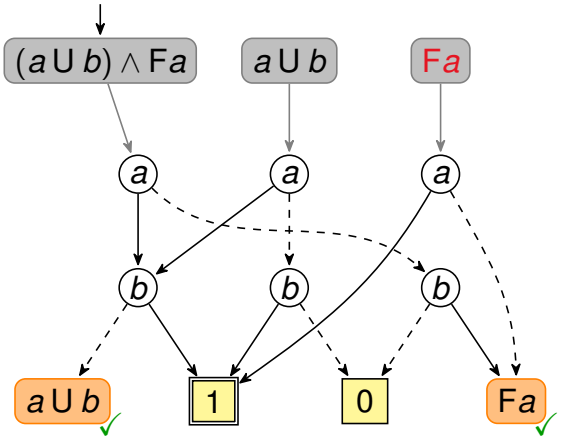

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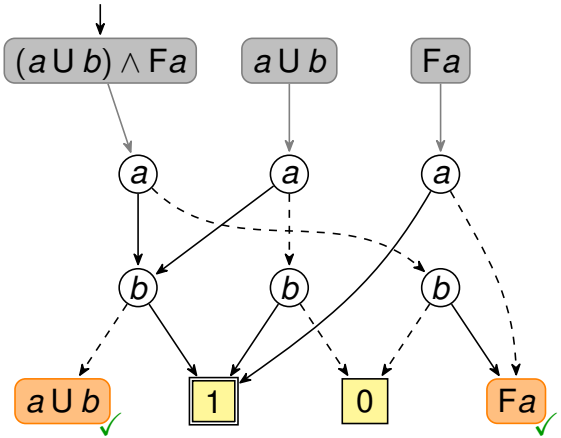

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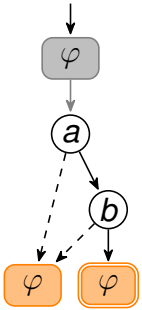
3. Done.

Quick Note on Accepting Terminals

Our use of accepting terminals differs from Mona's implementation of MTDFAs.



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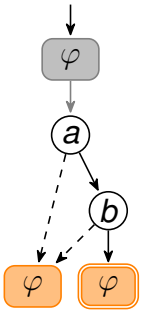
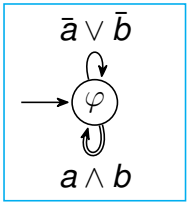


If you interpret the MTBDD roots as states, you get a transition-based DFA:



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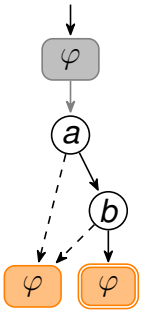

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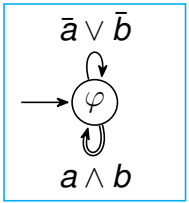

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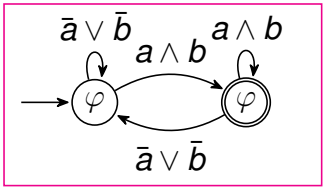

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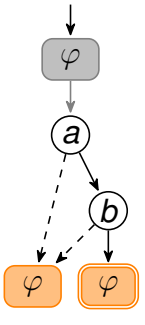

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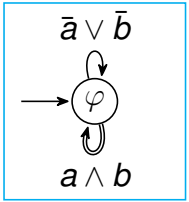

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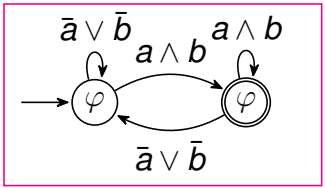

In any case, when using an MTDFA for synthesis,
accepting terminals can all be replaced by the accepting sink 1.

LTL_f Synthesis with MTDFA

What we Suggest

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2. Solving the game on the MTDFA directly. ✓
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Building the MTDFA & Solving the Game On-The-Fly

$\varphi = (i_0 \wedge \mathsf{G} i_1) \leftrightarrow (o_0 \wedge \mathsf{X}^!\mathsf{X}^! o_1)$

The MTDFA

The Game Interpretation

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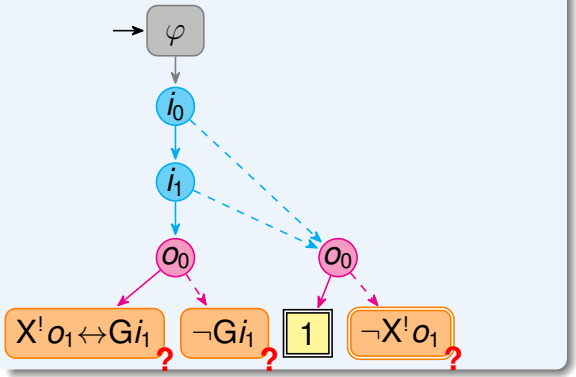

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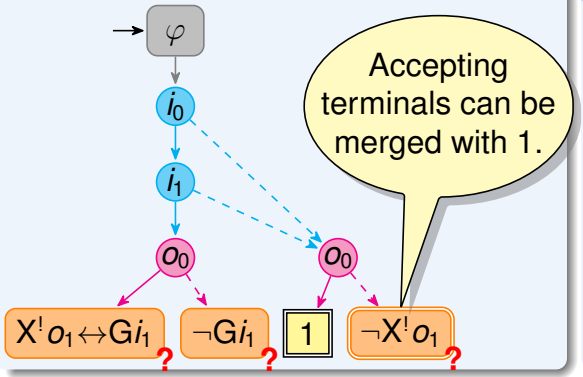

The Game Interpretation

Building the MTDFA & Solving the Game On-The-Fly

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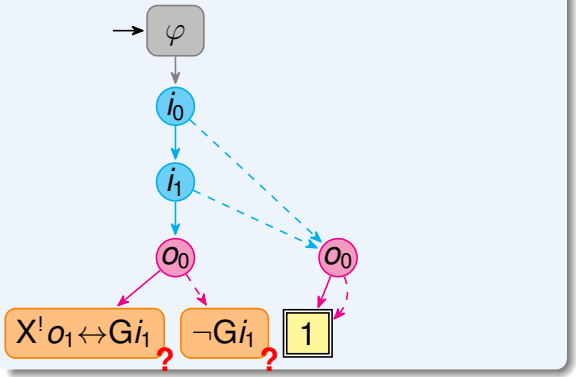

