Empirical Performance Investigation of a Büchi Complementation Construction

Master's Thesis Presentation

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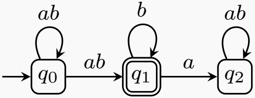
Outline

1. **GOAL**

2. **Results**

Basics

Büchi automata



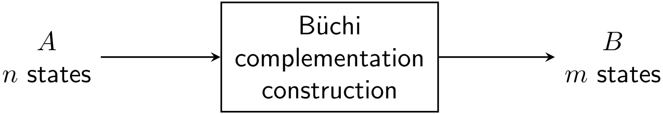
- Finite state automata running on infinite words (ω-words) $\in \Sigma^\omega$
- A word is accepted if it has an accepting run
- A run is accepting if it visits an accepting state infinitely often

Büchi complementation

The complement of a Büchi automaton A is another Büchi automaton B, such that:

B accepts a word if and only if it is not accepted by A

Büchi Complementation Constructions



- Different constructions produce different complements B for the same automaton A
- Main performance measure: number m of states of B in relation to number n of states of A
  - State complexity
  - Also known as state growth, state blow-up, or state explosion
  - E.g. if $n = 10$ and $m = 100$, then $m = n^2$
  - Biggest problem of Büchi complementation

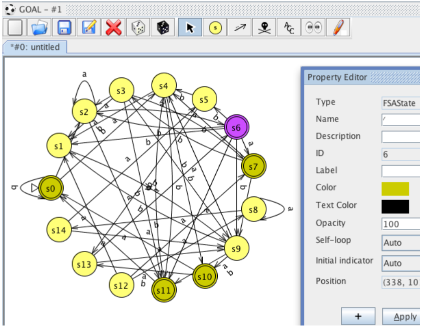
The Fribourg Construction

- Slice-based complementation construction
- Worst-case state complexity: $(1.59n)^n$
- Optimisations:
  - R2C: if input automaton is complete, remove states whose rightmost component is 2-coloured
  - M1: merge certain adjacent components $(1.195n)^n$)
  - M2: keep not more than one 2-coloured component in every state $(0.86n^n)$

GOAL

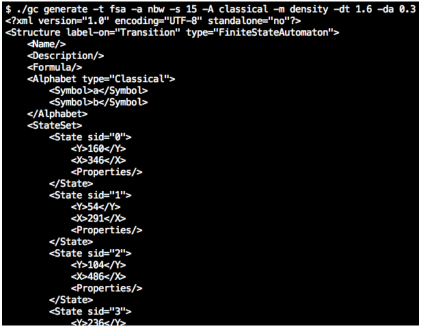
- **G**raphical Tool for **O**mega-**A**utomata and **L**ogics
- http://goal.im.ntu.edu.tw/wiki/doku.php
- Create and manipulate ω-automata

Graphical user interface



Type FSAState
Name
Description
ID 6
Label
Color
Text Color
Opacity 100
Self-loop Auto
Initial indicator Auto
Position (338, 10

Command line interface



```
$ ./gc generate -t fsa -a nbw -s 15 -A classical -m density -dt 1.6 -da 0.3
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<Structure label-on="Transition" type="FiniteStateAutomaton">
    <Name/>
    <Description/>
    <Formula/>
    <Alphabet type="Classical">
        <Symbol>a</Symbol>
        <Symbol>b</Symbol>
    </Alphabet>
    <StateSet>
        <State sid="0">
            <Y>160</Y>
            <X>346</X>
            <Properties/>
        </State>
        <State sid="1">
            <Y>54</Y>
            <X>291</X>
            <Properties/>
        </State>
        <State sid="2">
            <Y>104</Y>
            <X>486</X>
            <Properties/>
        </State>
        <State sid="3">
            <Y>236</Y>
```

