Task scheduling for dual-arm industrial robots through constraint programming

MiniZinc modeling and solver comparison

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February 23, 2015

Outline

Introduction - YuMi®

- Dual-armed robot
- Flexible - multiple tools
- Fine motor skills

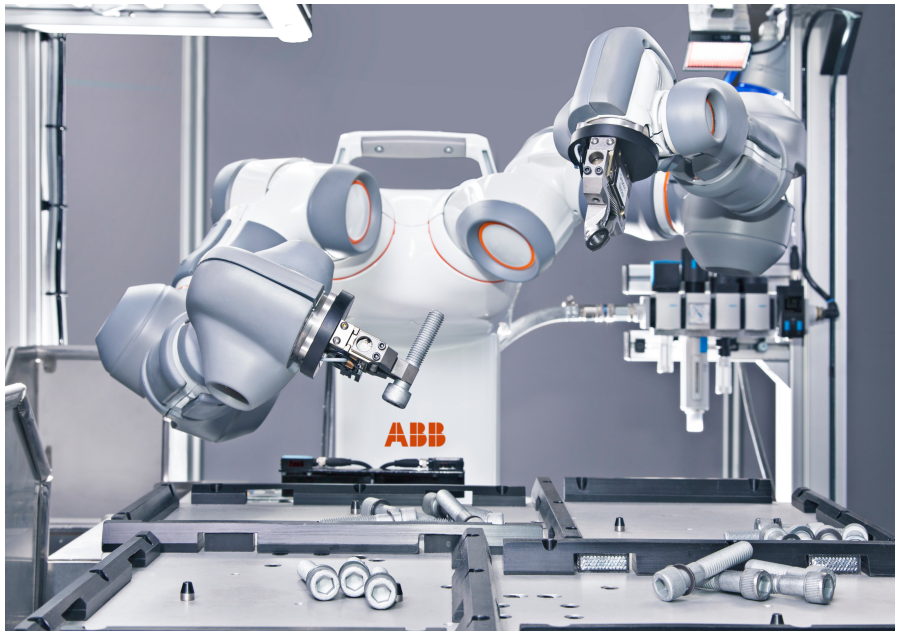


Photo: ABB

Introduction - Project goal

- Constraint Programming model for dual-armed robots such as YuMi®
  - Change tools
  - Carry only one component at the time
  - Same duration for tool changes, regardless of direction
  - Use trays, fixtures and outputs
- Implement the model in MiniZinc
- Test the model with 6 solvers and compare the results

Introduction - MiniZinc

- Declarative language
- Medium level
- Translates to FlatZinc
- Aims to be standard
- Many solvers can read FlatZinc

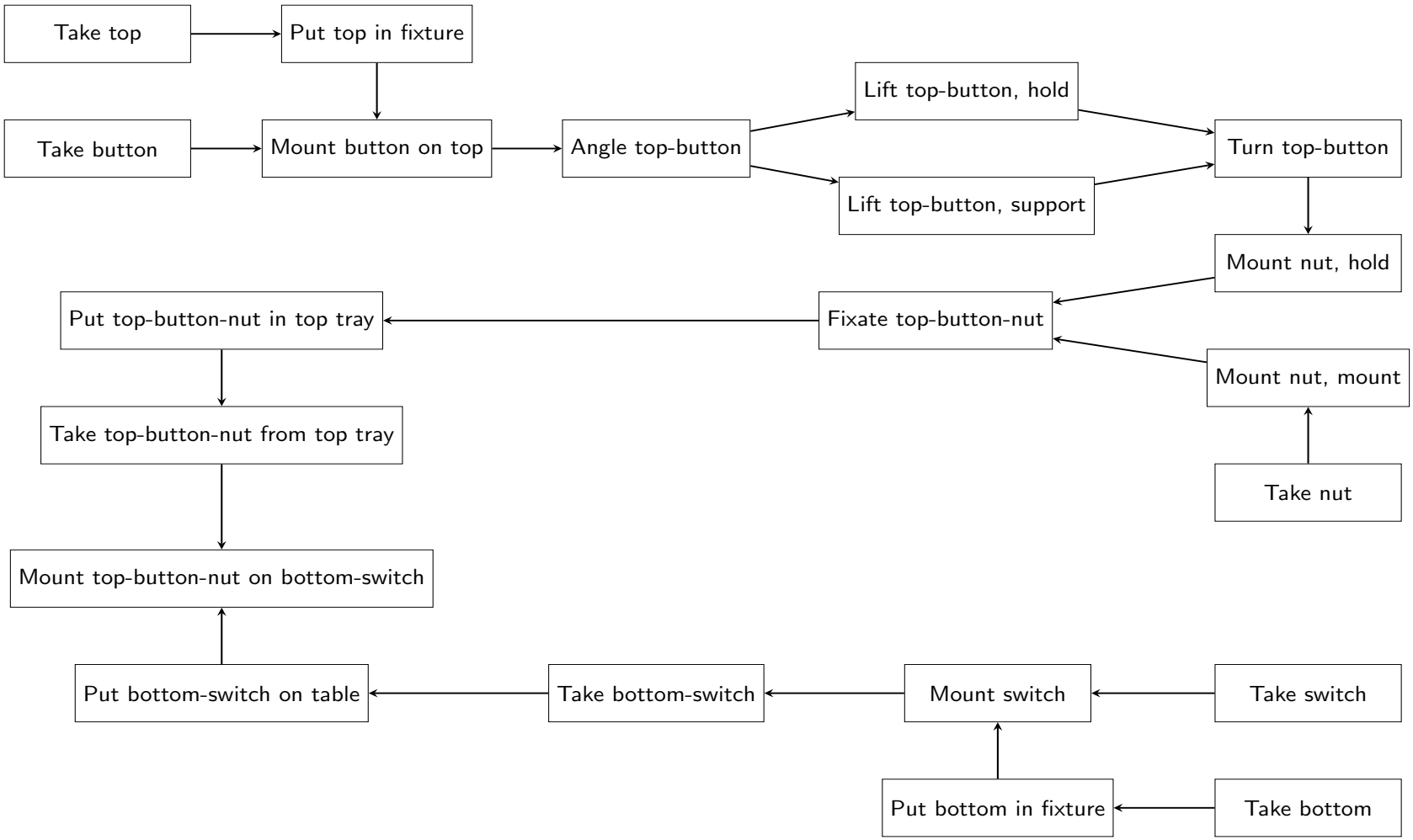
Case Study

Case Study

Physical Entities

- Machines
- Tools
- Components
- Tray
- Fixture
- Output

Assembly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Take button
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Turn top-button
Mount nut, hold
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Take bottom

Model

Job Shop Problem

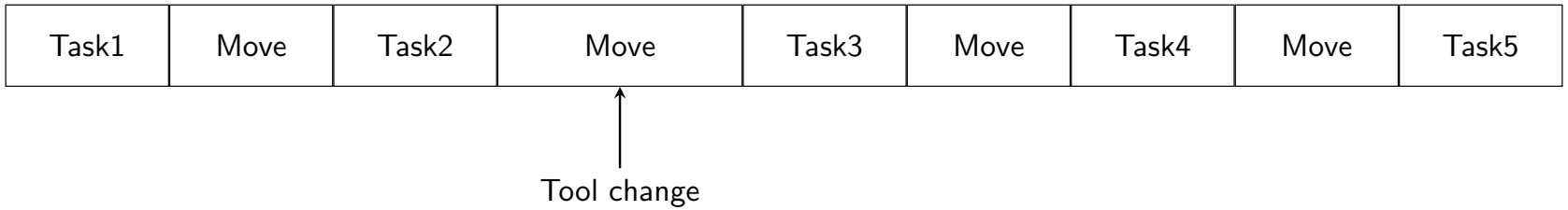
- n jobs, varying size
- m identical machines
- NP-complete for $m \geq 2$ and $n \geq 3$