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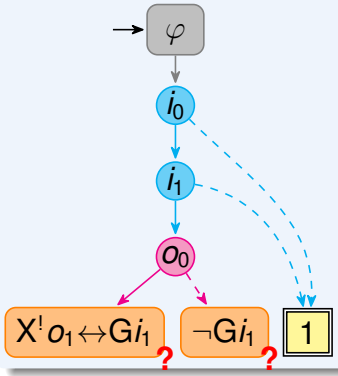

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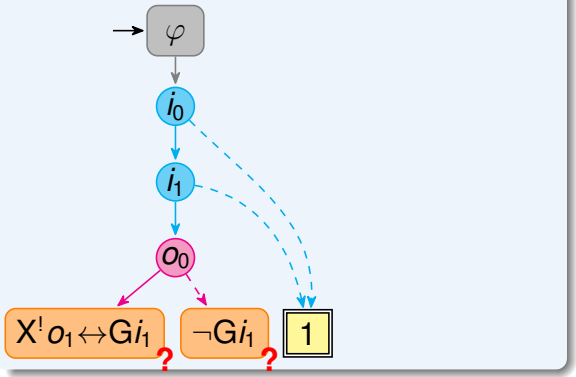

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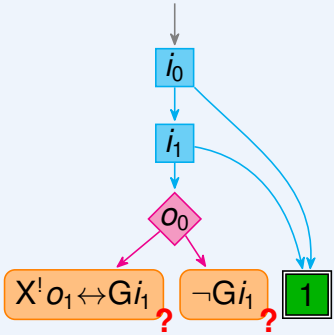

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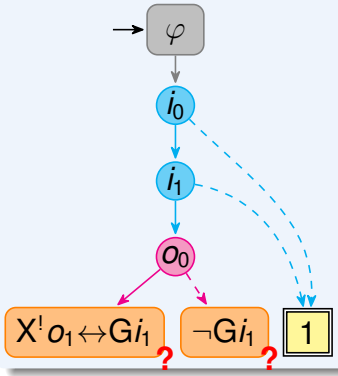

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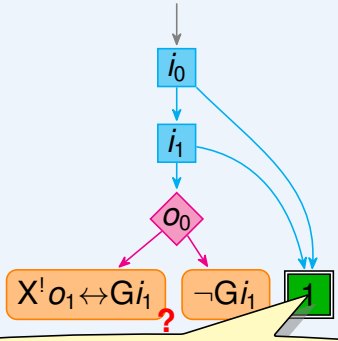

Backpropagation runs during construction.

Building the MTDFA & Solving the Game On-The-Fly

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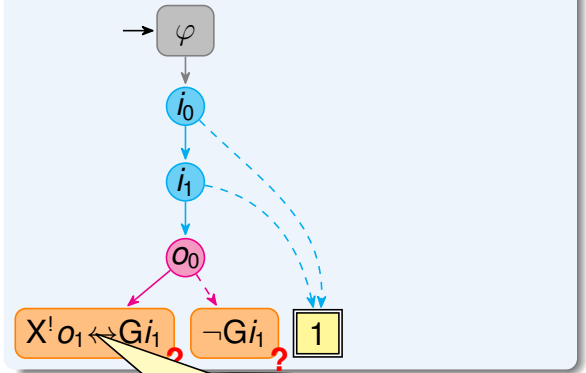

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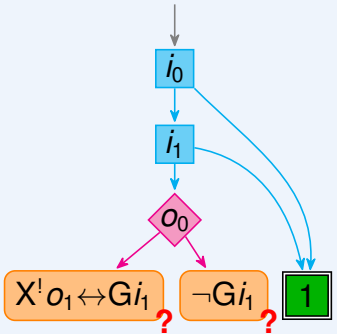

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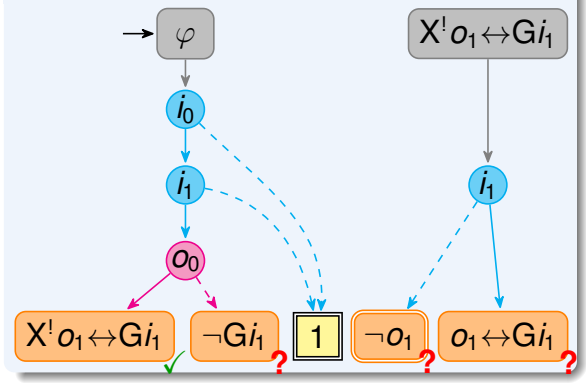

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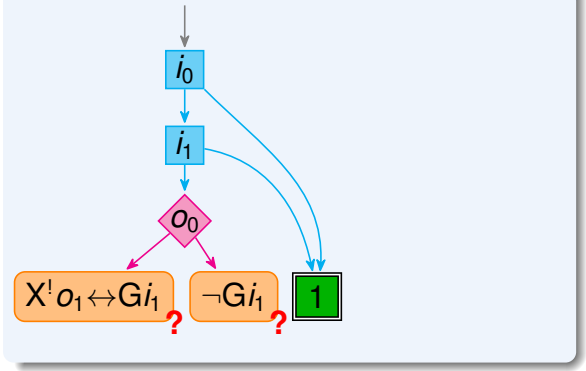

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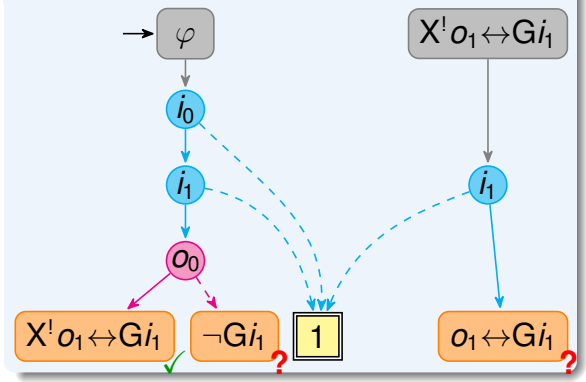

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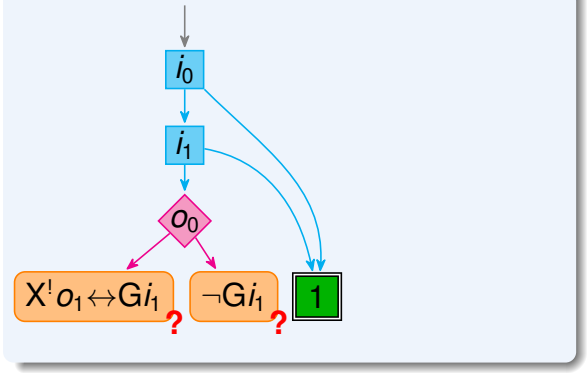