GOAL: Büchi Complementation Constructions

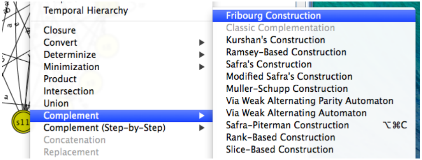
- Implementations of several Büchi complementation constructions (GOAL version 2014–11–17)

GOAL Name	Reference
Ramsey	[Sistla et al., 1985, Sistla et al., 1987]
Safra	[Safra, 1988a, Safra, 1988b]
MS	[Muller and Schupp, 1995]
ModifiedSafra	[Althoff et al., 2006]
Piterman	[Piterman, 2006, Piterman, 2007]
WAA	[Kupferman and Vardi, 1997, Kupferman and Vardi, 2001]
WAPA	[Thomas, 1999]
Rank	[Schewe, 2009]
Slice+P	[Vardi and Wilke, 2007]
Slice	[Kähler and Wilke, 2008]

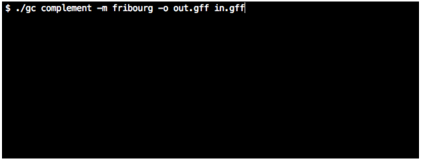
Fribourg Construction Plugin for GOAL

- GOAL is built with the Java Plugin Framework (JPF)[1]
  - Extensibility: create **plugins** containing **extensions** for pre-defined **extension points**
- Our plugin adds the Fribourg construction to GOAL
  - ... in a fully integrated way

Graphical user interface



Command line interface



```
$ ./gc complement -m fribourg -o out.gff in.gff
```

- Download: https://frico.s3.amazonaws.com/goal_plugins/ch.unifr.goal.complement.zip

[1] http://jpf.sourceforge.net/

GOAL and Plugin Demo

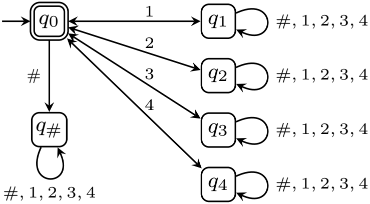
Test Data: GOAL Test Set

- Created and used for [Tsai et al., 2011]
- 11,000 automata
  - 15 states
  - Alphabet $\Sigma = \{0, 1\}$
  - 11 transition densities
    - $\mathcal{T} = (1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0)$
  - 10 acceptance densities
    - $\mathcal{A} = (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0)$
  - 110 classes at 100 automata for each combination of $\mathcal{T} \times \mathcal{A}$
- Analysis
  - 61.8% universal automata
  - 0.6% empty automata
  - 9.0% complete automata
- Download: https://frico.s3.amazonaws.com/test_sets/goal.zip

Test Data: Michel Test Set

- Four Michel automata
  - Michel 1: 3 states, 2 symbols, 5 transitions
  - Michel 2: 4 states, 3 symbols, 8 transitions
  - Michel 3: 5 states, 4 symbols, 11 transitions
  - Michel 4: 6 states, 5 symbols, 14 transitions

Michel 4:



- Automata used by [Michel, 1988] to prove $n!$ lower bound
- Very high state complexity
- Download: https://frico.s3.amazonaws.com/test_sets/michel.zip

Test Setup

- Internal tests
  - Compare different versions of the Fribourg construction
- External tests
  - Compare Fribourg construction with other constructions

	GOAL test set	Michel test set
Internal tests	– Fribourg – Fribourg+R2C – Fribourg+R2C+C – Fribourg+M1 – Fribourg+M1+R2C – Fribourg+M1+R2C+C – Fribourg+M1+M2 – Fribourg+R	– Fribourg – Fribourg+R2C – Fribourg+M1 – Fribourg+M1+M2 – Fribourg+M1+M2+R2C – Fribourg+R
External tests	– Fribourg+M1+R2C – Piterman+EQ+RO – Rank+TR+RO – Slice+P+RO+MADJ+EG	– Fribourg+M1+M2+R2C – Piterman+EQ+RO – Rank+TR+RO – Slice+P+RO+MADJ+EG

Test Setup

- Shorthand naming for test scenarios:

	GOAL test set	Michel test set
Internal	**IG**	**IM**
External	**EG**	**EM**

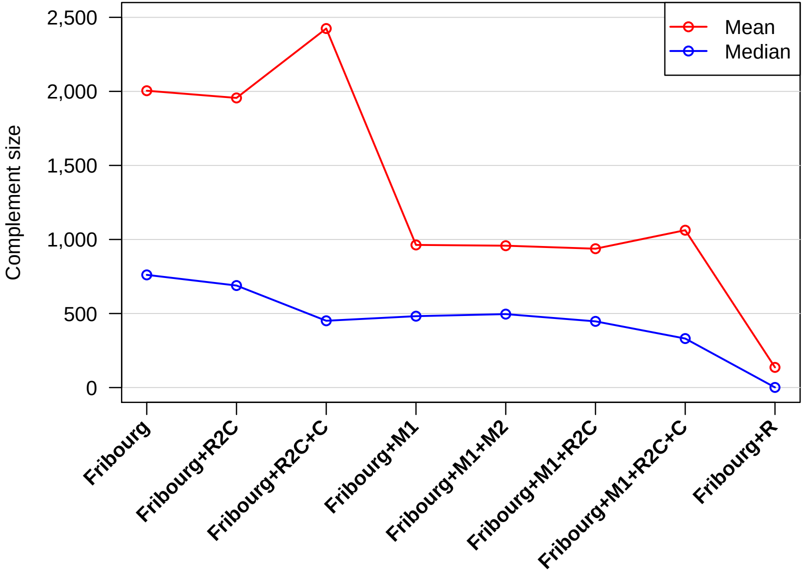
- IG and EG
  - Time limit: 600 seconds CPU time
  - Memory limit: 1 GB Java heap
  - Effective samples:
    - Automata which have been succesfully complemented by **all** constructions of a test scenario
- IM and EM: no limits

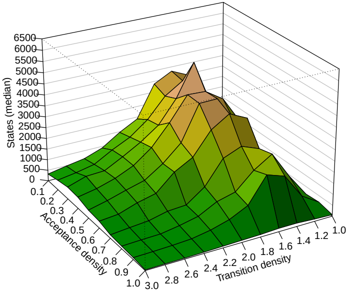
Results: Internal Tests on GOAL Test Set

	GOAL test set	Michel test set
Internal	**IG**	**IM**
External	**EG**	**EM**

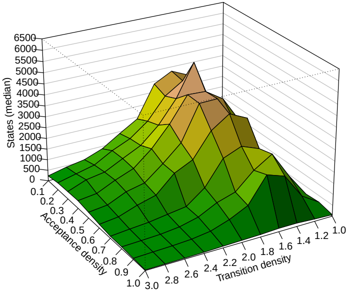
- Fribourg
- Fribourg+R2C
- Fribourg+R2C+C
- Fribourg+M1
- Fribourg+M1+R2C
- Fribourg+M1+R2C+C
- Fribourg+M1+M2
- Fribourg+R

IG: Complement Sizes (10,939 Eff. Samples)

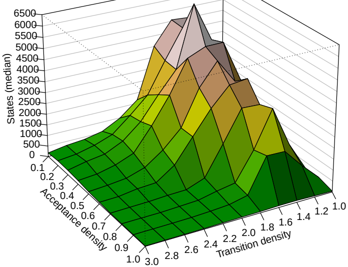




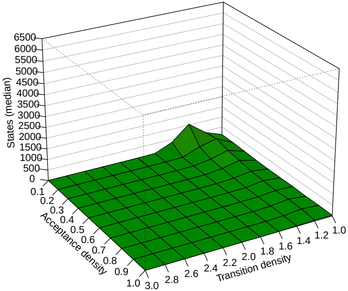
Fribourg



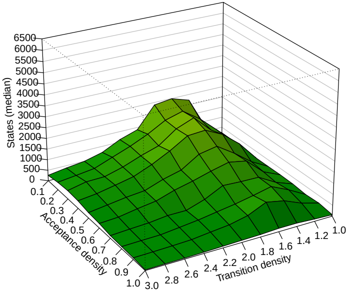
Fribourg+R2C



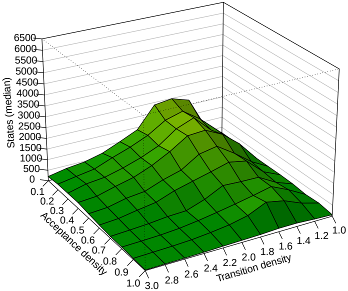
Fribourg+R2C+C



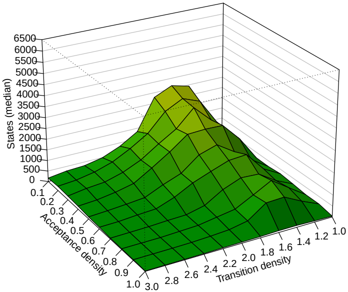
Fribourg+R



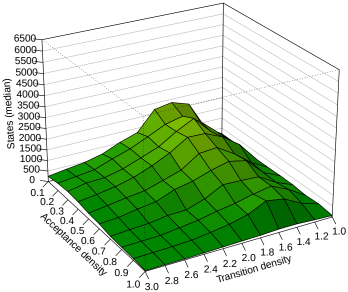
Fribourg+M1



Fribourg+M1+R2C



Fribourg+M1+R2C+C



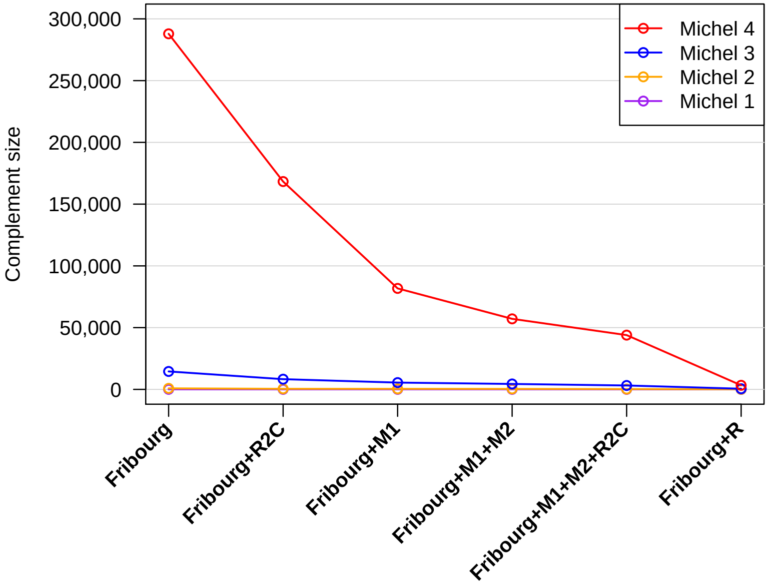
Fribourg+M1+M2

Results: Internal Tests on Michel Test Set