Model

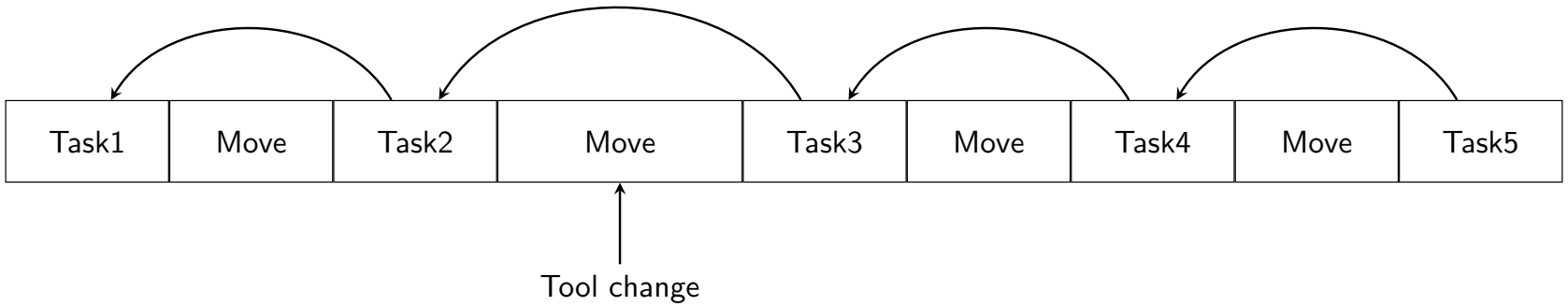
Model

Task1	Move	Task2	Move	Task3	Move	Task4	Move	Task5

Model


Task1
Move
Task2
Move
Task3
Move
Task4
Move
Task5
Tool change

Model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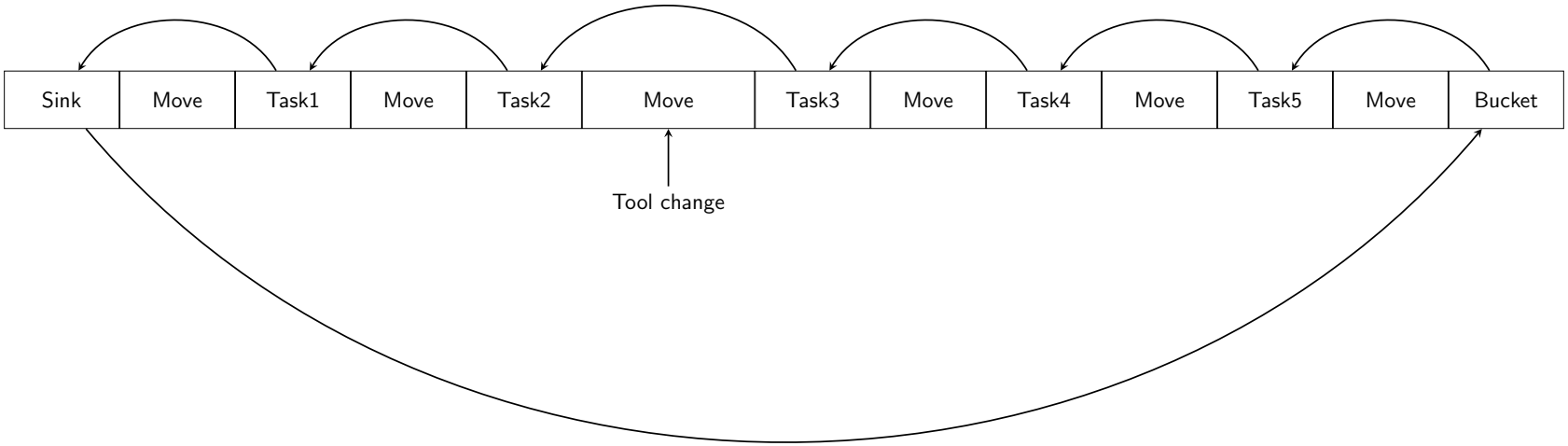
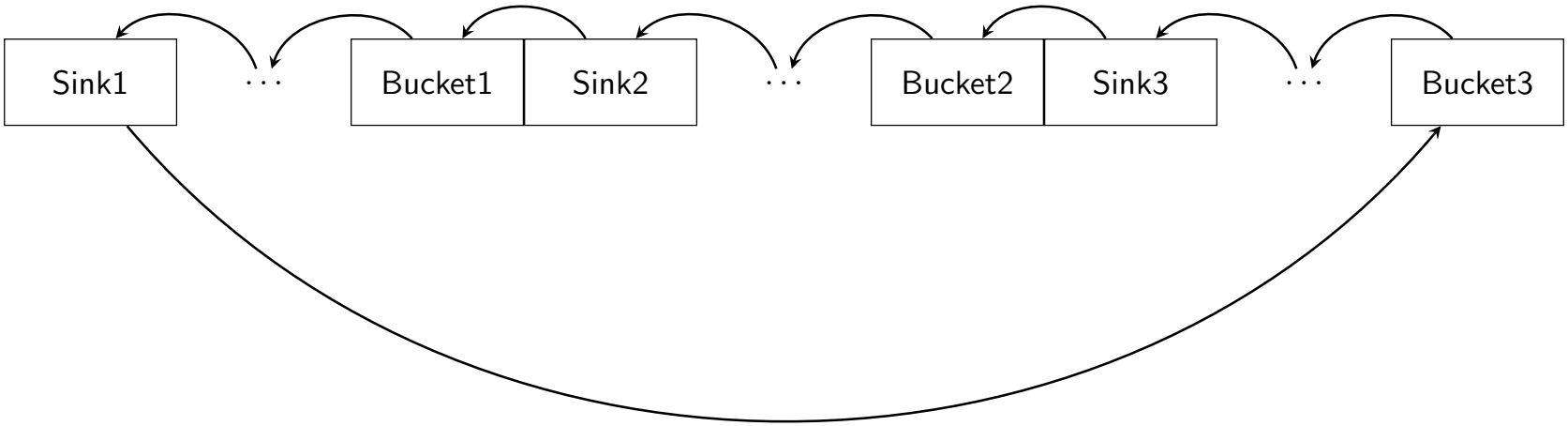

Sink
Move
Task1
Move
Task2
Move
Task3
Move
Task4
Move
Task5
Move
Bucket
Tool change