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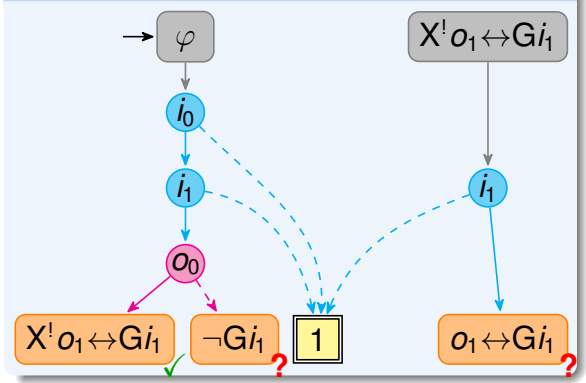

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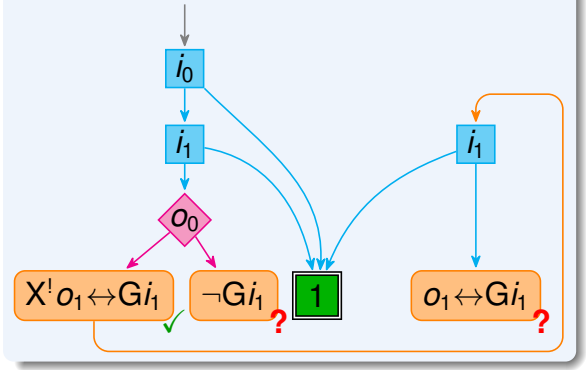

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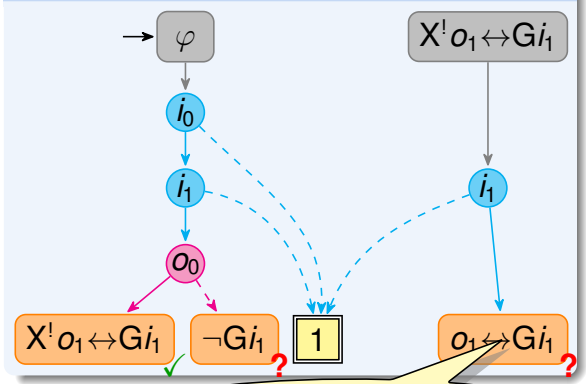

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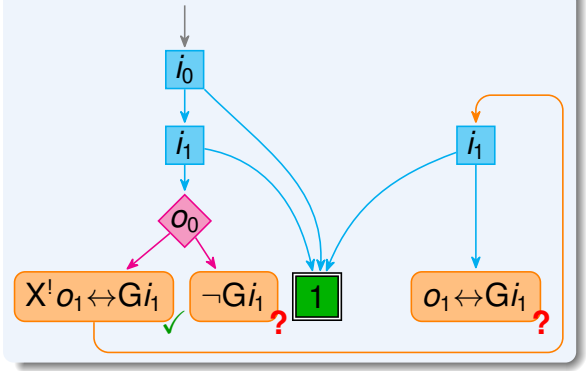

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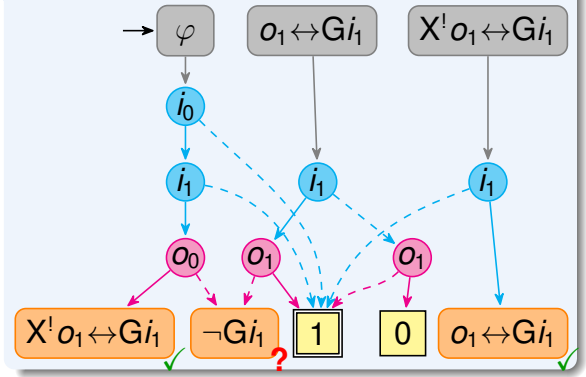

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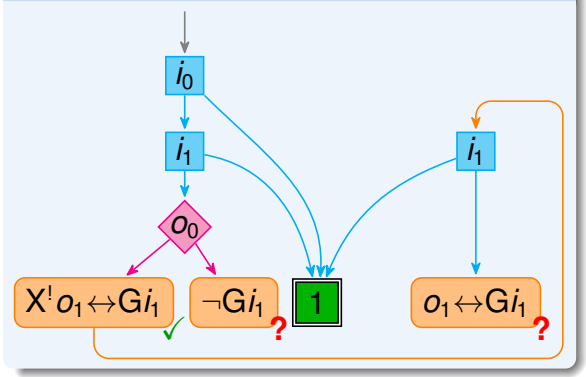

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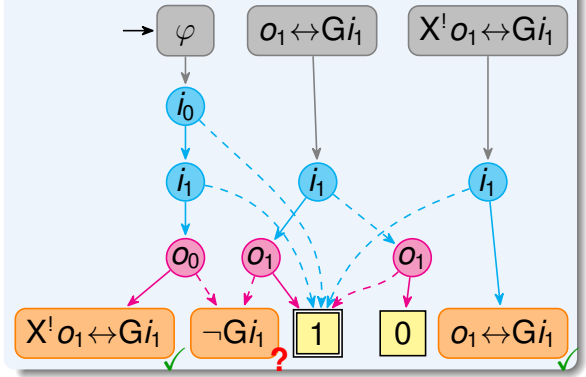

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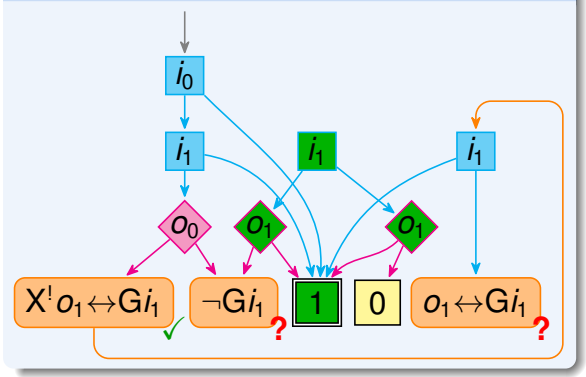