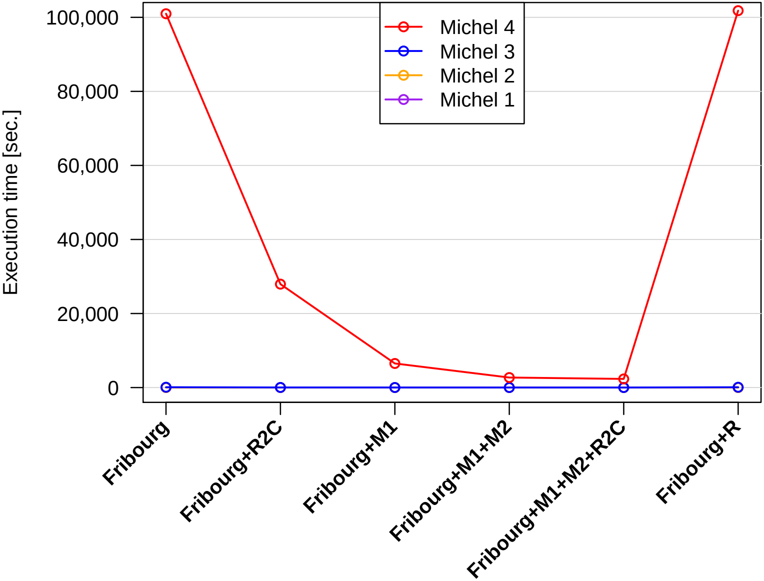
	GOAL test set	Michel test set
Internal	**IG**	**IM**
External	**EG**	**EM**

- Fribourg
- Fribourg+R2C
- Fribourg+M1
- Fribourg+M1+M2
- Fribourg+M1+M2+R2C
- Fribourg+R

IM: Complement Sizes



IM: Execution times

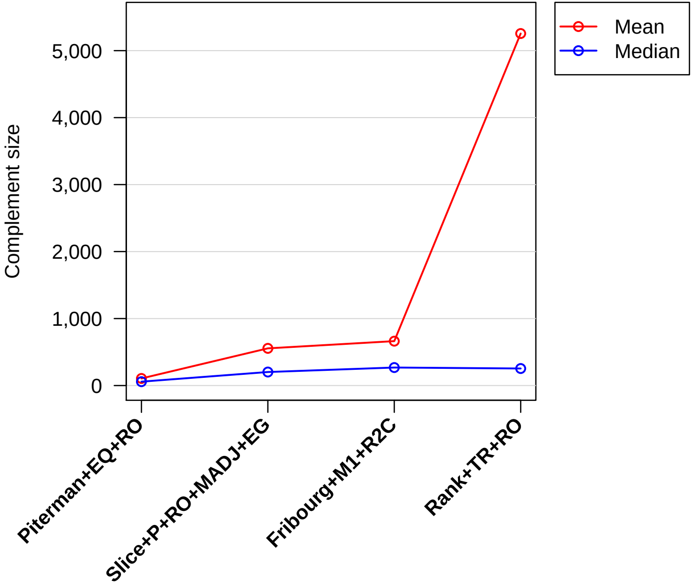


Results: External Tests on GOAL Test Set

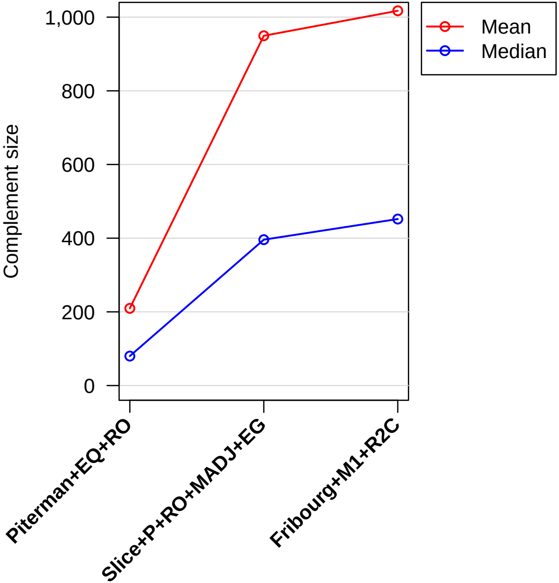
	GOAL test set	Michel test set
Internal	**IG**	**IM**
External	**EG**	**EM**

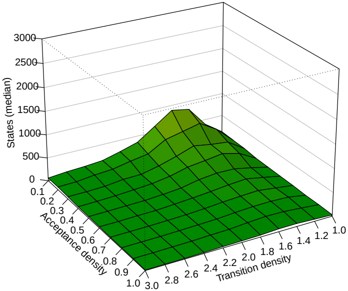
- Fribourg+M1+R2C
- Piterman+EQ+RO
- Rank+TR+RO
- Slice+P+RO+MADJ+EG

EG: Complement Sizes (7,204 Eff. Samples)

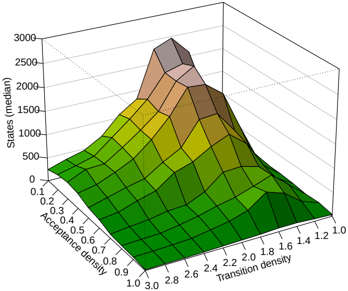


EG: Complement Sizes (10,998 Eff. Samples)

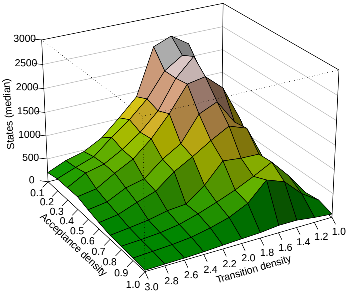




Piterman+EQ+RO



Slice+P+RO+MADJ+EG



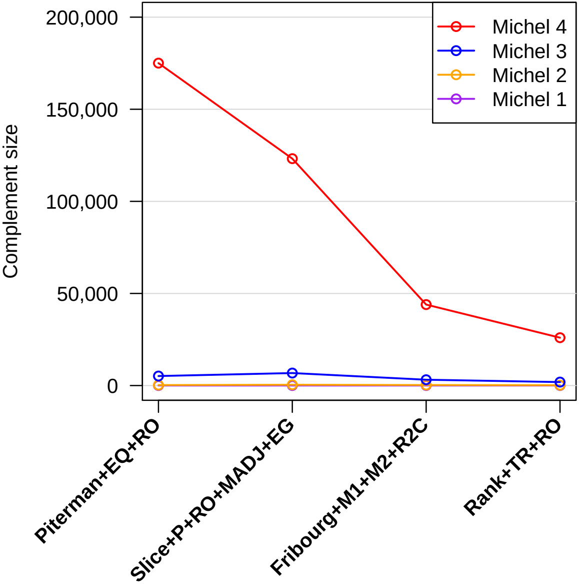
Fribourg+M1+R2C

Results: External Tests on Michel Test Set

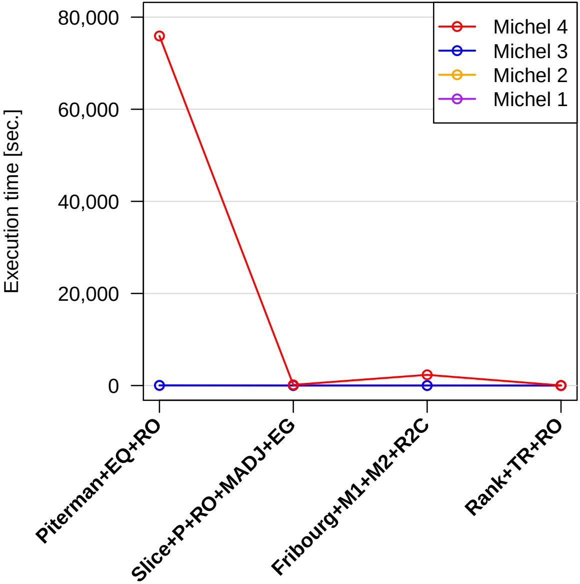
	GOAL test set	Michel test set
Internal	**IG**	**IM**
External	**EG**	**EM**

- Fribourg+M1+M2+R2C
- Piterman+EQ+RO
- Rank+TR+RO
- Slice+P+RO+MADJ+EG

EM: Complement Sizes



EM: Execution times



The End

Thank you very much for listening!

Thank you
for listening!

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