Model



Components

Components

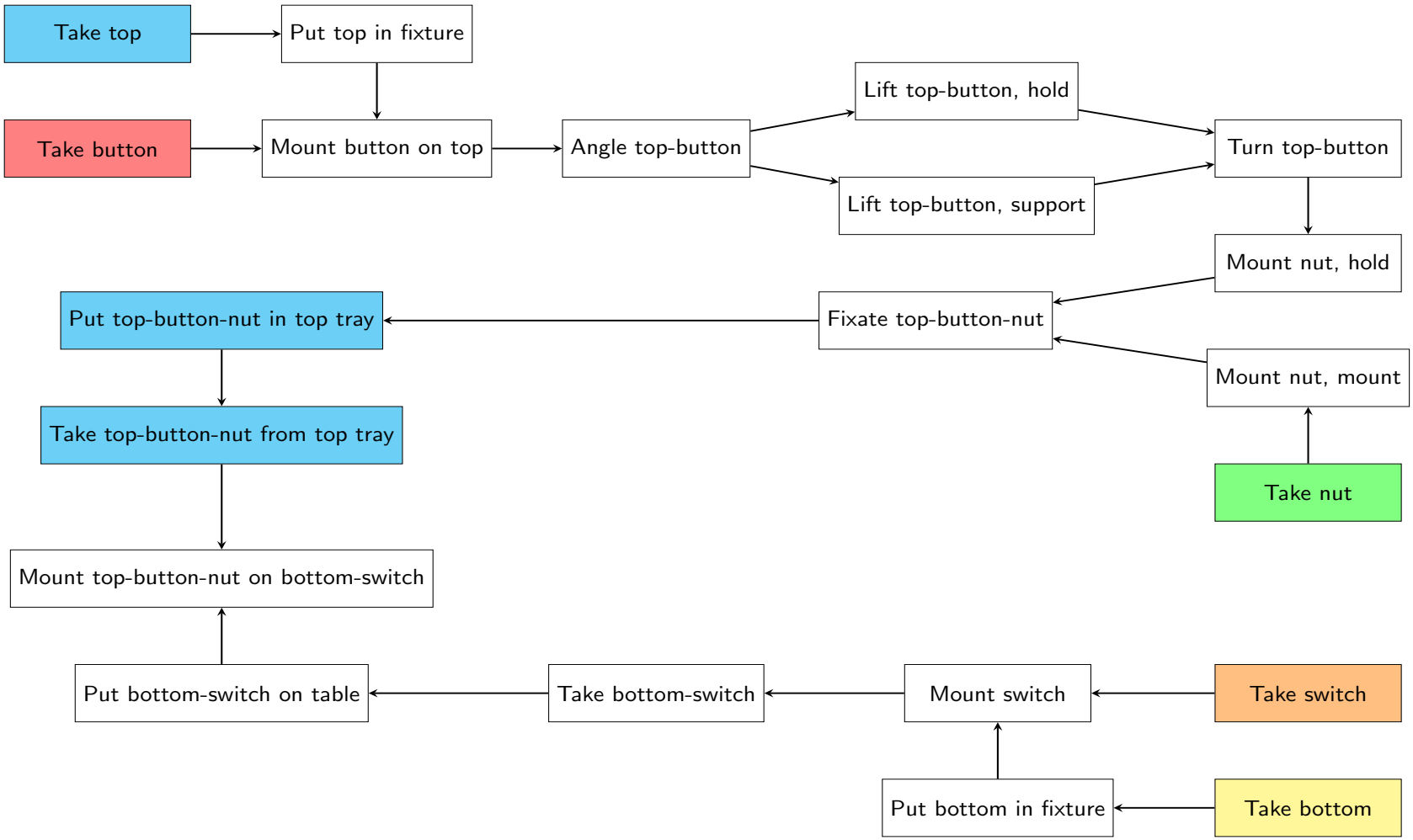
- Primitive components
- Sub-assemblies

Storage Mediums

Storage mediums

- Tray - Top tray, Button tray, etc.
- Fixture
- Output

Tray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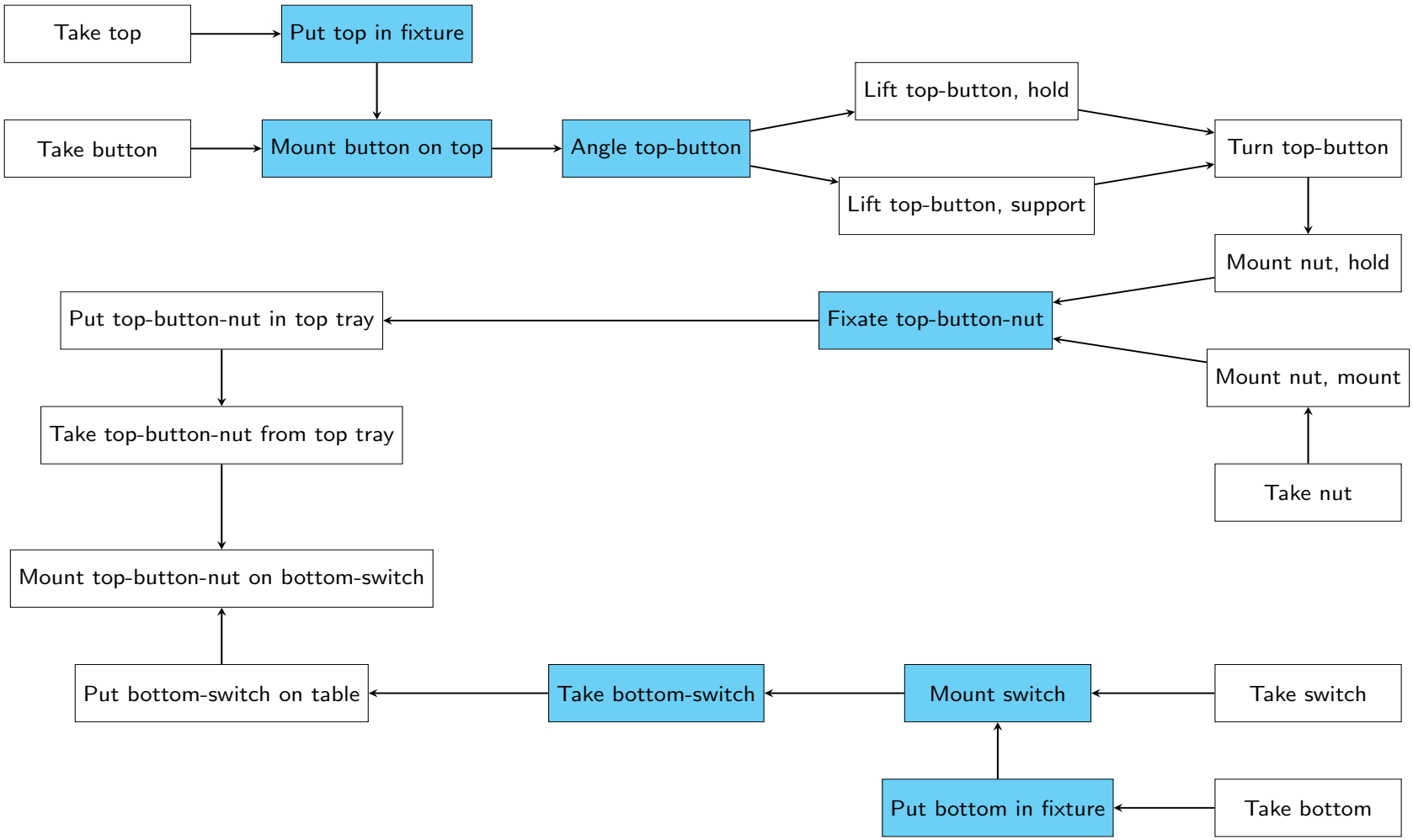
Fixture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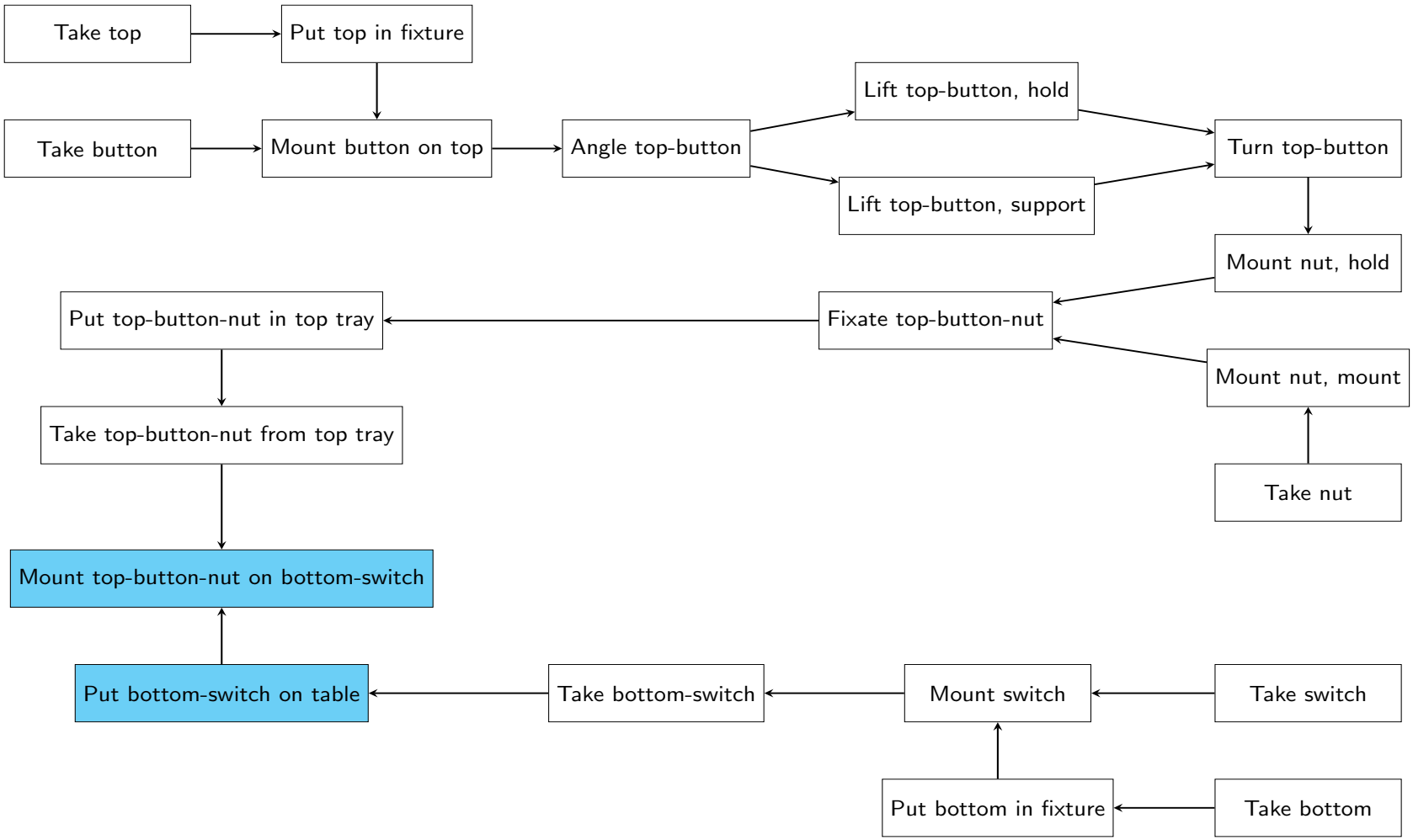
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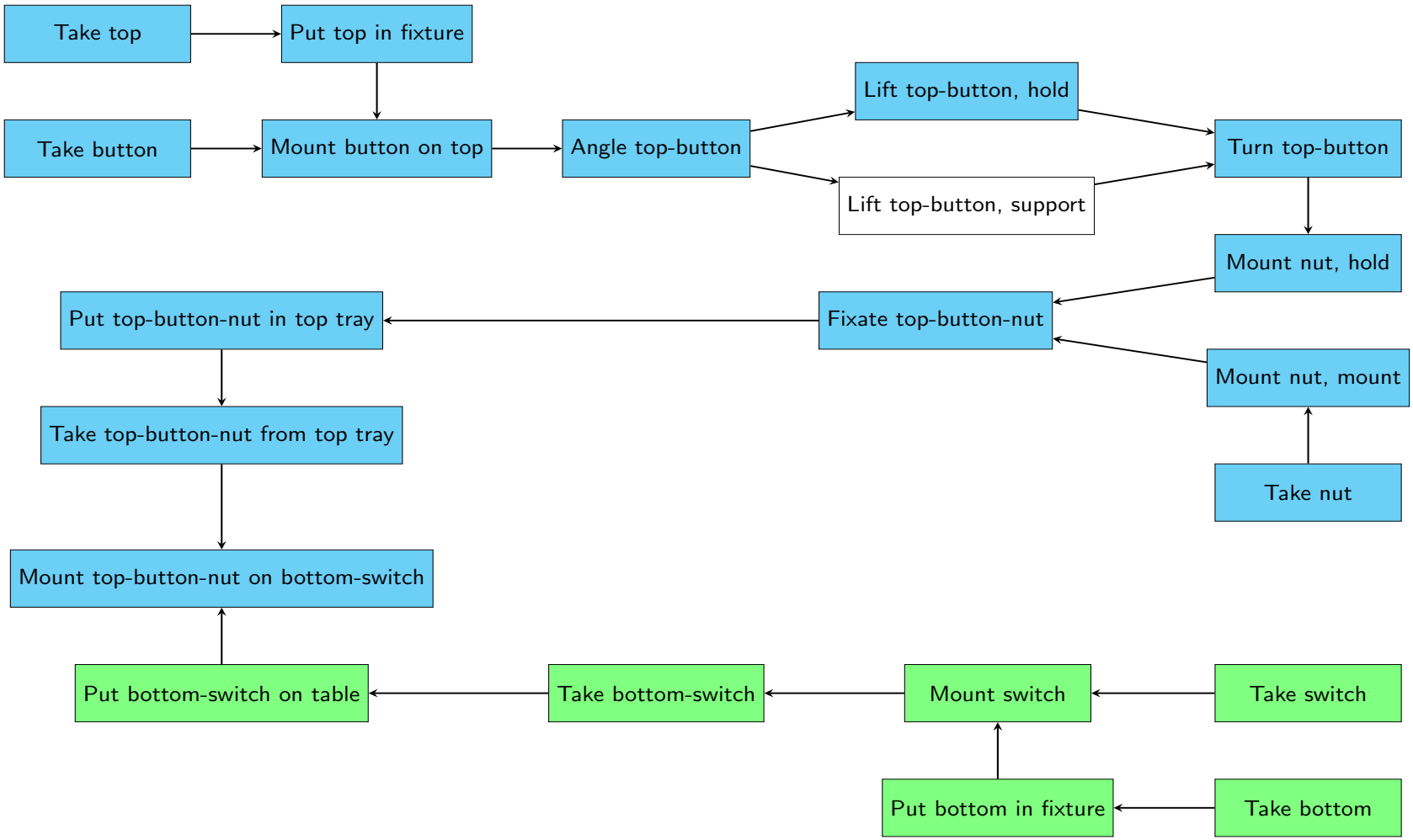
Tools