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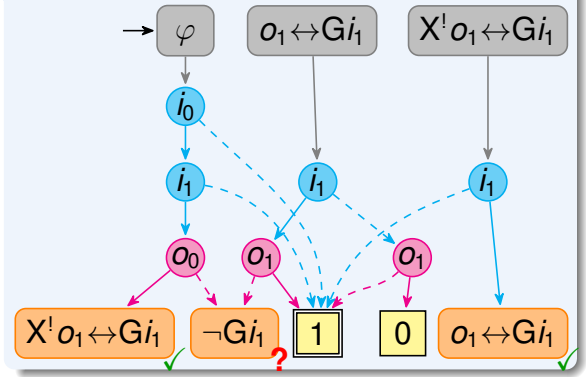

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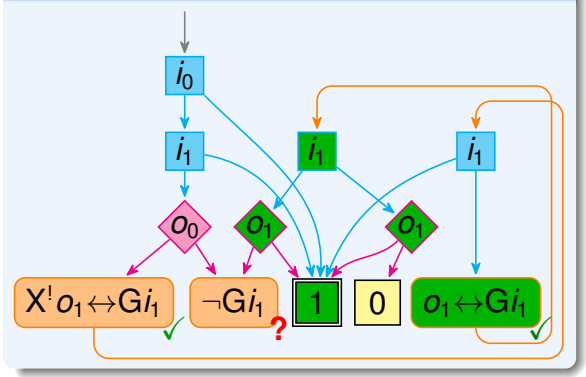

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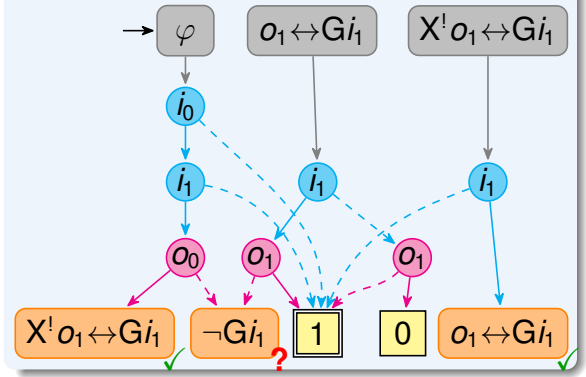

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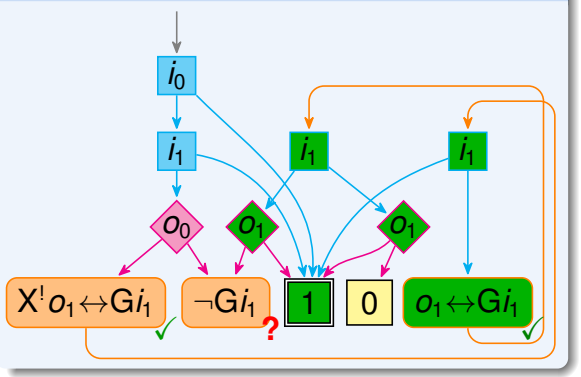

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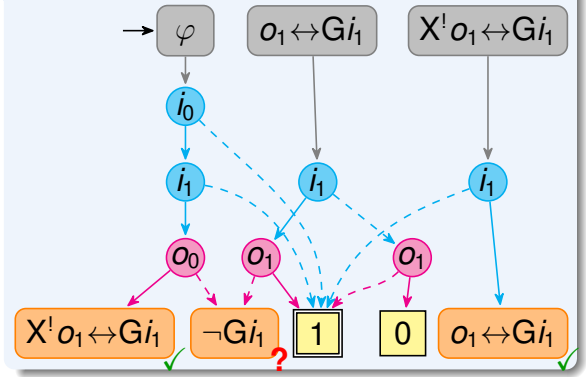

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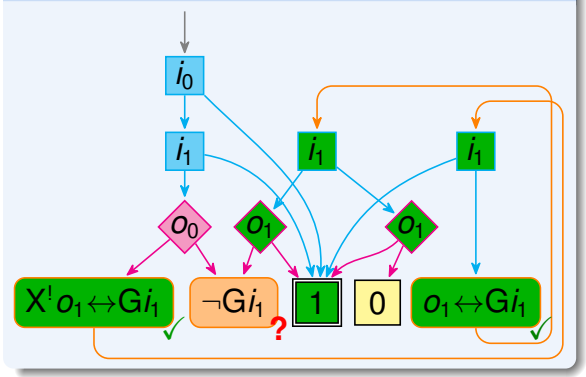

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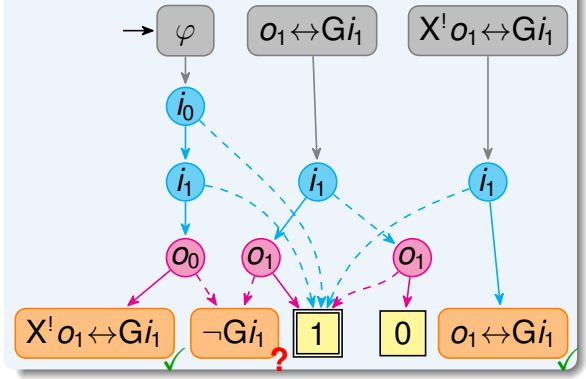

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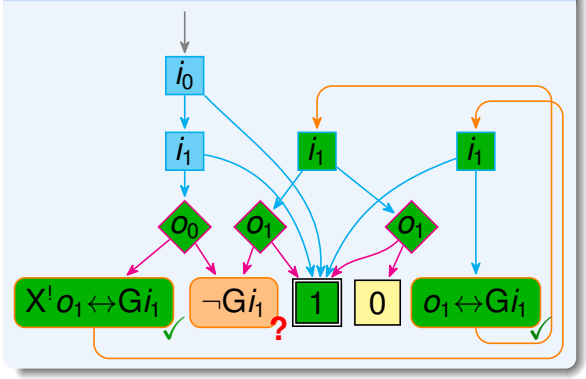

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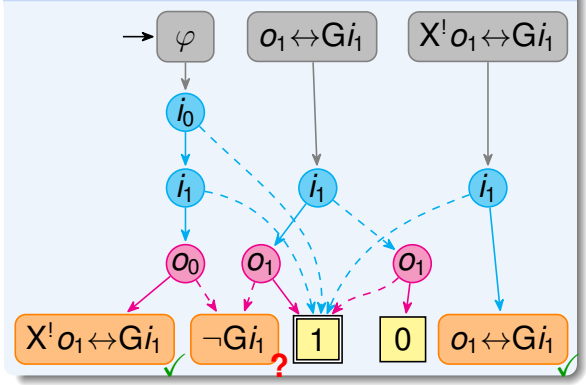

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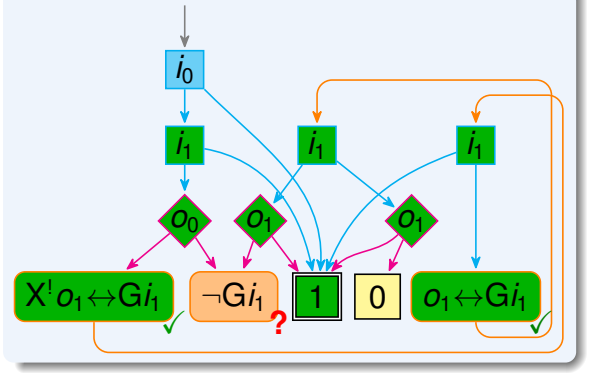

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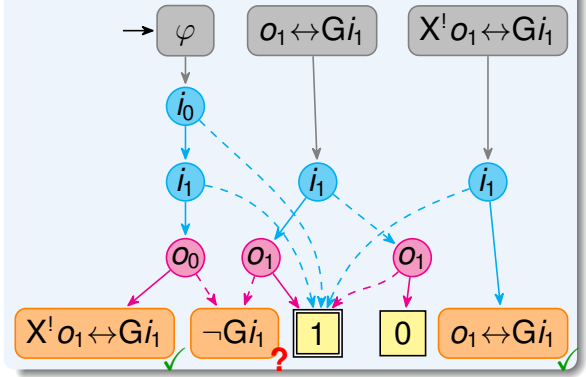

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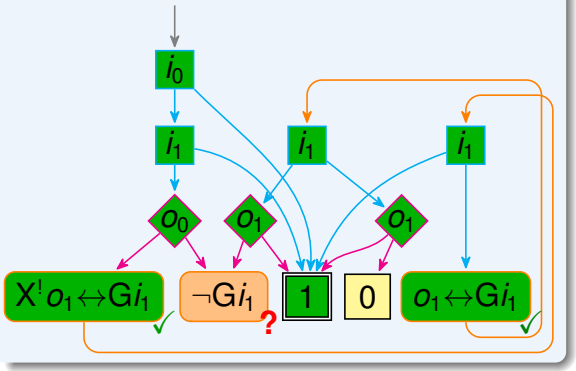

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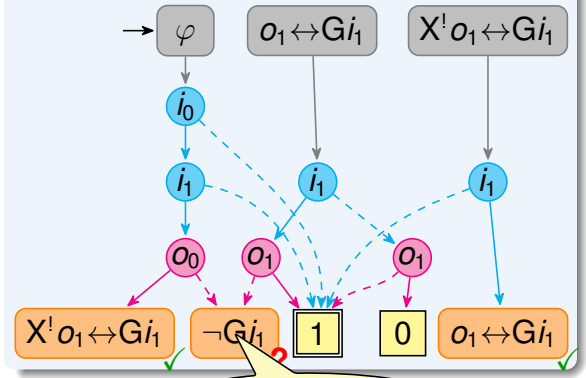
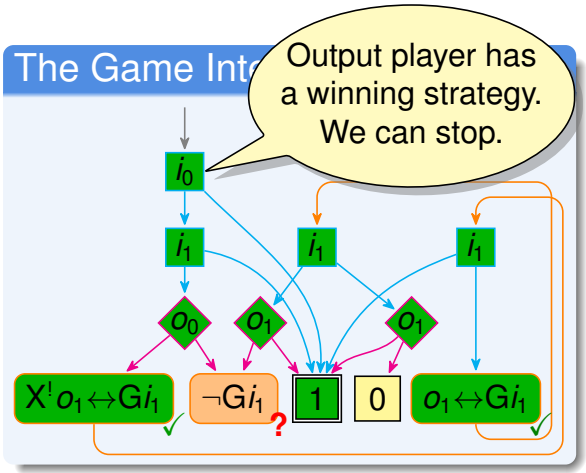
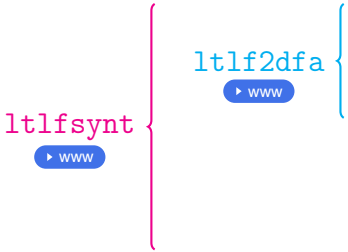


The Game Into



LTL_f Synthesis with MTDFA

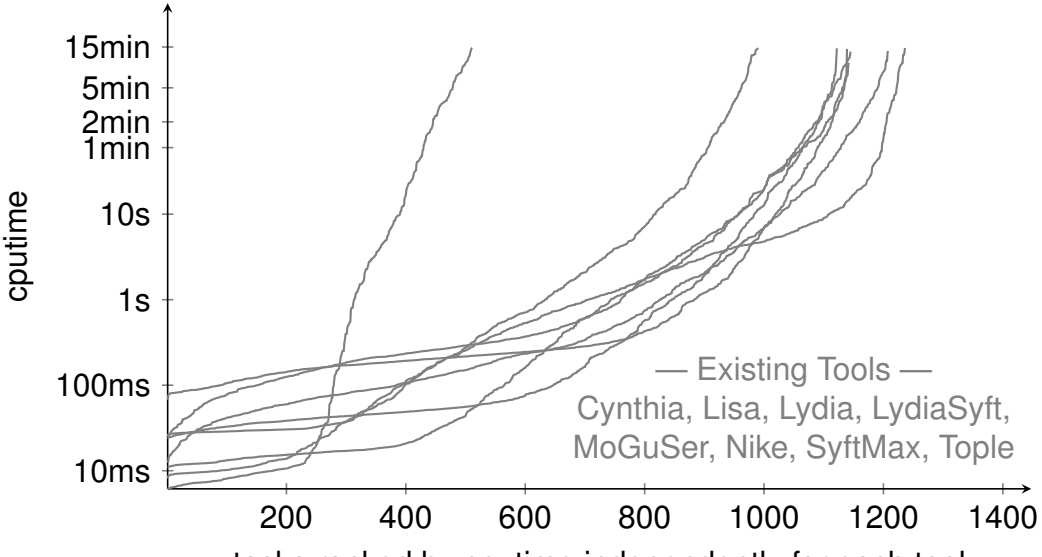
Implemented in two new tools distributed with Spot 2.14 ▸ www



What we Suggest

1. Direct translation from LTL_f to MTBDD, building the MTDFA one state at a time. ✓
2. Solving the game on the MTDFA directly. ✓
3. Doing those on-the-fly. ✓

A Benchmark (Specifications from SyntComp)