- Tools available
- Tool used by tasks

Tools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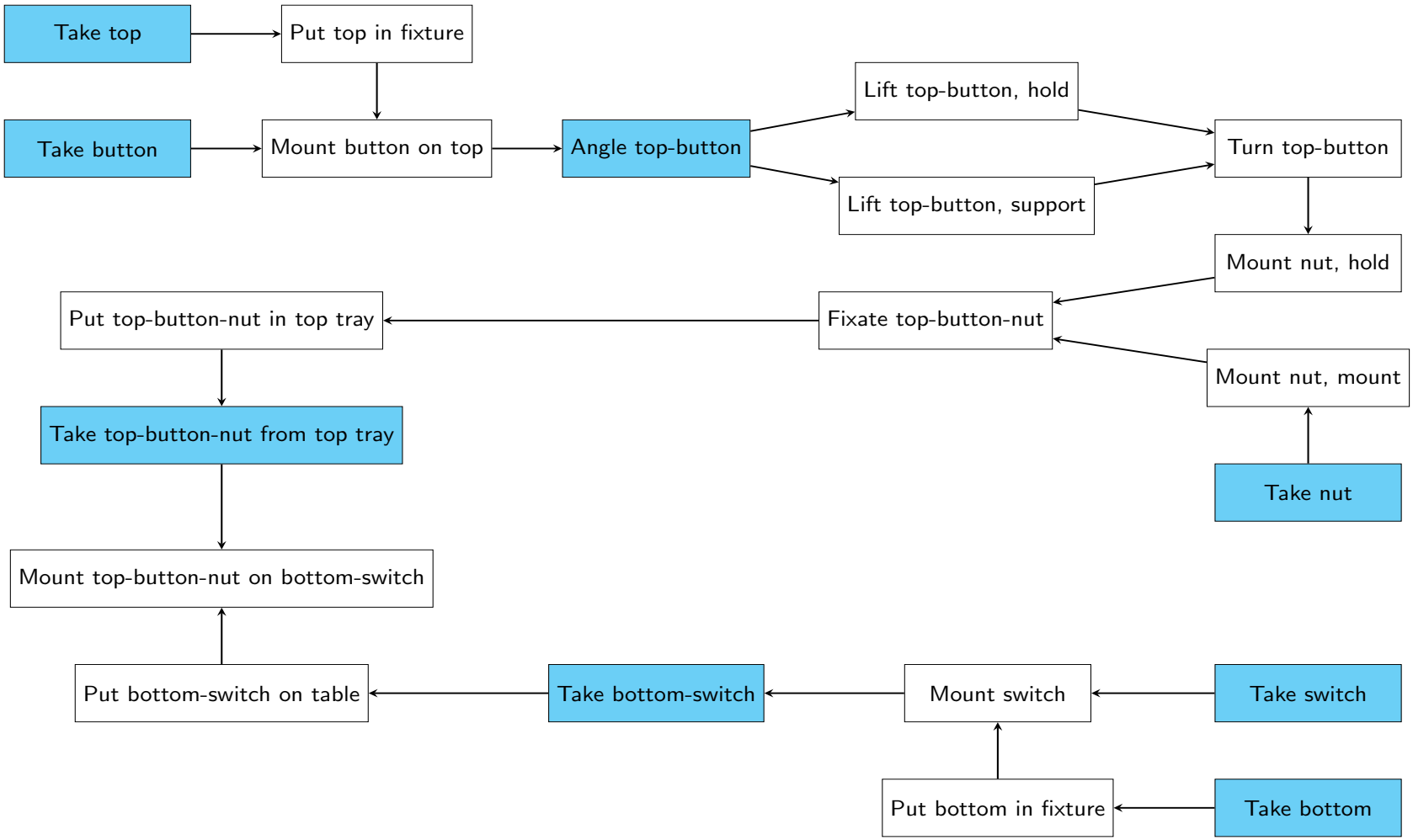
Action

Task actions

- Taking
- Mounting
- Putting
- Moving

Taking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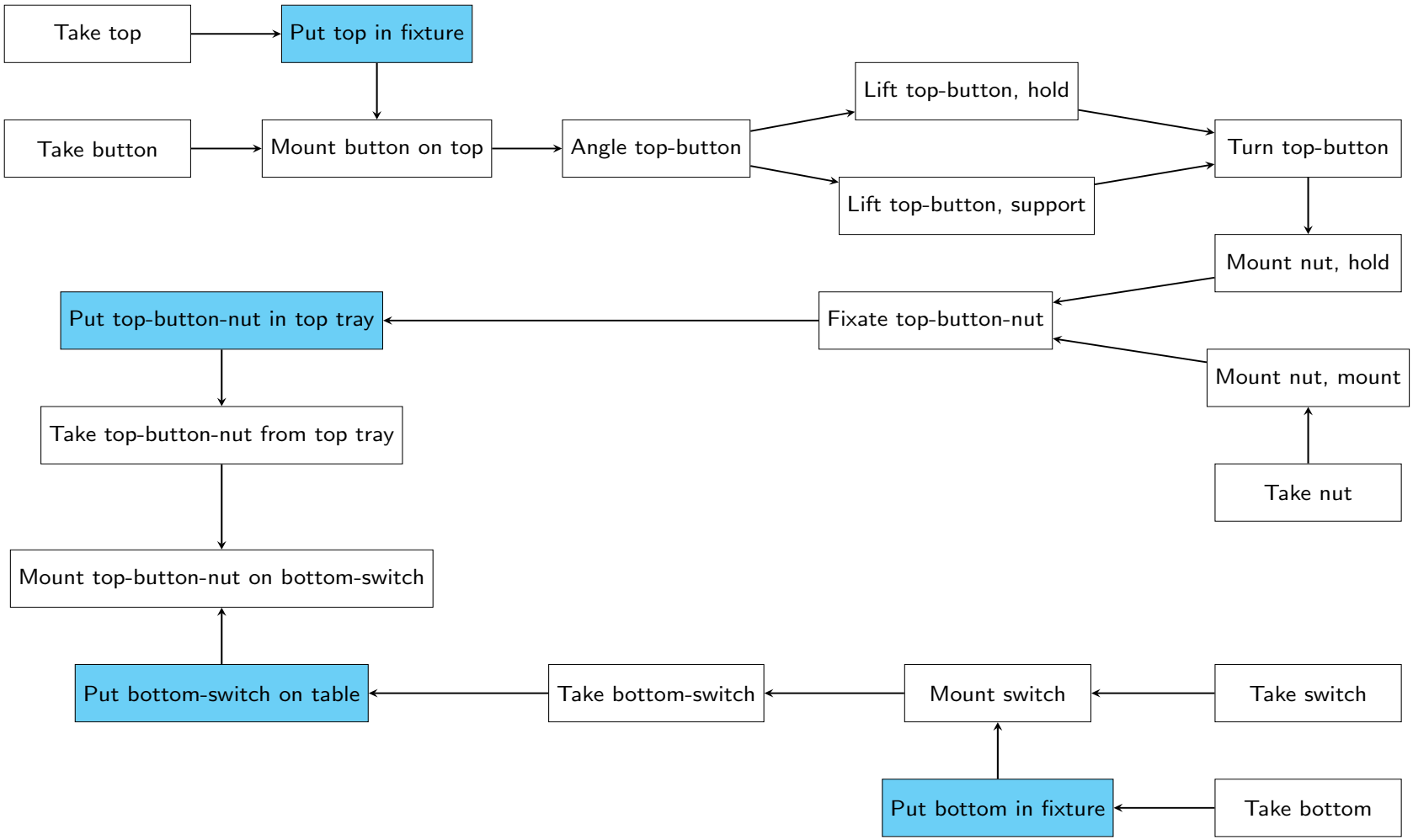