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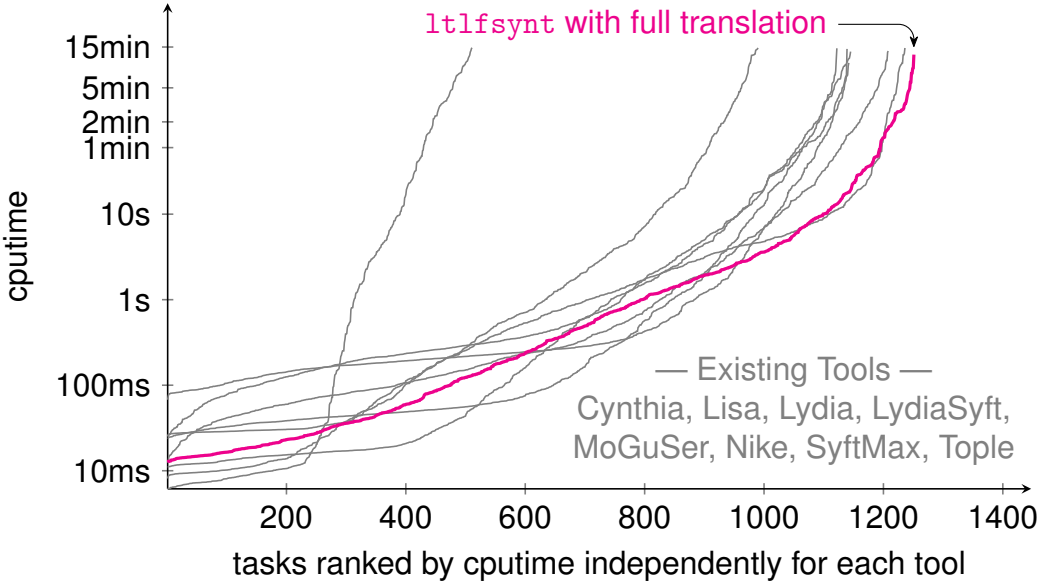

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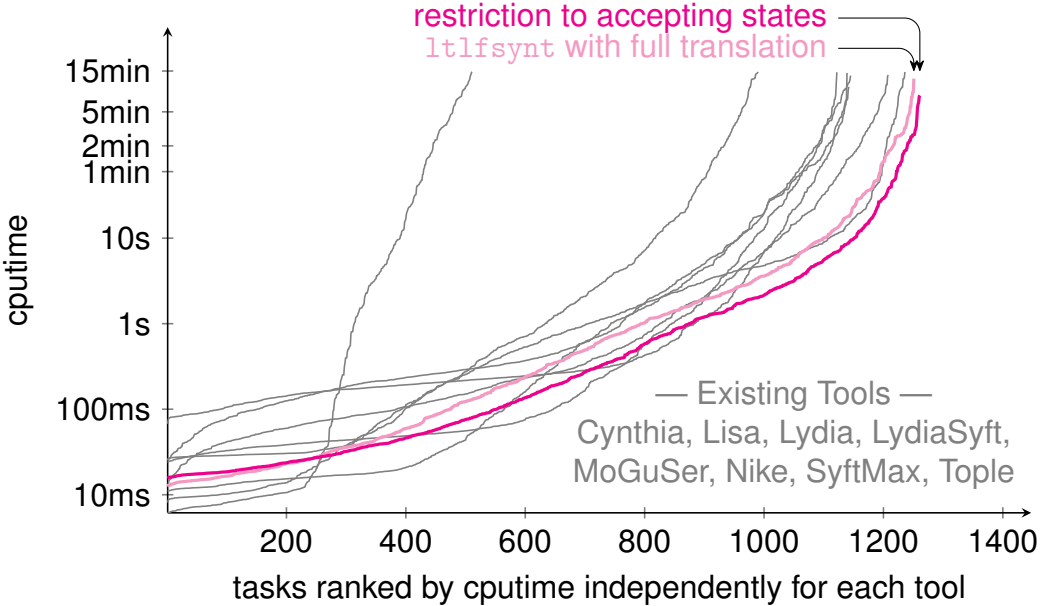

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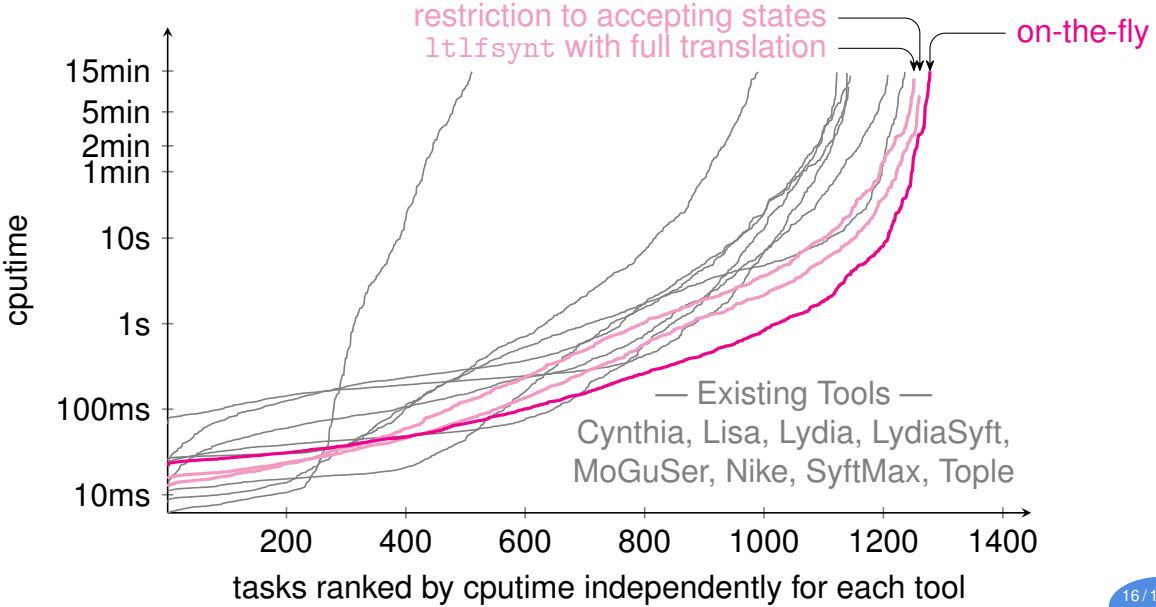

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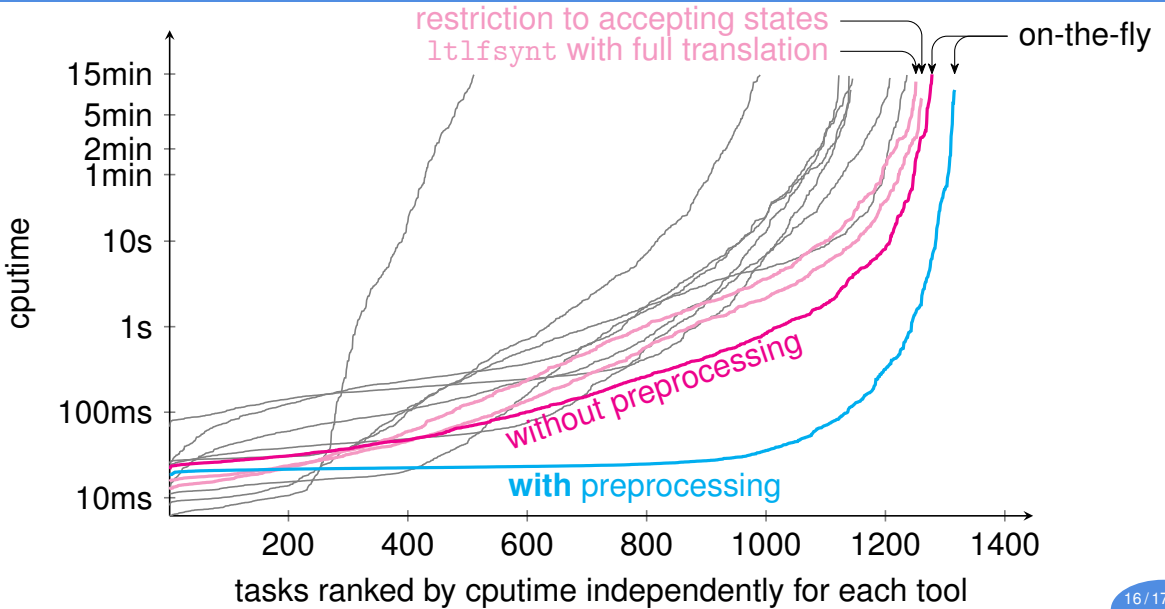


Conclusion

Efficient LTL$_f$ tools to build upon

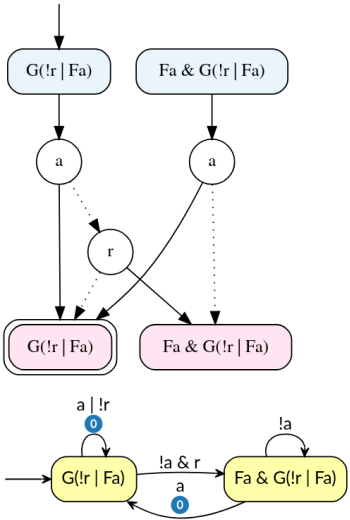
Distributed with Spot 2.14:

- `ltlf2dfa`
- `ltlfsynt` (🏆 won SyntComp'25)
- C++ & Python APIs available

Ideas to take away

- MTBDDs are great for deterministic automata with propositional alphabets.
- Such automata can be interpreted as games at the level of MTBDD nodes (deciding one proposition at a time).

```
In [20]: a3 = spot.ltlf_to_mtdfa("G(!r | Fa)")
         display(a3, a3.as_twa())
```



Warp Zone

1. Title
2. Reactive Synthesis
3. Text-Book Approach
4. Stopping on Final States
5. MTBDD/MTDFA
6. Outline
7. MTDFA as game
9. $\mathrm{LTL}_f \rightarrow$MTBDD example
10. $\mathrm{LTL}_f \rightarrow$MTBDD formal
11. $\mathrm{LTL}_f \rightarrow$MTDFA
12. Accepting Terminals
14. On-the-Fly
16. Benchmark
17. Conclusion

19. Preprocessings
20. Propositional Equivalence
21. Simplify Mealy

Preprocessings

Simplify specification using polarity of propositions

- If an output proposition is always positive/negative in the specification, replace it by $\top/\bot$.
- If an input proposition is always positive/negative in the specification, replace it by $\bot/\top$.

Example: $\mathsf{G}(i \to o)$ becomes $\mathsf{G}(\top \to \top) \equiv \top$.

Use cheap rewritings to reduce number of MTBDD operations

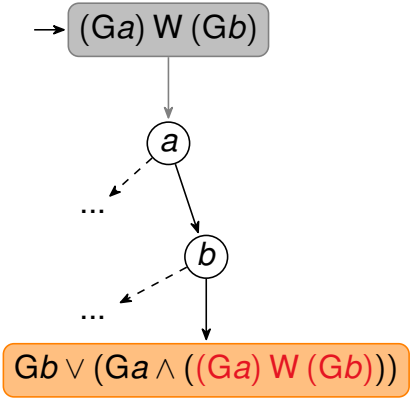
$$\mathsf{X}\alpha \wedge \mathsf{X}\beta \rightsquigarrow \mathsf{X}(\alpha \wedge \beta), \qquad (\alpha \to \beta) \wedge (\alpha \to \gamma) \rightsquigarrow \alpha \to (\beta \wedge \gamma), \qquad \ldots$$

Split specification into output disjoint specifications when possible

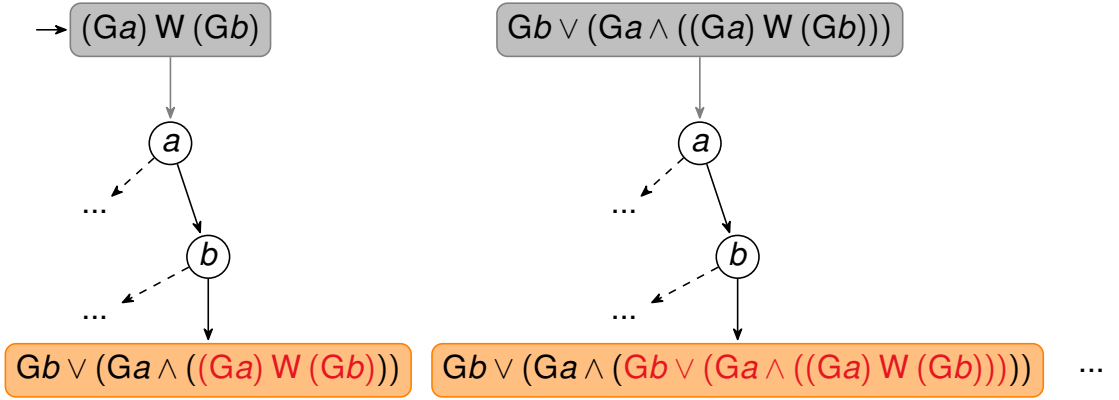
$\Psi_1 \wedge \Psi_2$ can be solved as two independent problems if Ψ_1 and Ψ_2 are output-disjoint, and admit controllers that agree on accepting lengths.