Putting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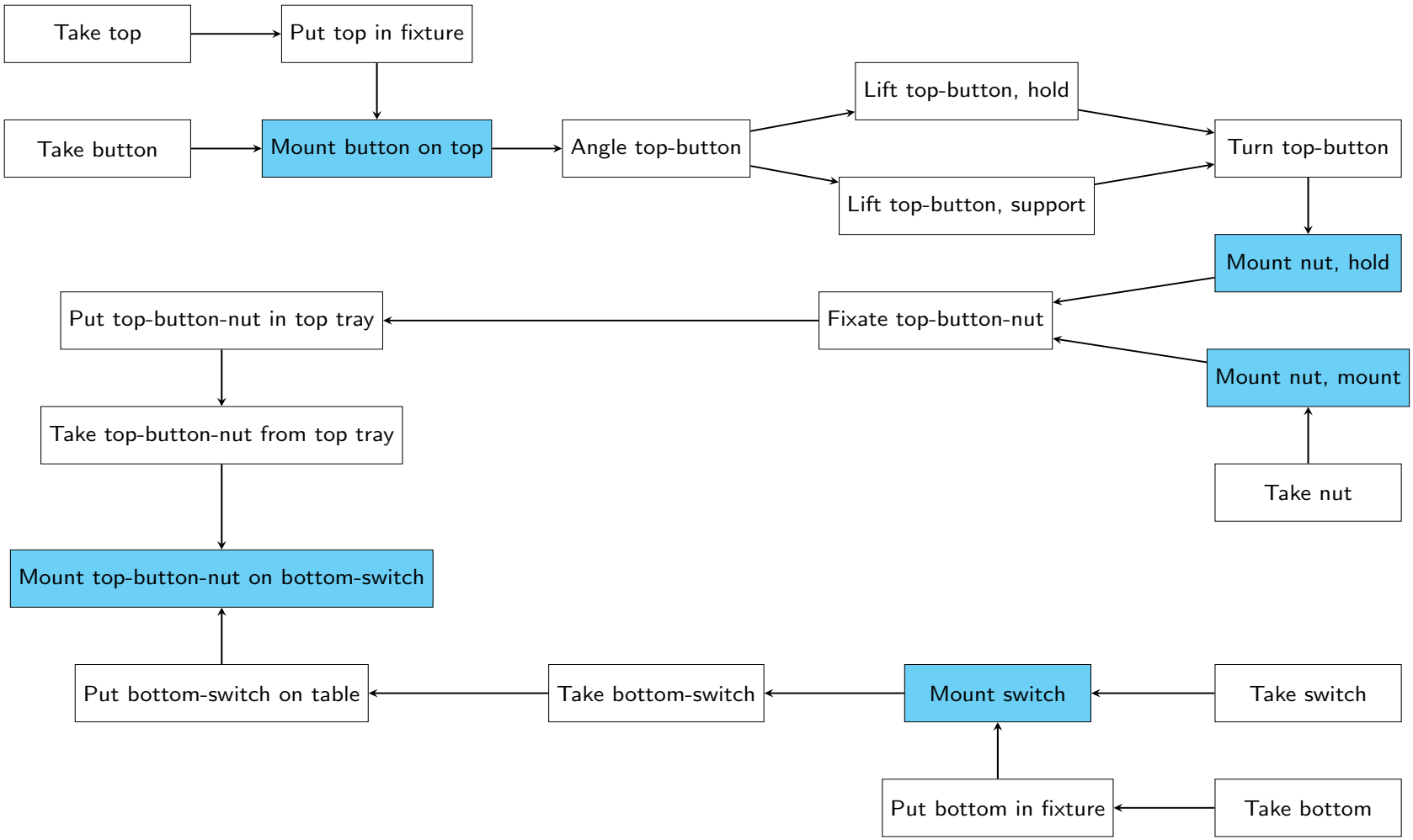
Mounting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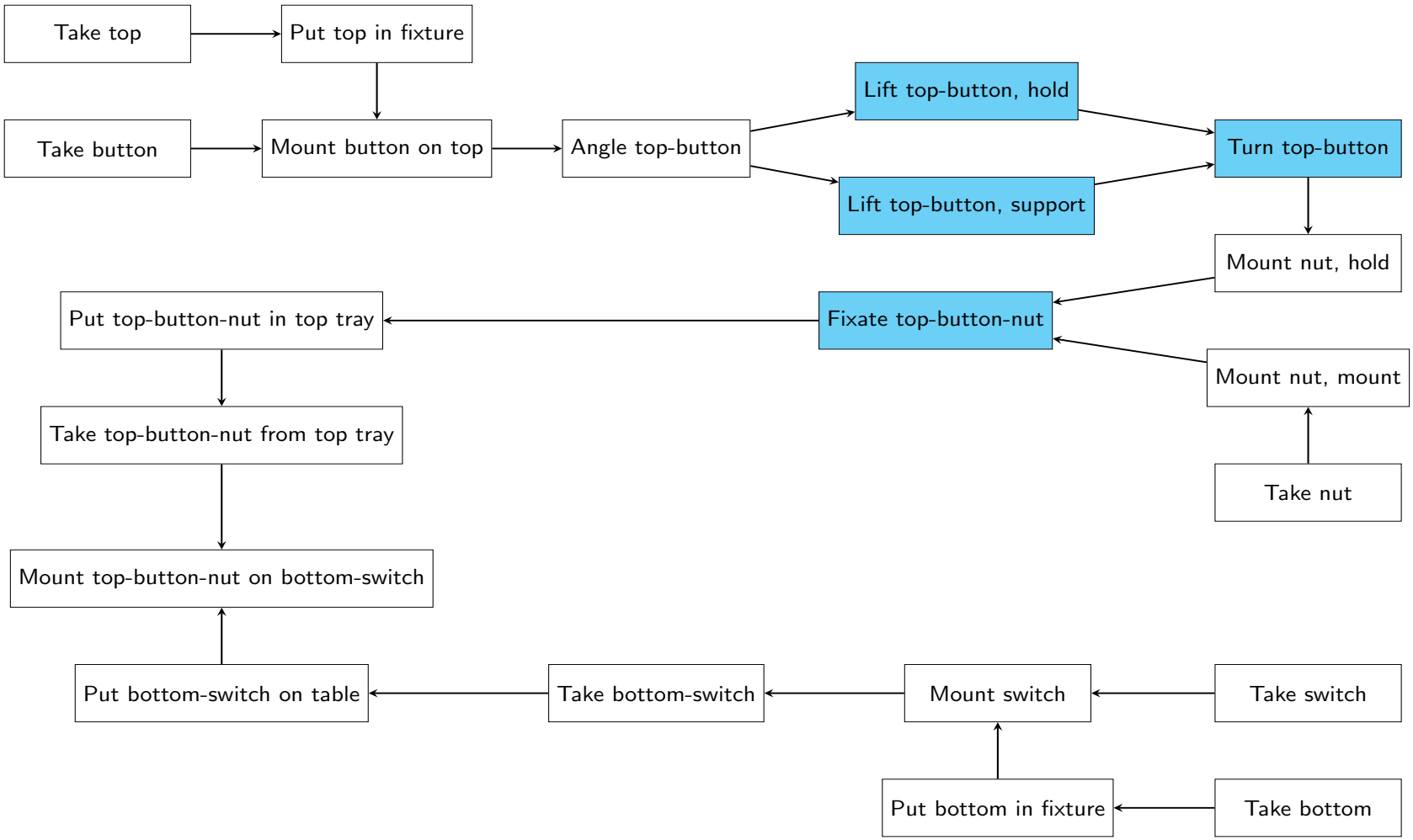
Moving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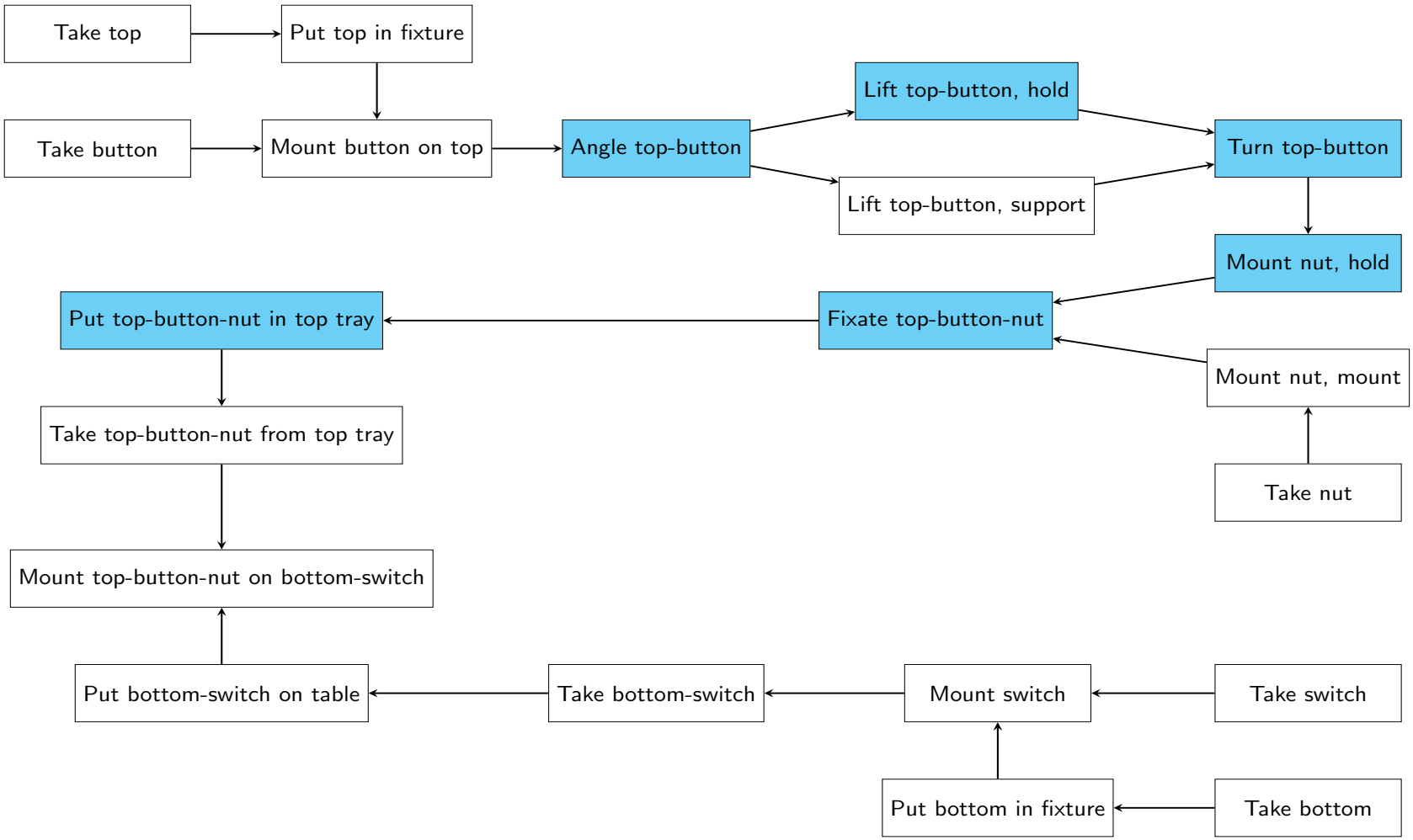
Model

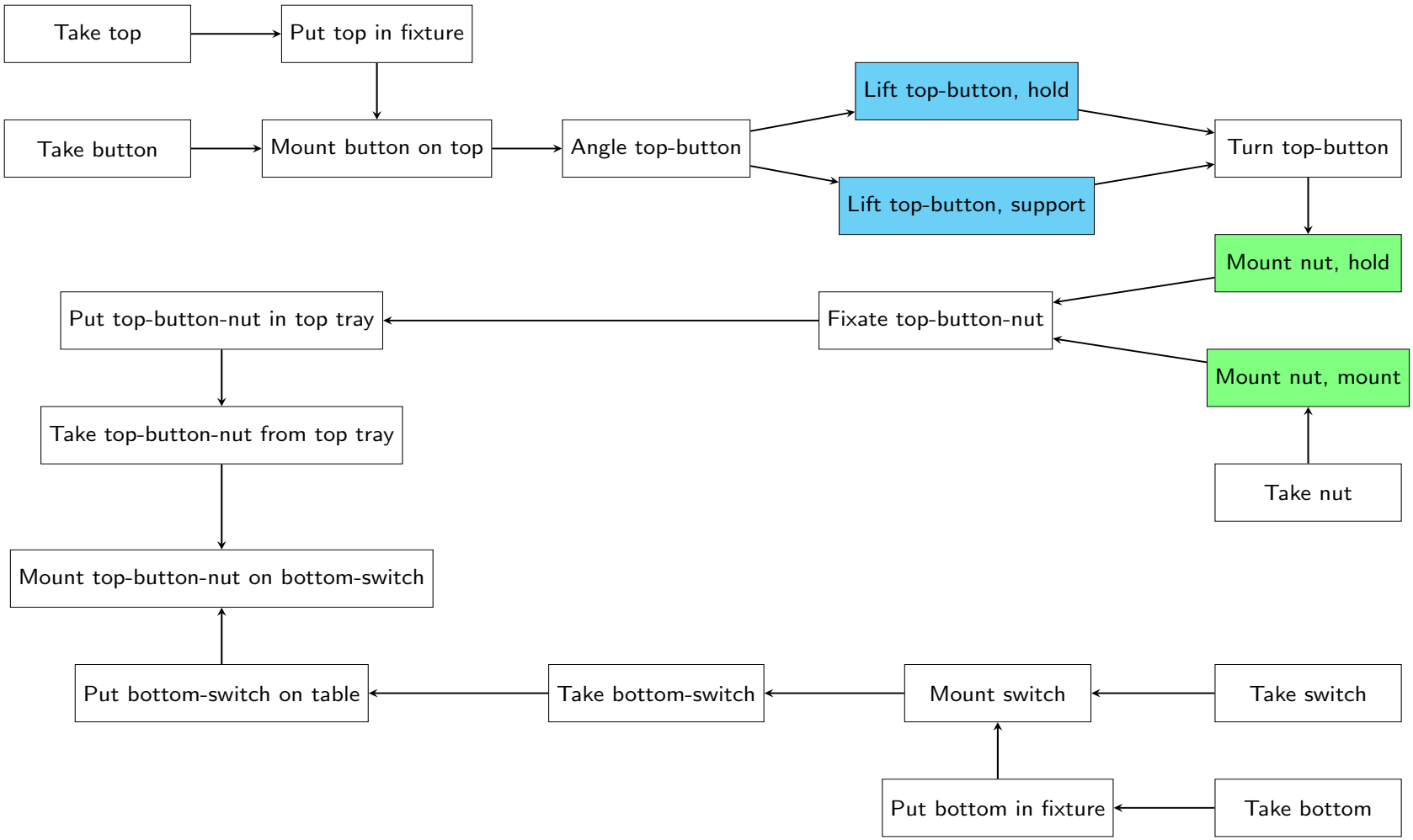
Group tasks

- Ordered group
- Concurrent group

Ordered group



Concurrent group



Filter

- Temporal filter
- Predecessor filter

Evaluation

- Test with 6 solvers
  - Solver time
  - FlatZinc file
- MiniZinc 1.6 & 2.0.1
- Combination of filters

Criteria

- FlatZinc parser
- Free

Solvers Tested

- G12/FD
- JaCoP
- Gecode
- or-tools
- Opturion CPX
- Choco3

G12/FD

- G12 Team, NICTA
- Mercury
- Default solver for MiniZinc

JaCoP

- Java Constraint Programming solver
- Open Source
- Developed since 2001 - Krzysztof Kuchcinski & Radoslaw Szymanek
- Silver medal

Gecode

- C++
- Open Source
- Christian Schulte
- Parallel searches - utilising multiple cores
- All gold medals 2008-2012

or-tools

- C++
- Google - Operational Research
- Open Source
- Utilising multiple cores
- Gold medals 2013-2014

Opturion CPX

- Opturion Pty Ltd
- Commercial
- SAT combo
- Gold medals 2013, all silver medals 2014

Choco3

- Java
- Open Source
- Developed since early 2000 - Jean-Guillaume Fages & Charles Prud'homme
- Not same as predecessor Choco2

Assembly Times

Manual Time

516 t.u.

Assembly Times

Manual Time	Solver Time
516 t.u.	512 t.u.

Solver Time

	Pred & Temp		Pred		Temp		None	
	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1
G12/FD	-	-	-	-	-	-	-	-
JaCoP	658	-	1011156	-	-	-	-	-
Gecode	-	60	-	71761	-	99	-	71186
or-tools	271	!	380	!	302	!	457	!
Opturion CPX	-	!	-	!	-	!	-	!
Choco3	-	-	-	-	-	-	-	-

Solver Time

	Pred							
	1.6							
G12/FD	-	-	-	-	-	-	-	-
JaCoP	658	-	1011156	-	-	-	-	-
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Solver Time

	Pred							
	1.6							
G12/FD	-							
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Solver Time

	Pred & Temp		Pr					
	1.6	2.0.1	1.6					
G12/FD	-	-	-					
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Solver Time

	Pred & Temp		Pr				
	1.6	2.0.1	1.6				
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Choco3	-	-	-	-	-	-	-	-

Solver Time

G12/FD								
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or-tools								
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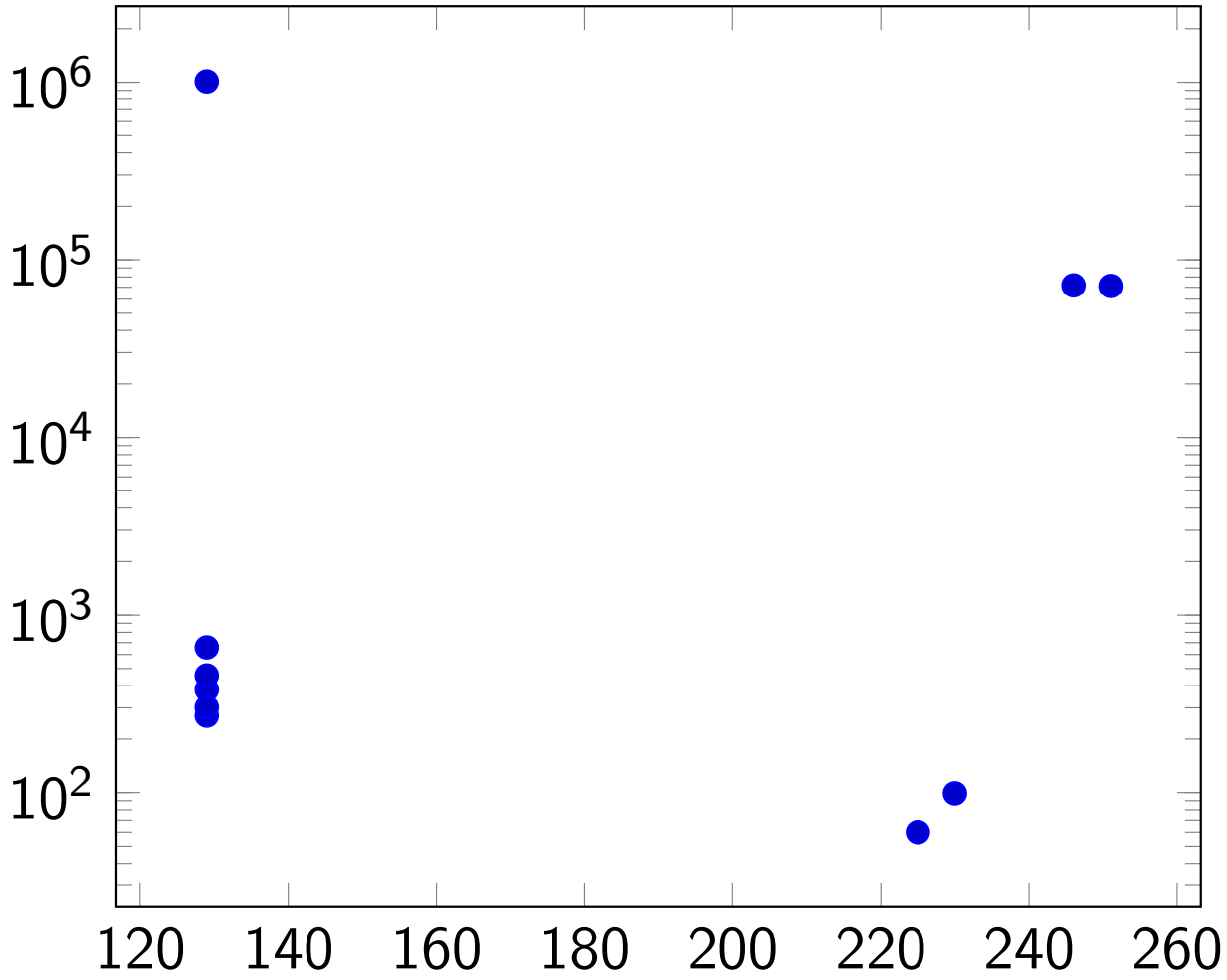
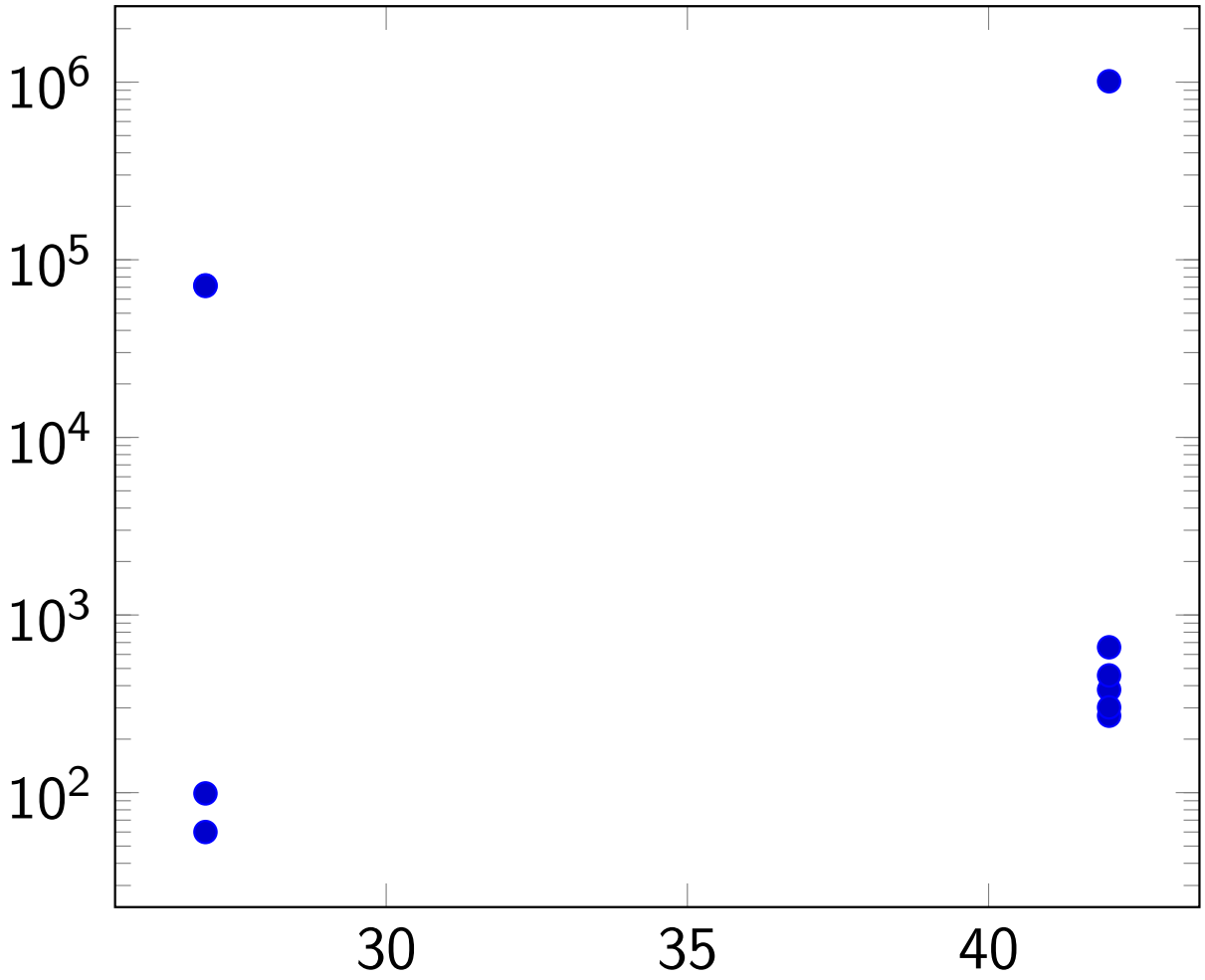
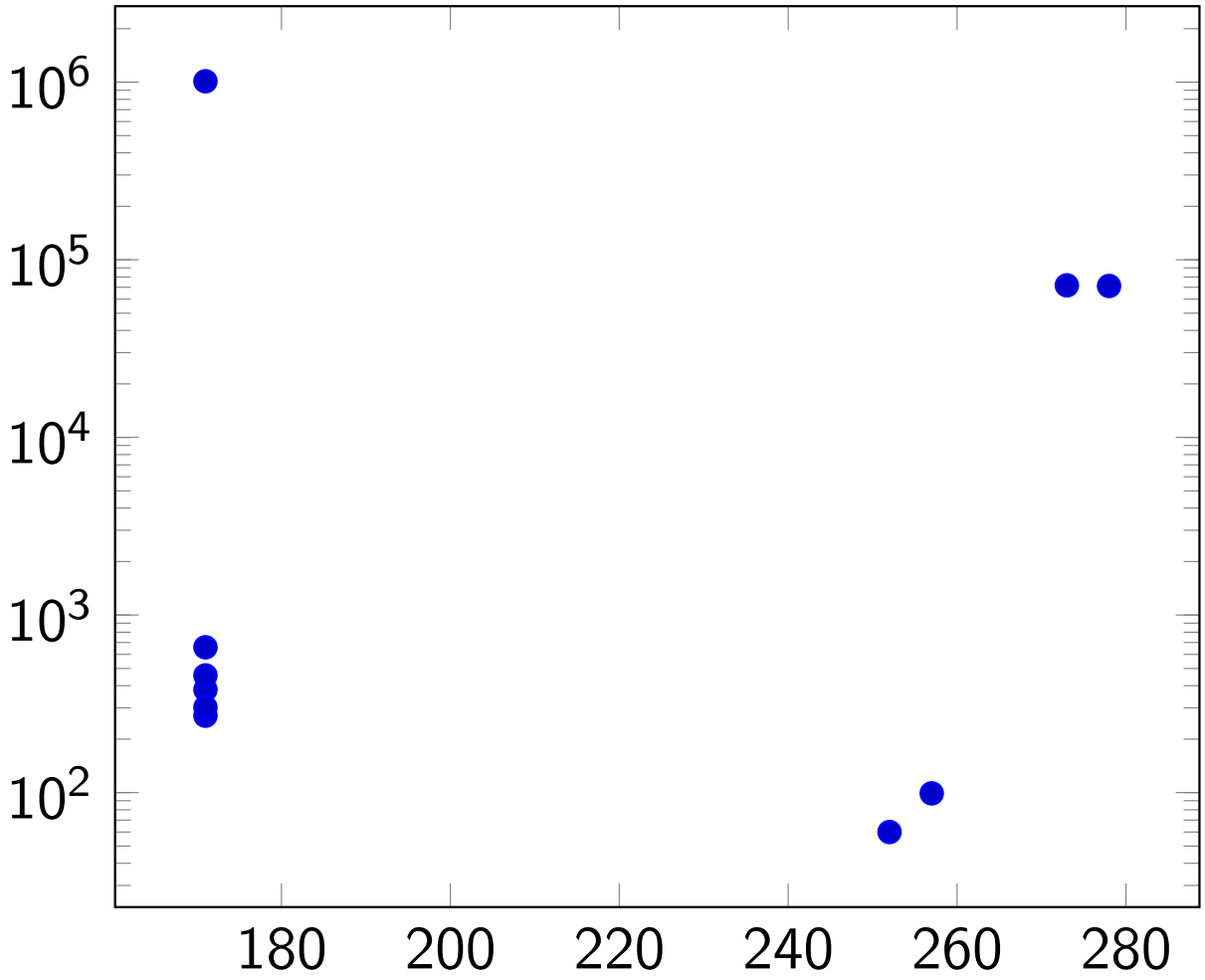
Choco3	-	-	-	-	-	-	-	-



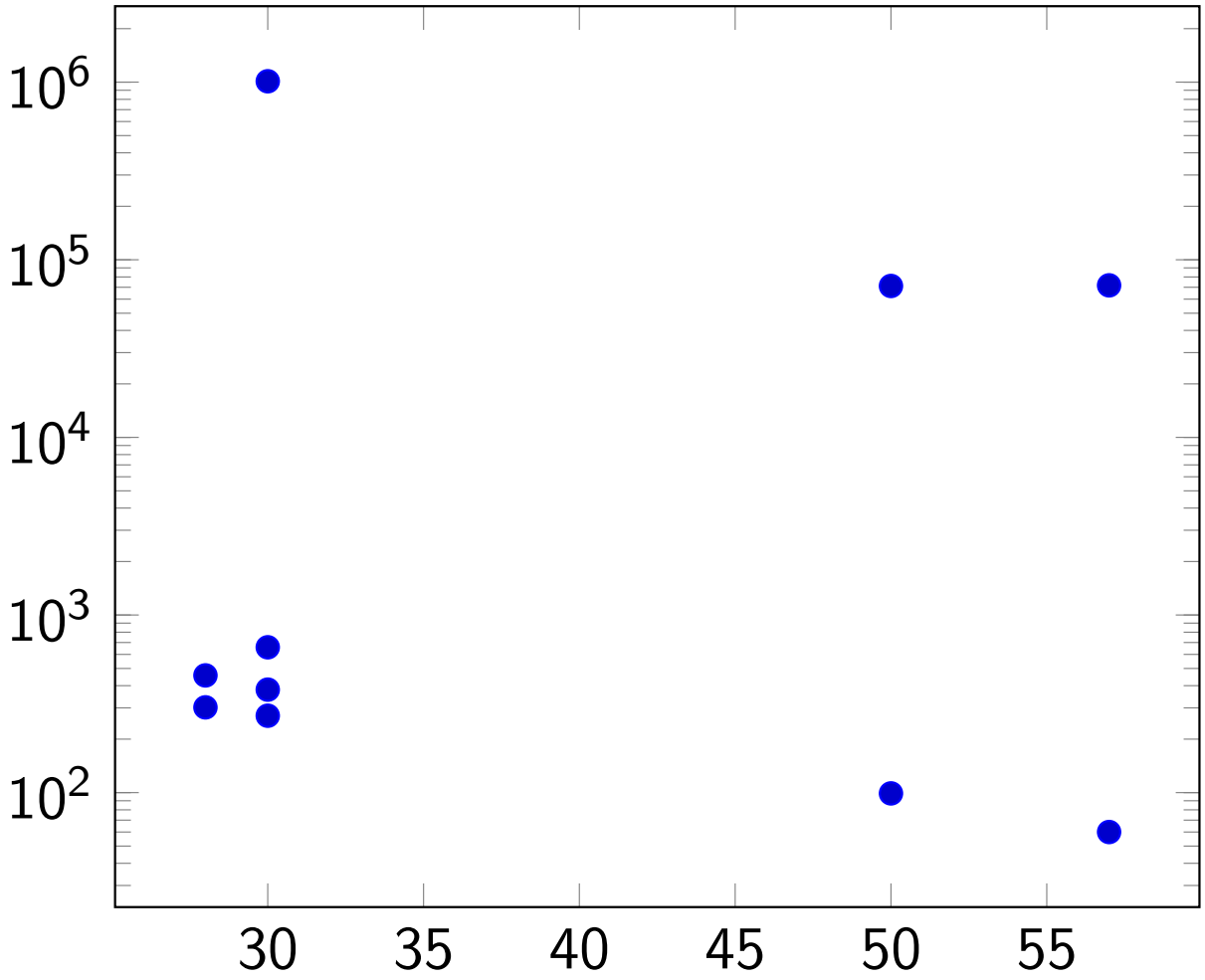
integer variables vs time



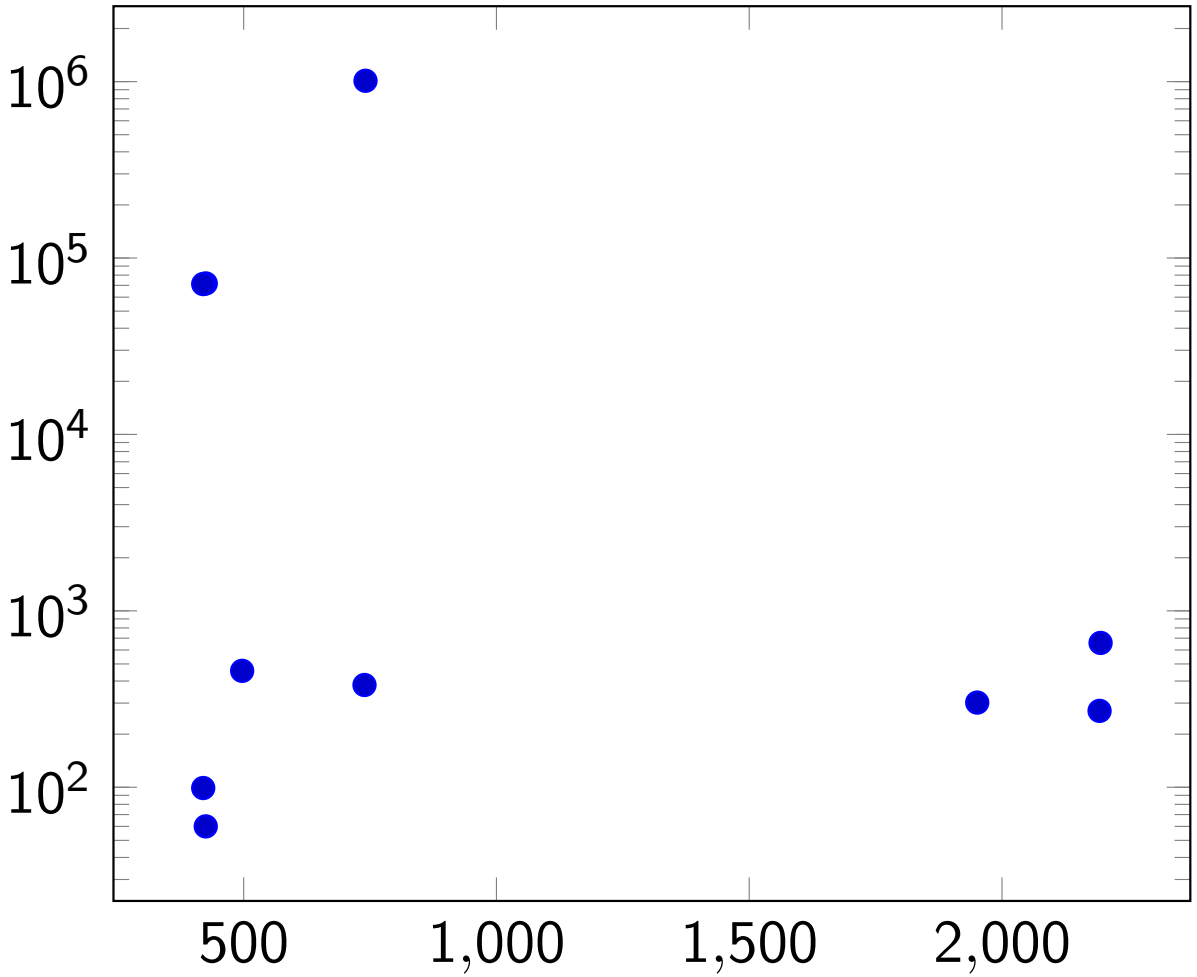
boolean variables vs time



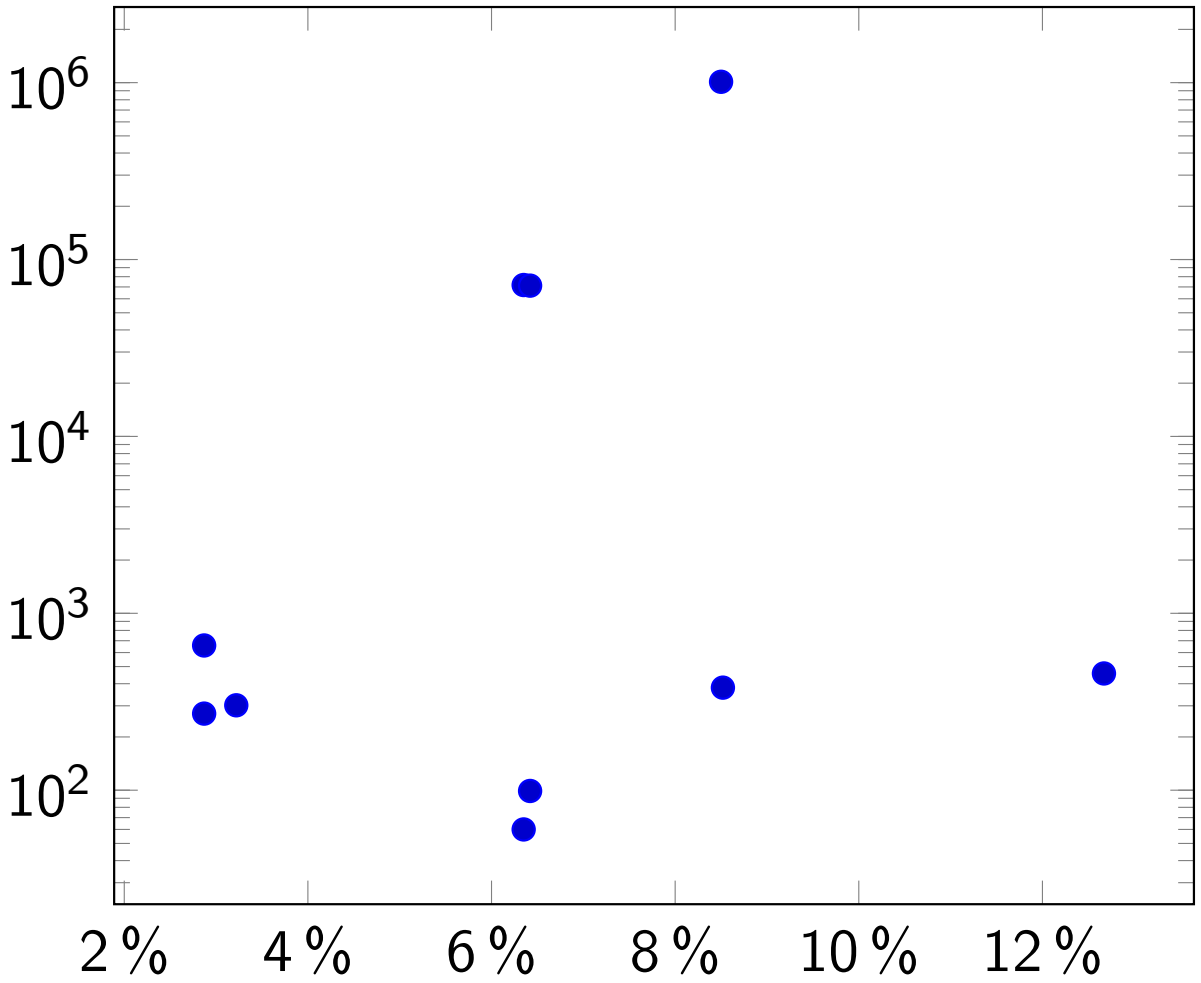
Total # of variables vs time



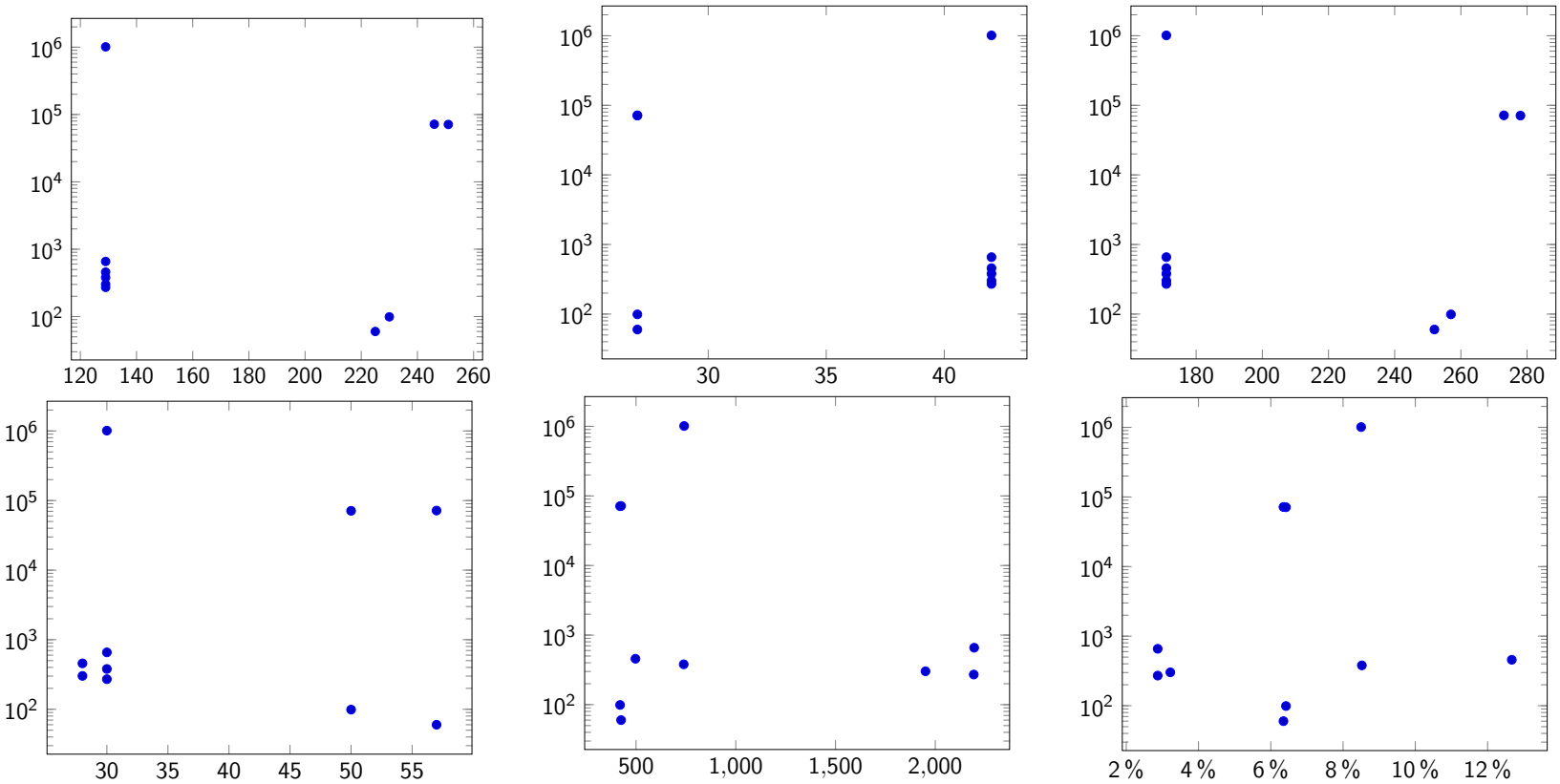
arrays vs time



constraints vs time



% reified vs time


10^6
10^5
10^4
10^3
10^2
120 140 160 180 200 220 240 260
30 35 40
180 200 220 240 260 280
30 35 40 45 50 55
500 1,000 1,500 2,000
2 % 4 % 6 % 8 % 10 % 12 %

Conclusions

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Conclusions

- Model produces solution just as good as handmade solution
- Solver performance varies a lot
- Best performance: Gecode, all filters, MiniZinc 2.0.1
- Filters presented have a positive impact on runtime
- No relation between FlatZinc output and solver runtime

Further work

- Test the result on a real robot
- Further testing of the filters
- More realistic representation of tools available
- Test solvers with more assemblies