▸ issue 610

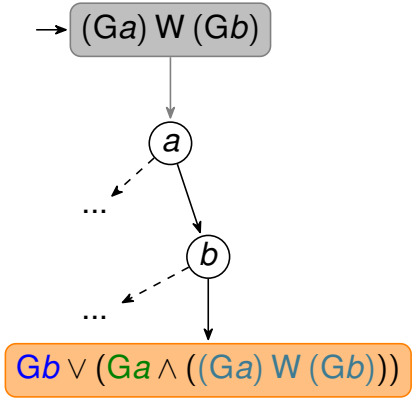
Propositional Equivalence

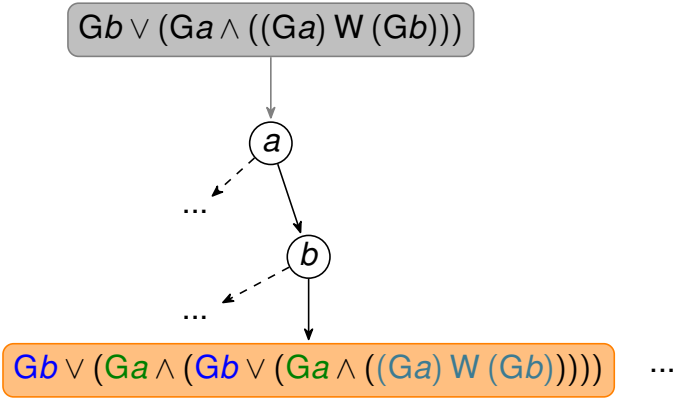


Propositional Equivalence



Propositional Equivalence

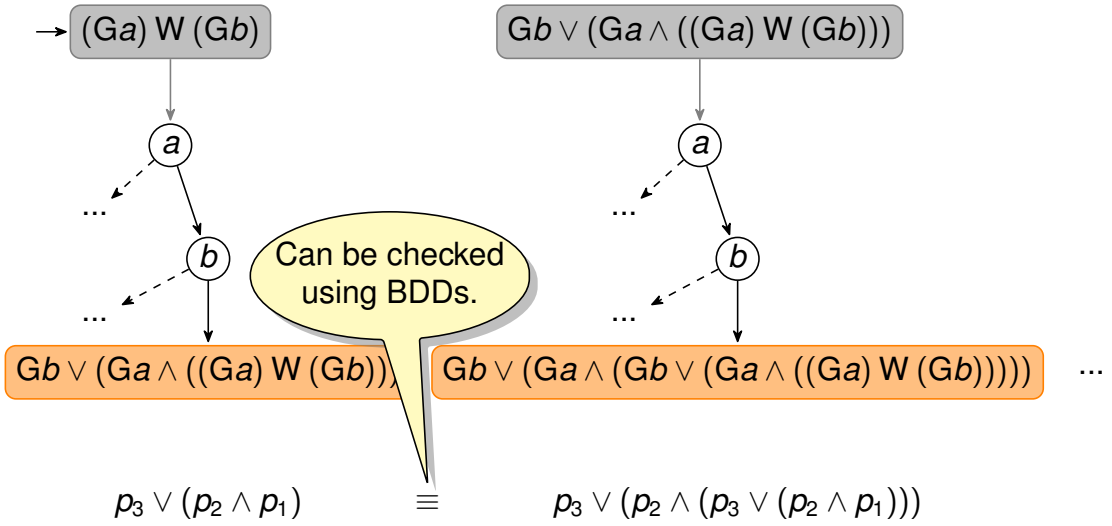




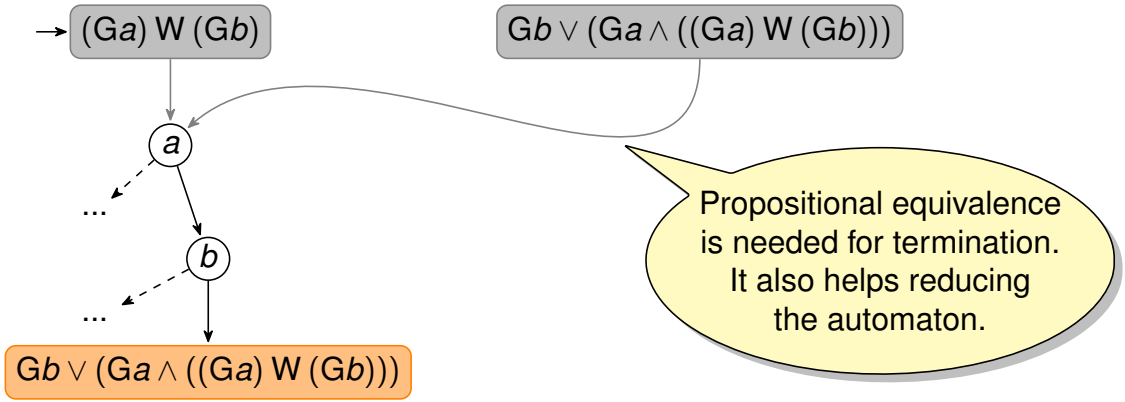
$p_3 \vee (p_2 \wedge p_1)$

$p_3 \vee (p_2 \wedge (p_3 \vee (p_2 \wedge p_1)))$

Propositional Equivalence

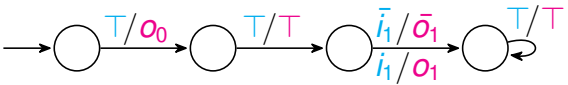


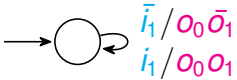
Propositional Equivalence



Simplifying Incompletely Specified Mealy Machines

This is an Incompletely Specified Mealy Machine:



An actual implementation would have to decide a value for each output signal at all steps.

This freedom can be used to reduce the size of the Mealy machine, as in: