Verification Algorithms for Automated Separation Logic Verifiers

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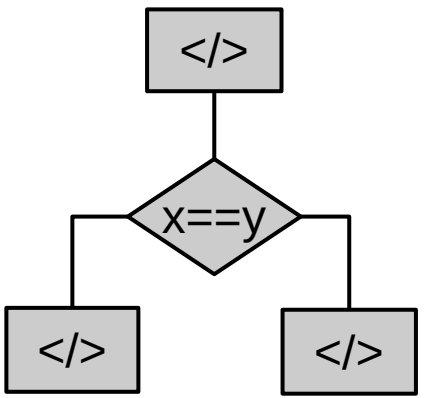
Malte Schwerhoff
Peter Müller

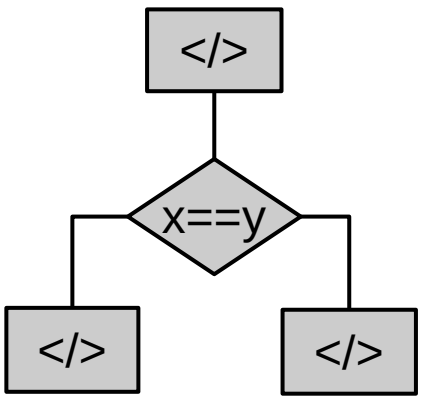
ETH zürich

Automating Separation Logic



Automating Separation Logic

{ P }



{ Q }

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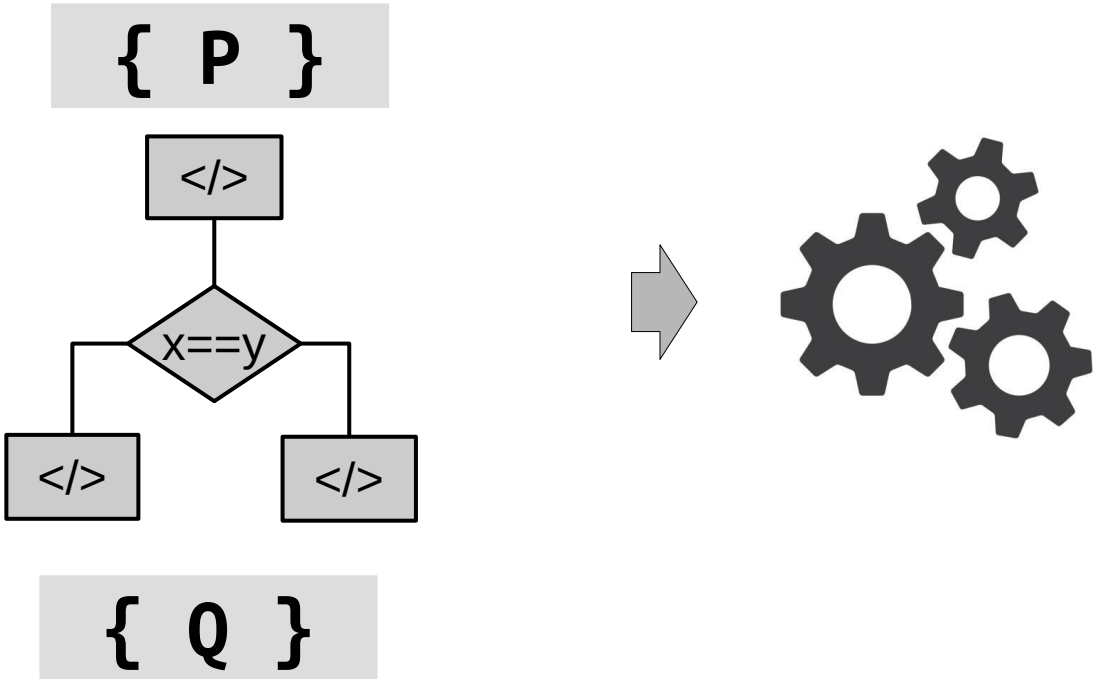

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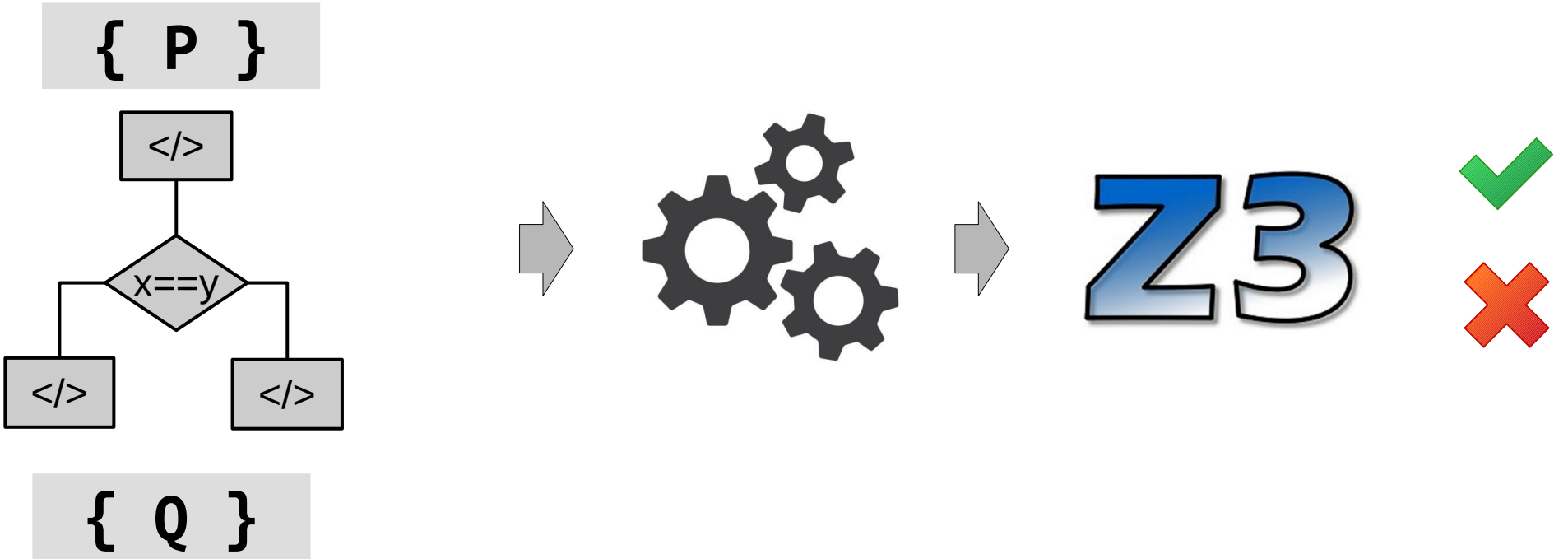
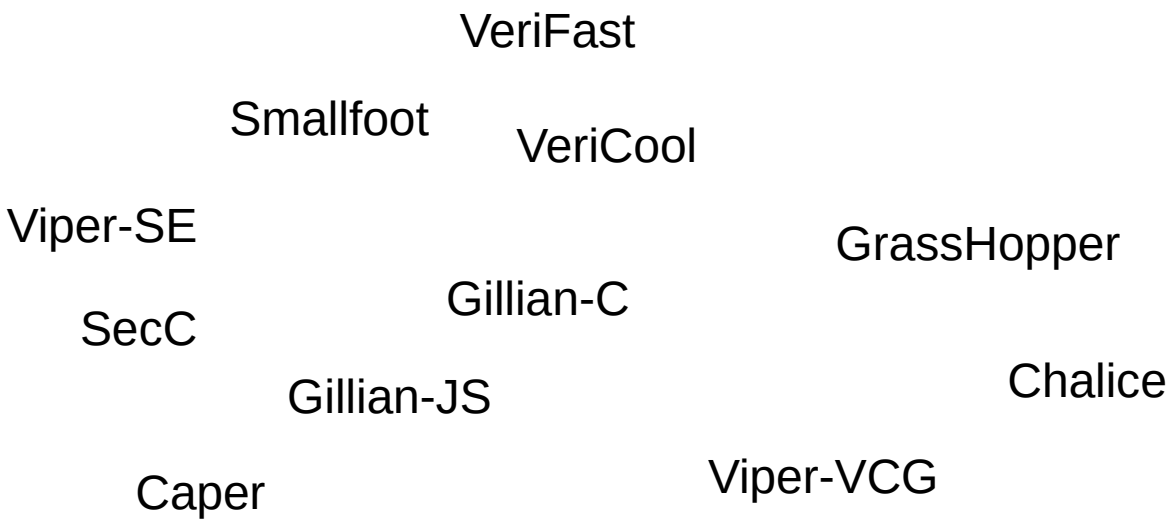


What verification algorithms exist
and
which is the best?

Automated Separation Logic Verification Tools



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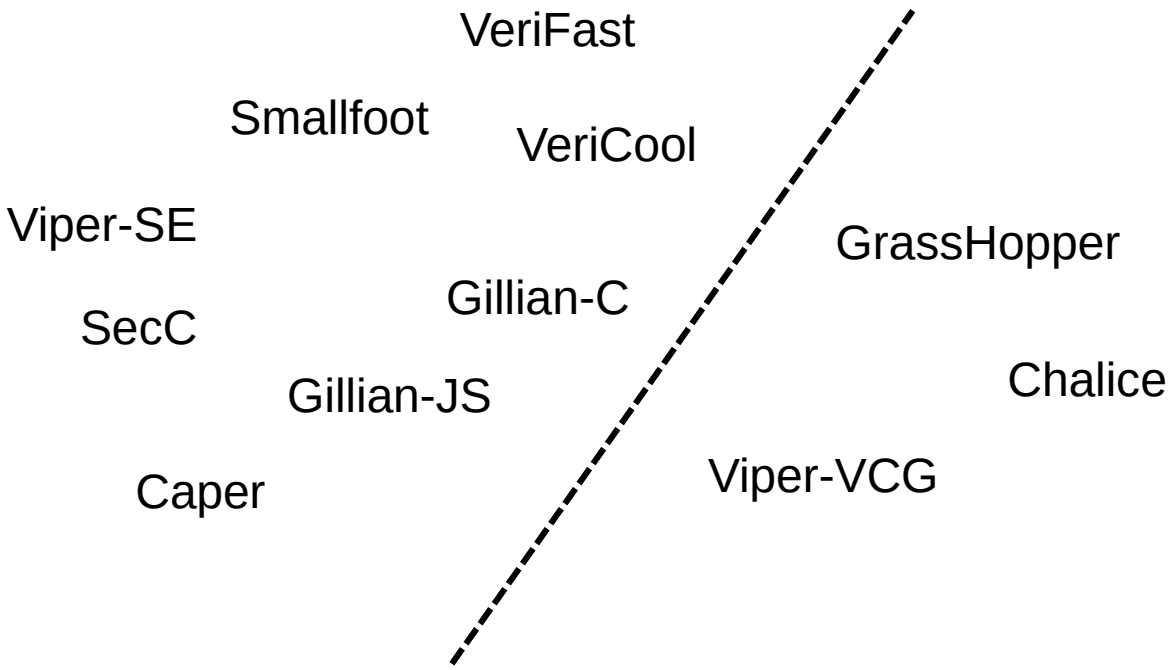

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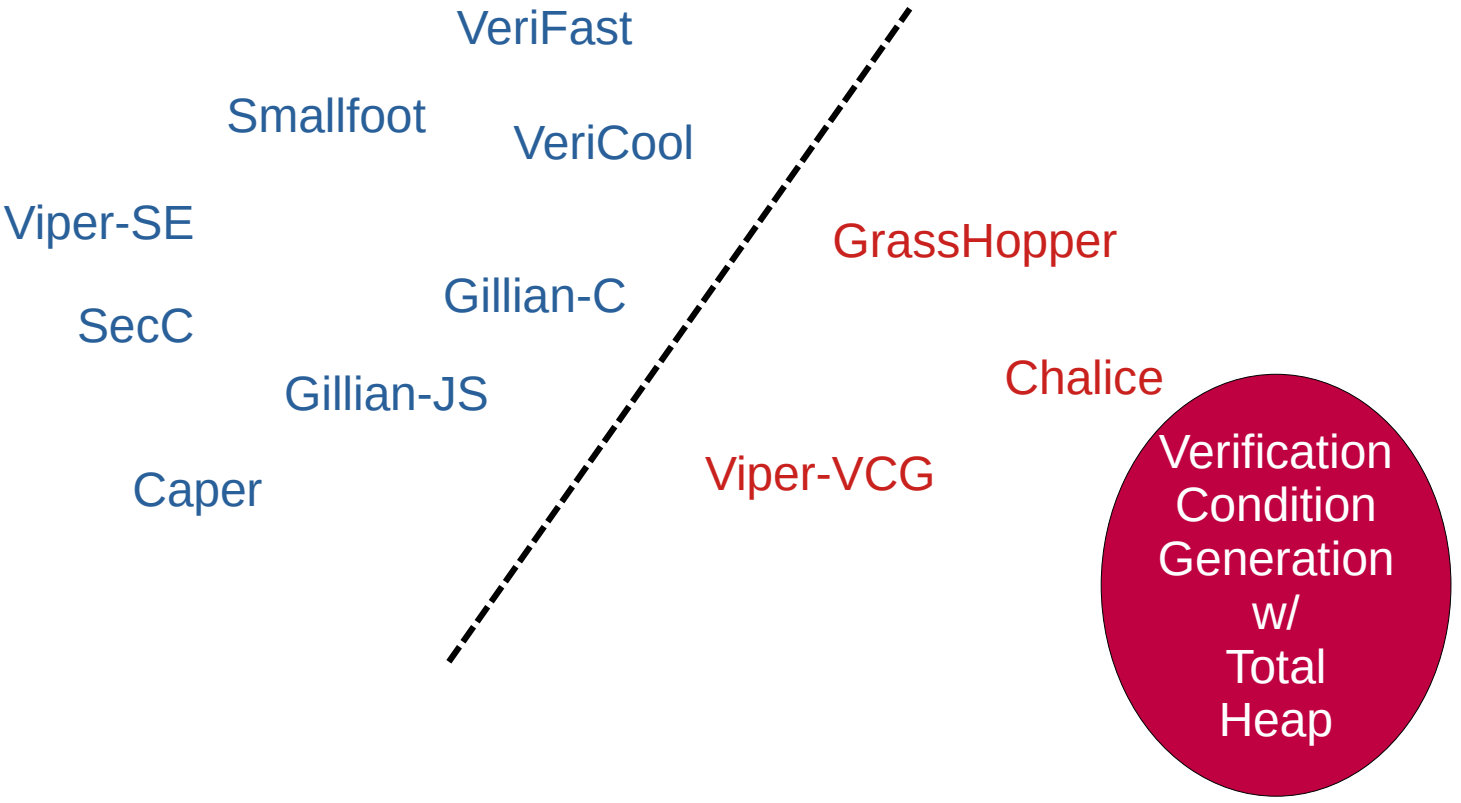

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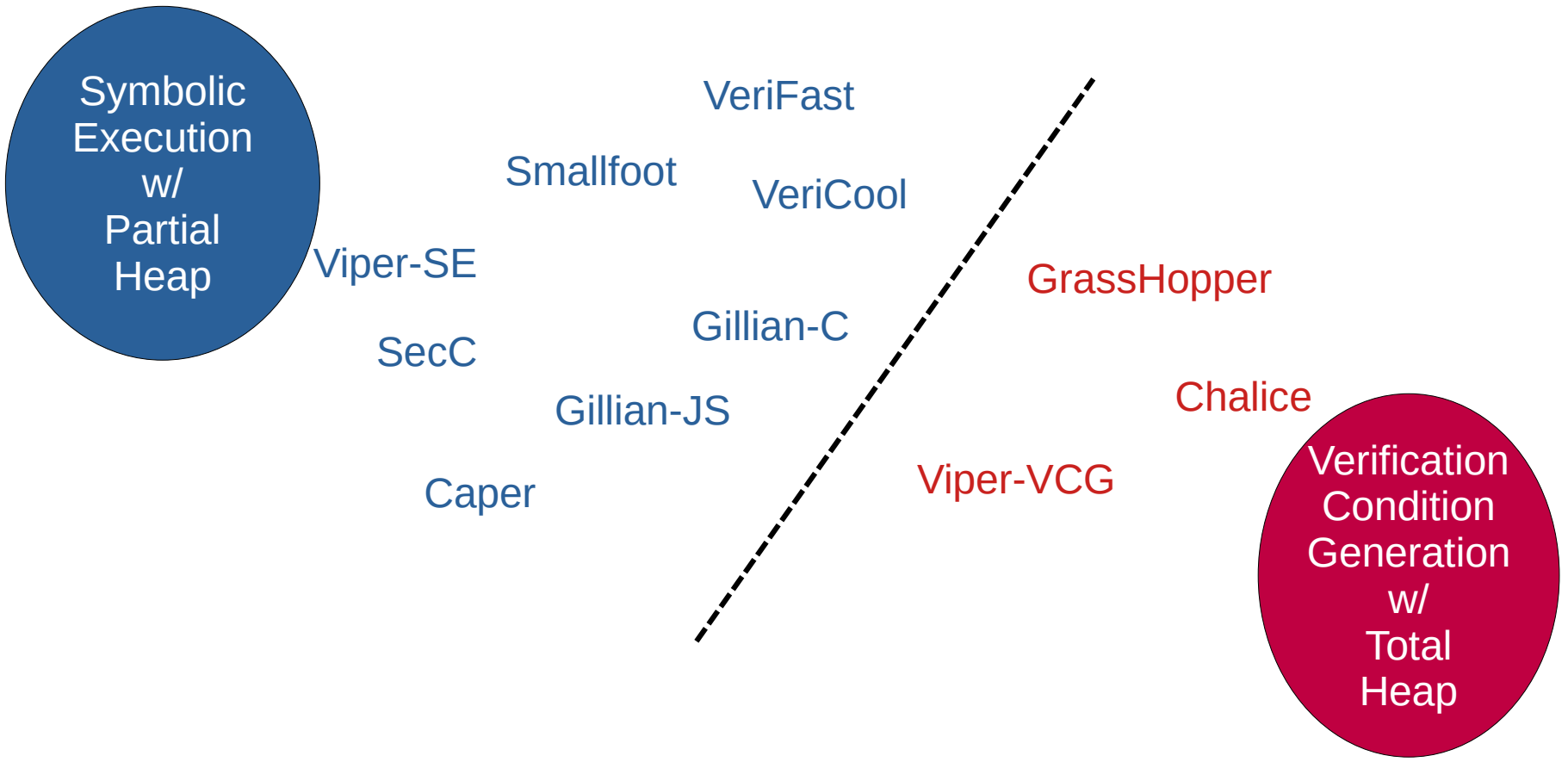

Contributions

- Survey of algorithms used in existing separation logic verifiers

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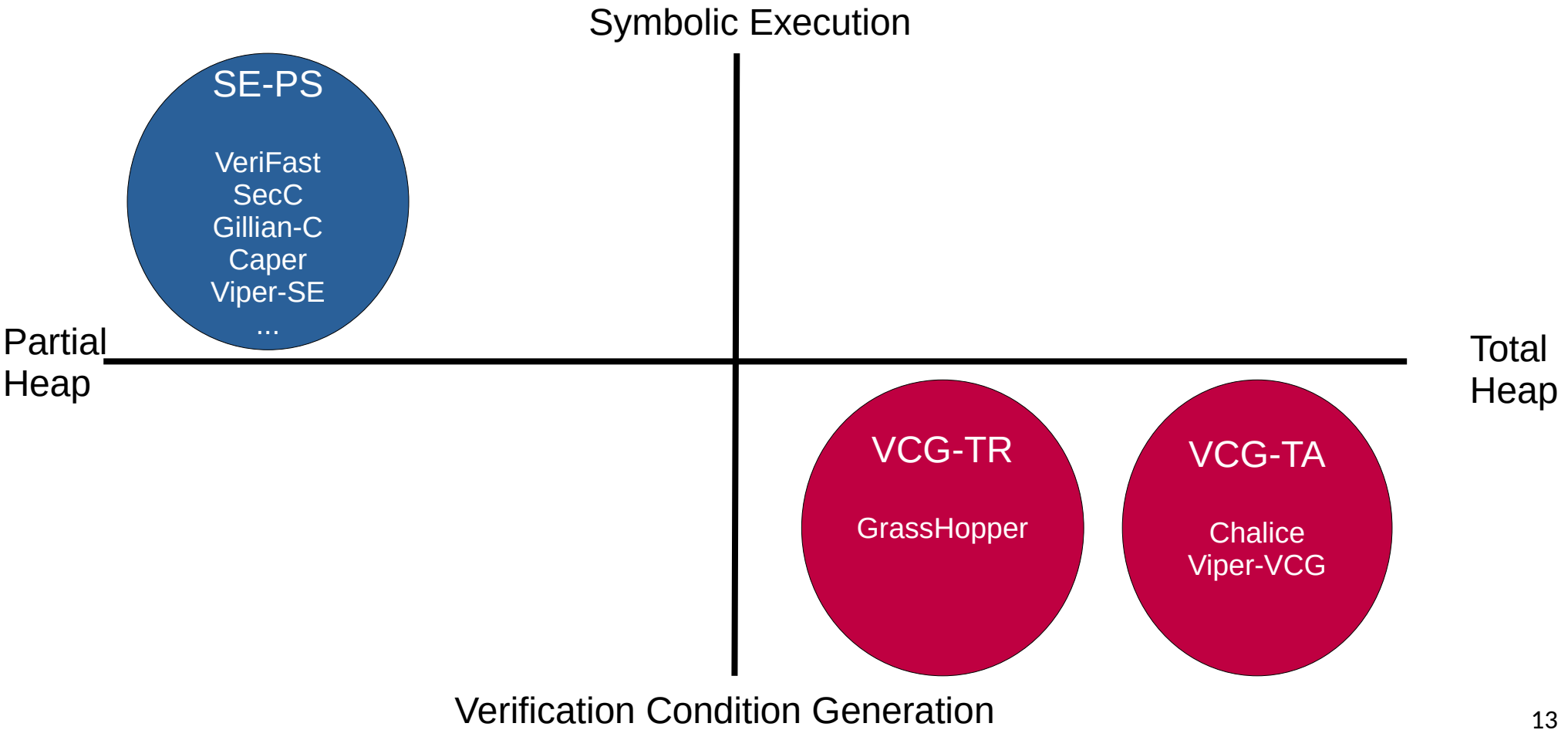
- Propose two new algorithms

Preview: Algorithm Comparison



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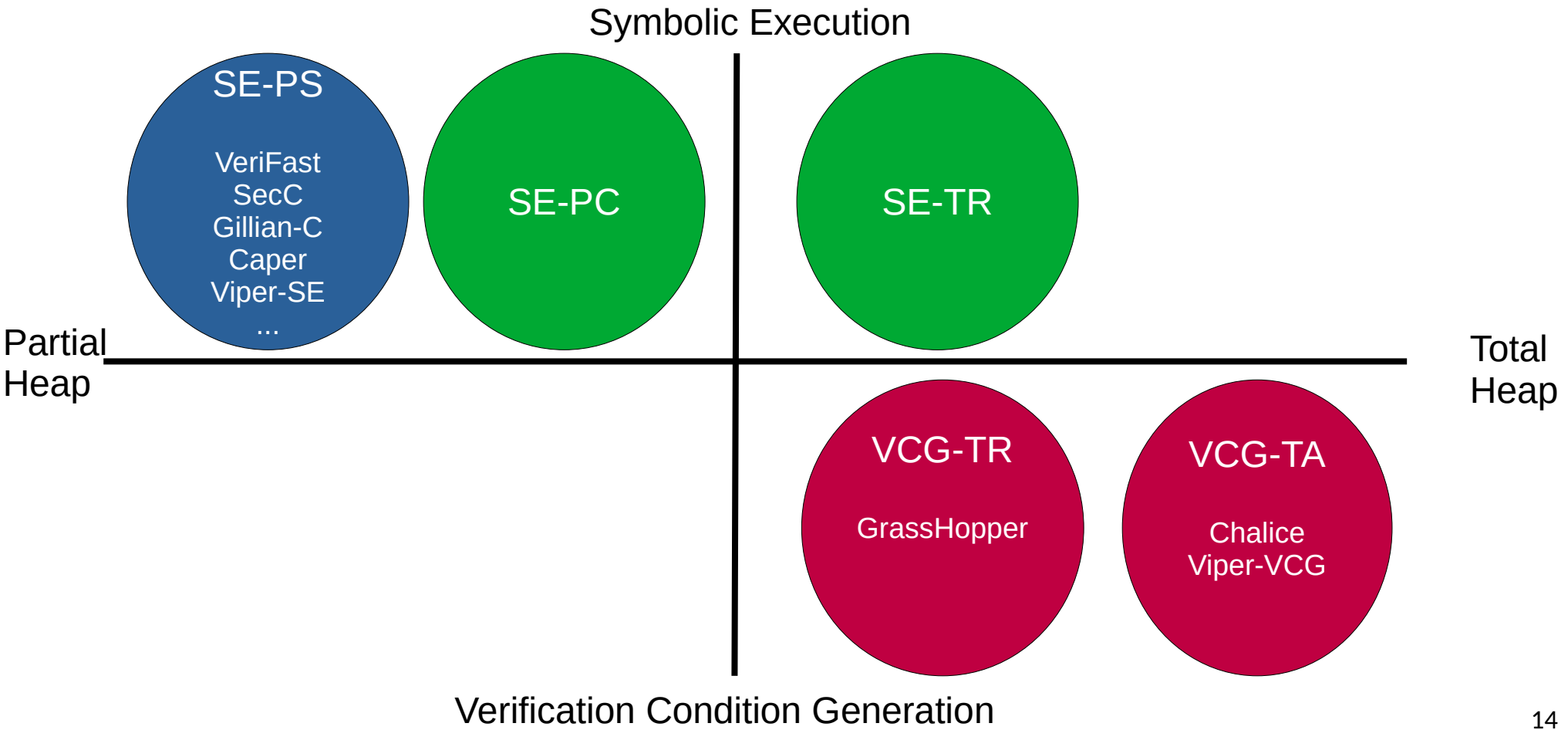

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  - Two already existed

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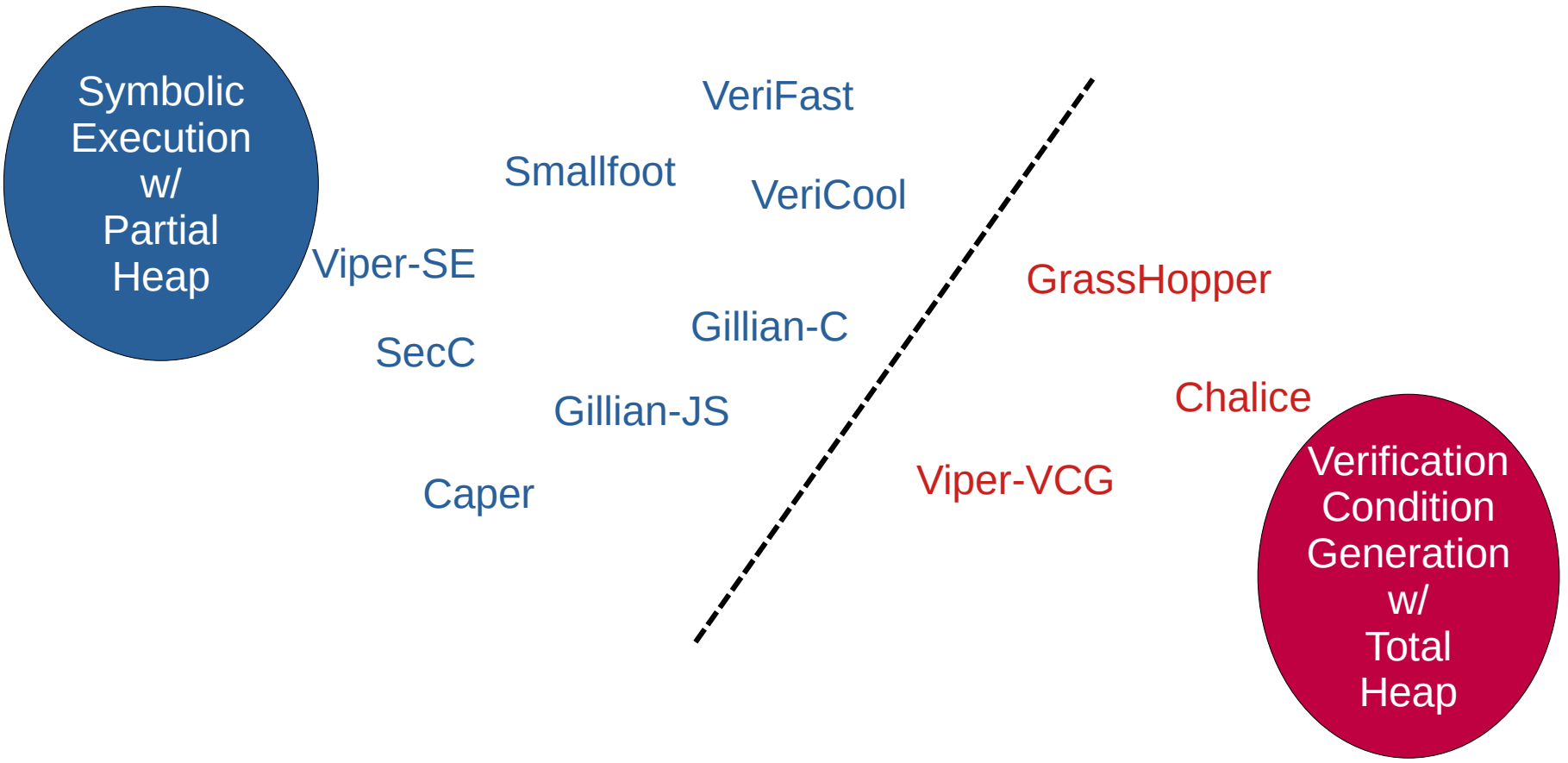
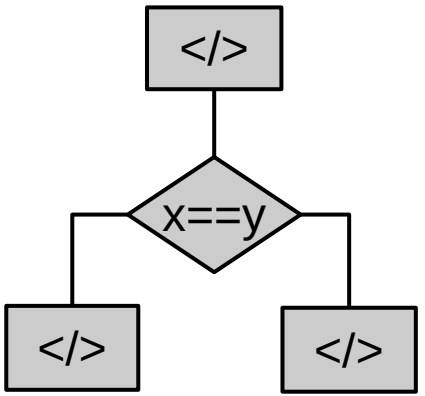
- Systematic empirical evaluation of completeness and performance

- Comparison of different portfolios

Automated Separation Logic Verification Tools



Verification Condition Generation (VCG)



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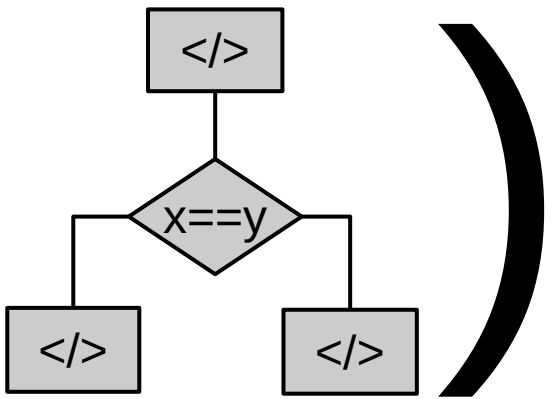
wp(

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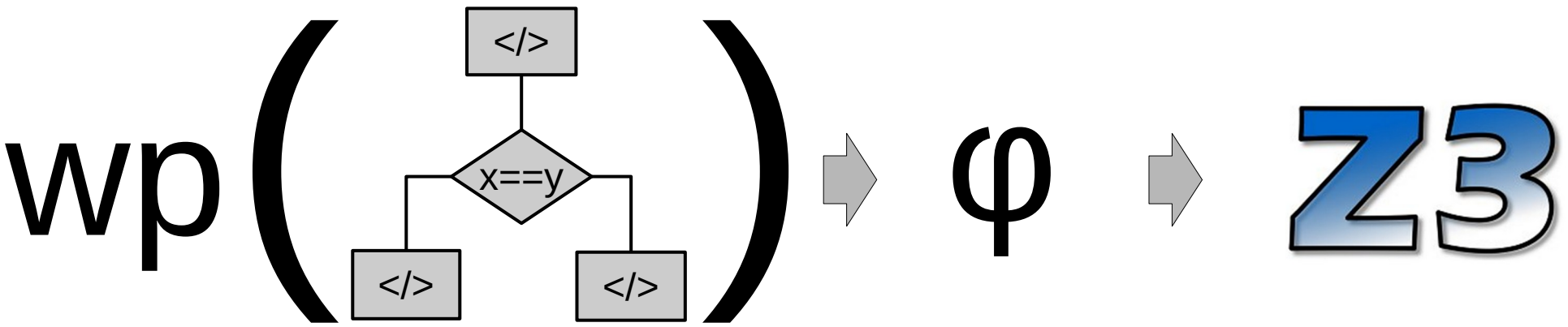
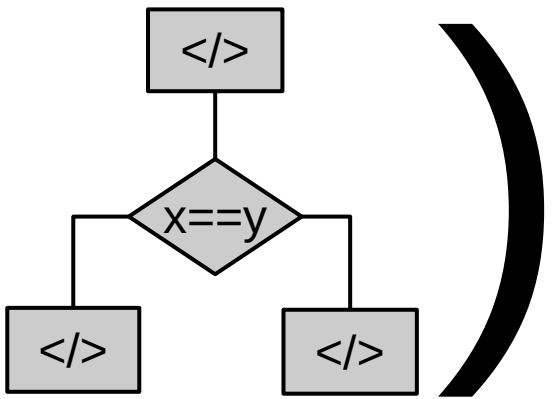
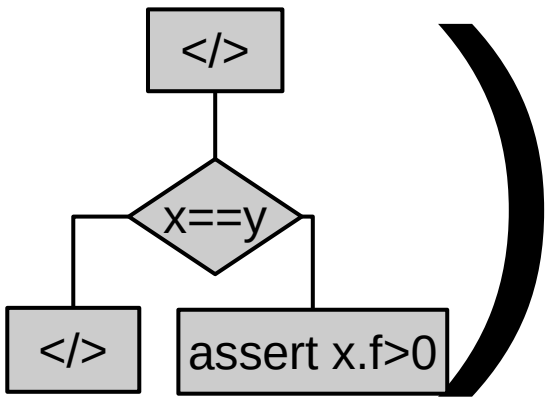


VCG with Total Heaps

wp(

) ⇨ φ ⇨ Z3

VCG with Total Heaps

wp(

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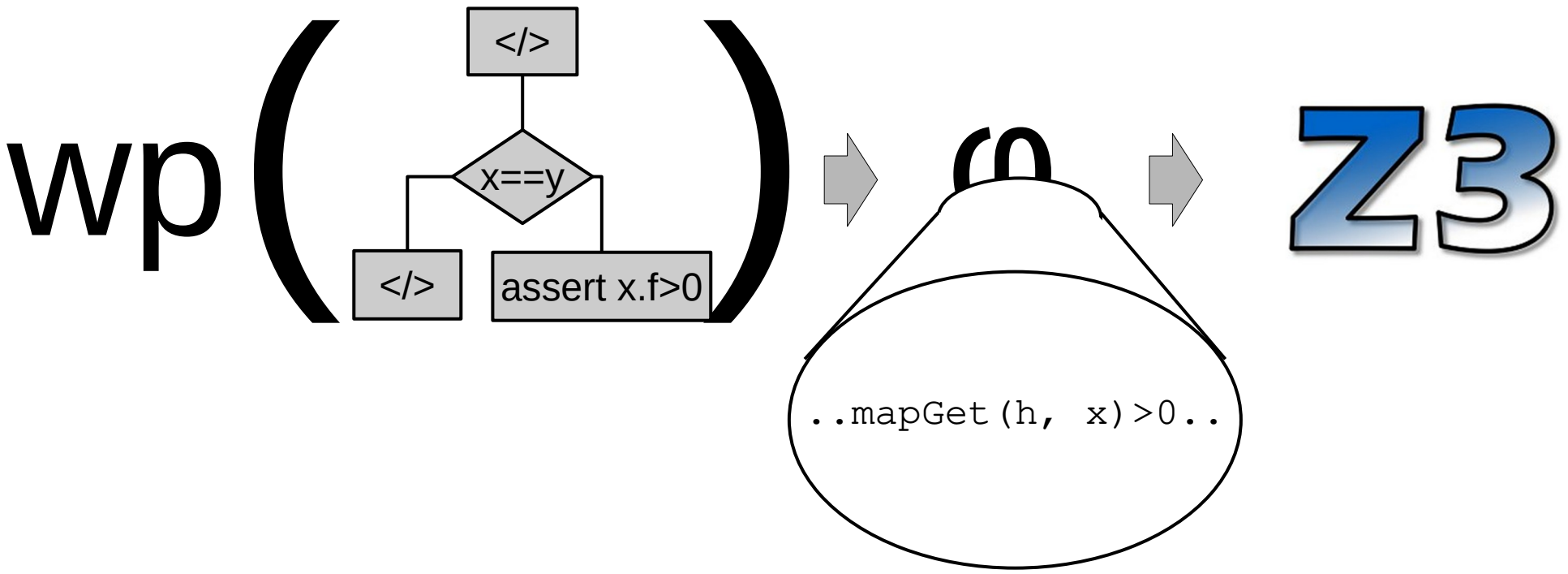

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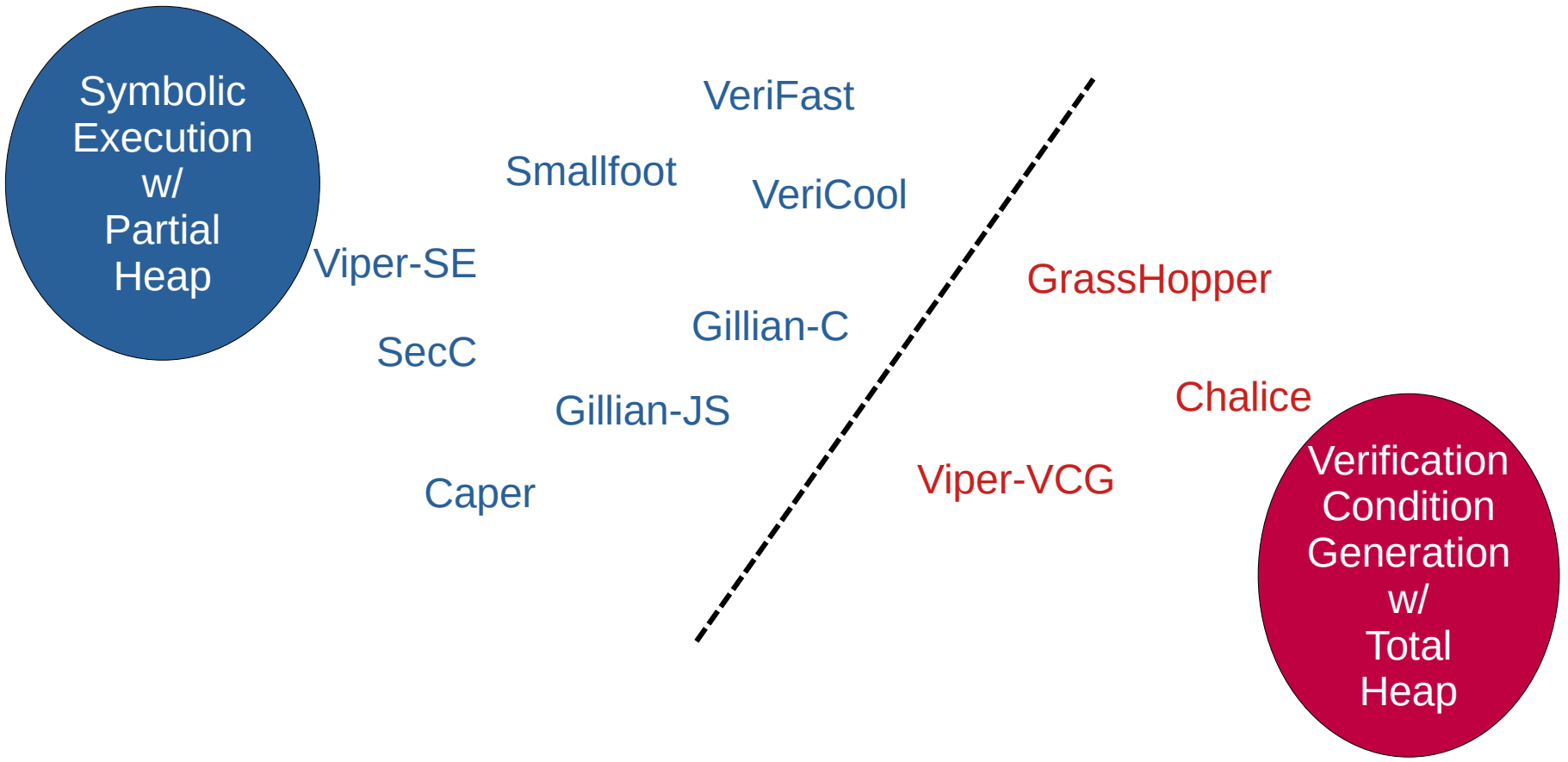
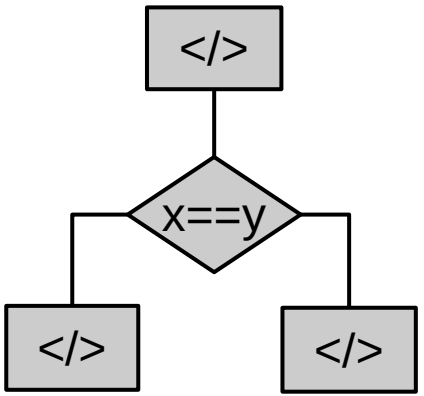


Symbolic Execution (SE)



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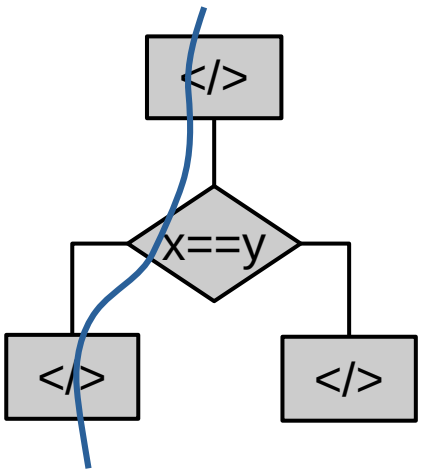
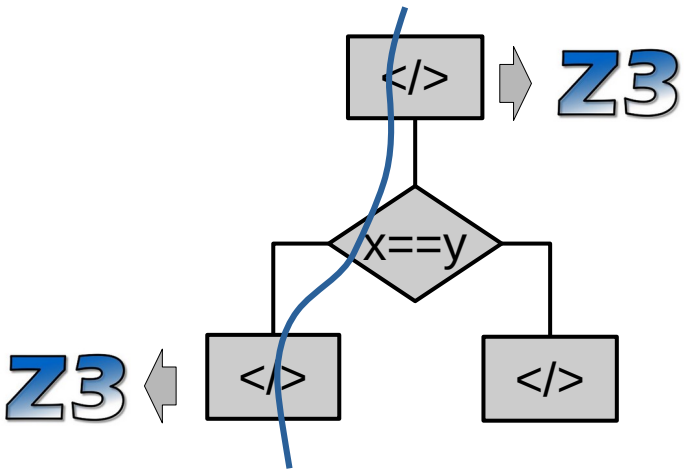


Store

```
X → x0
y → 1
```

Symbolic Execution (SE)



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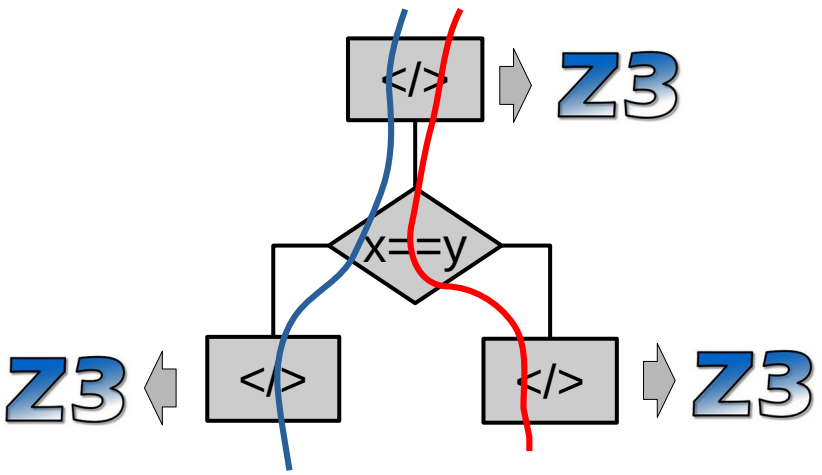

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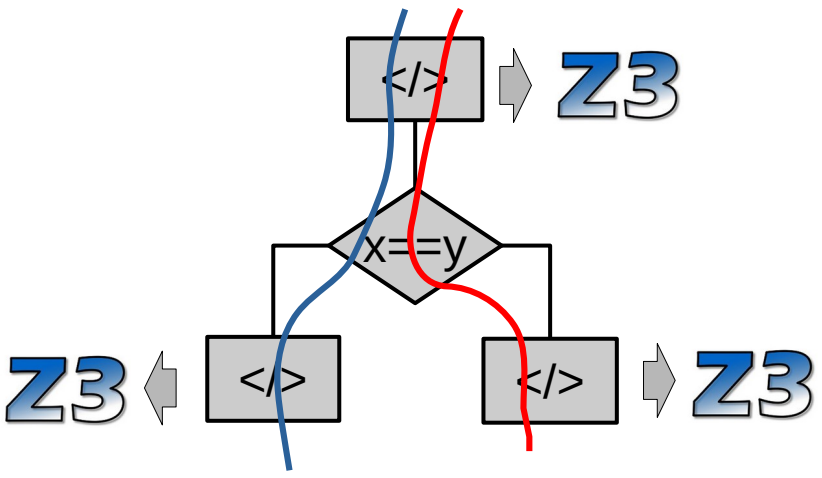
SE with Partial Heaps



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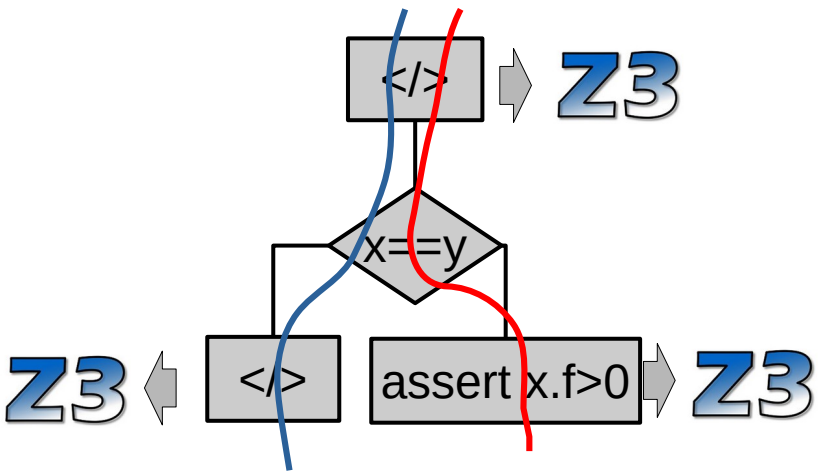
Heap

z0.f → v0

x0.f → v1

SE with Partial Heaps



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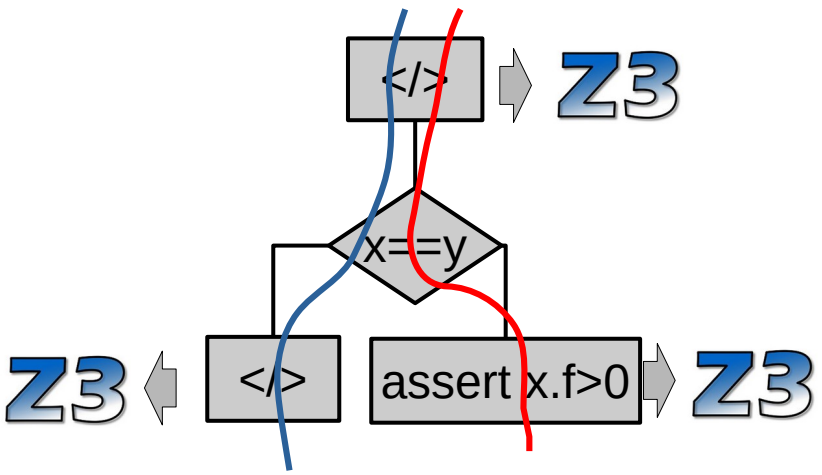

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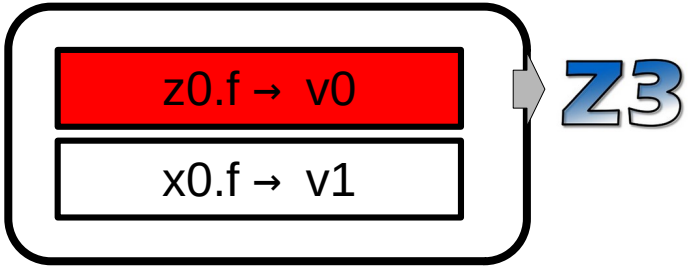

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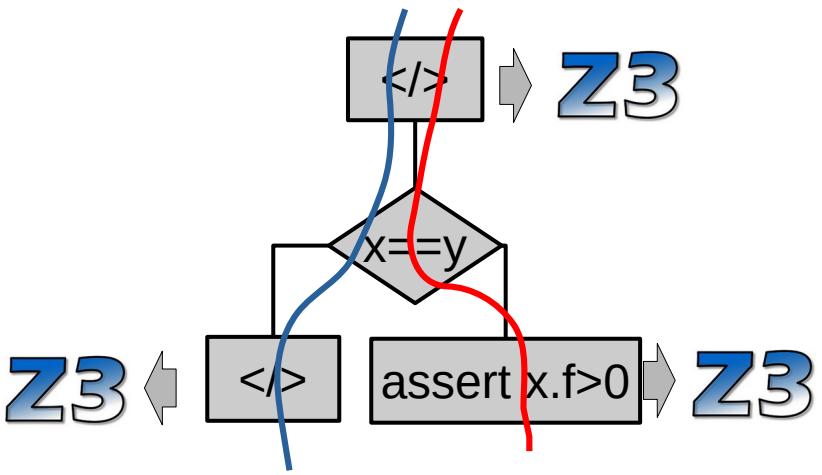

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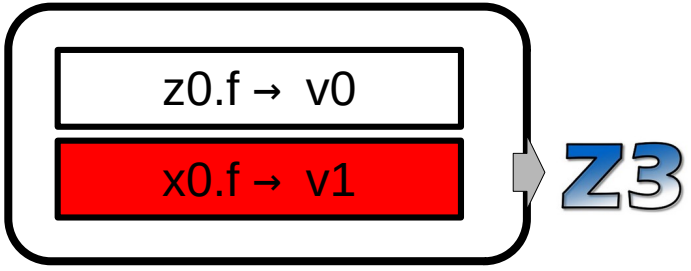

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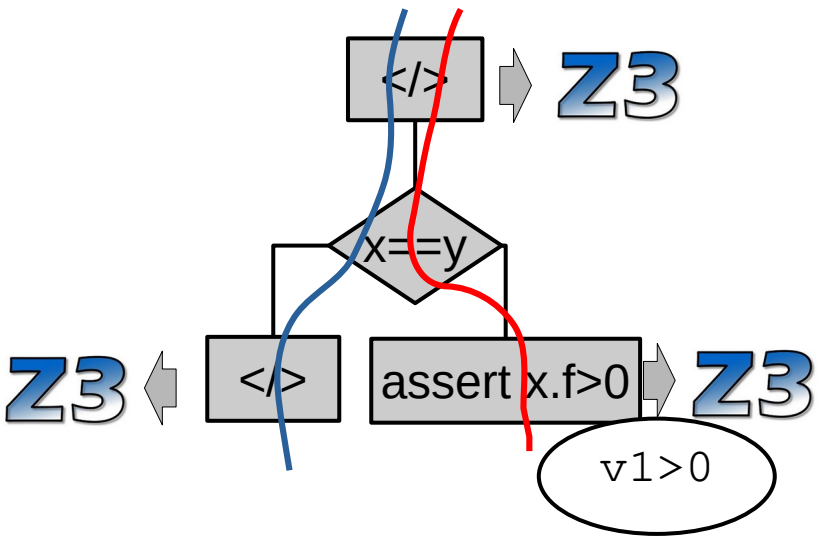

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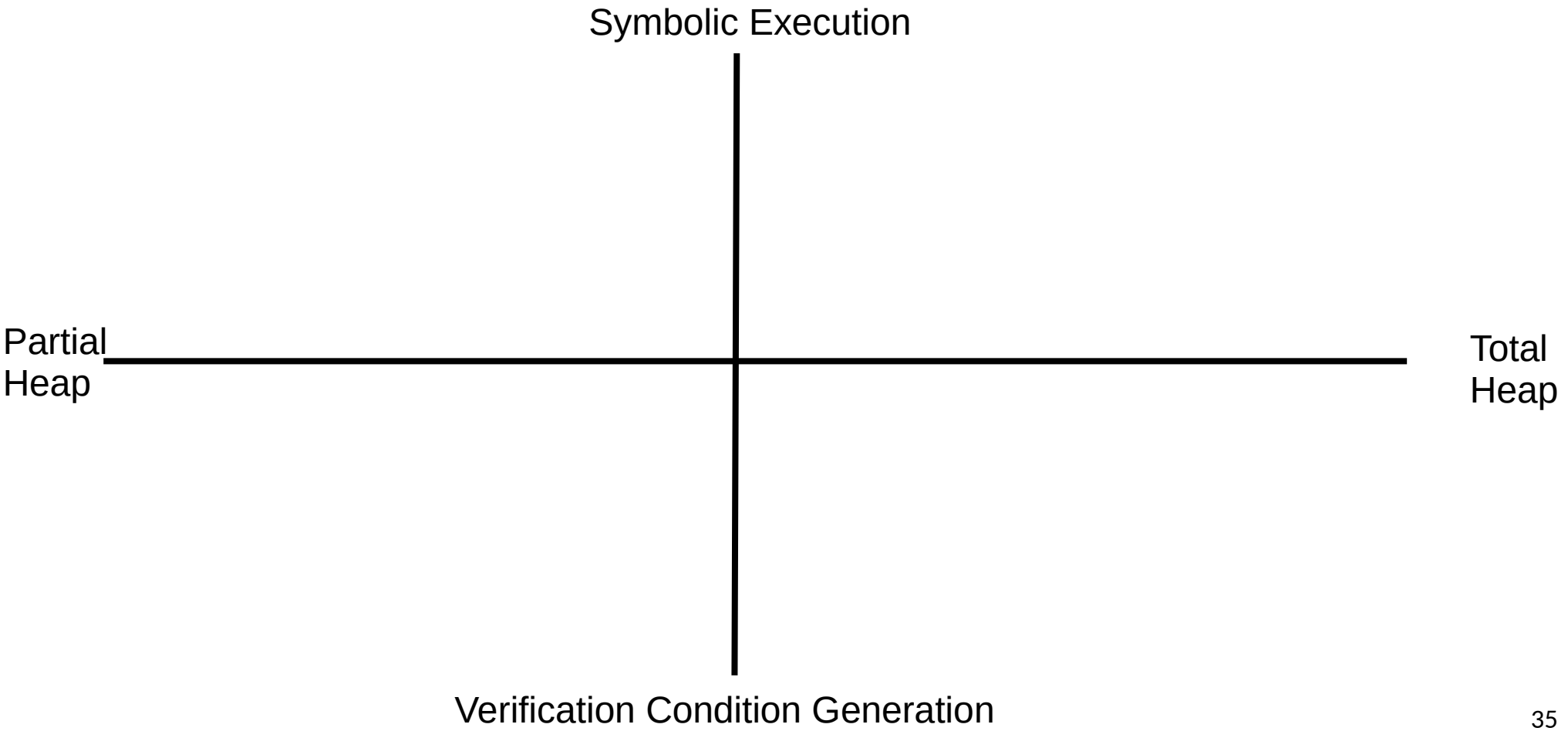

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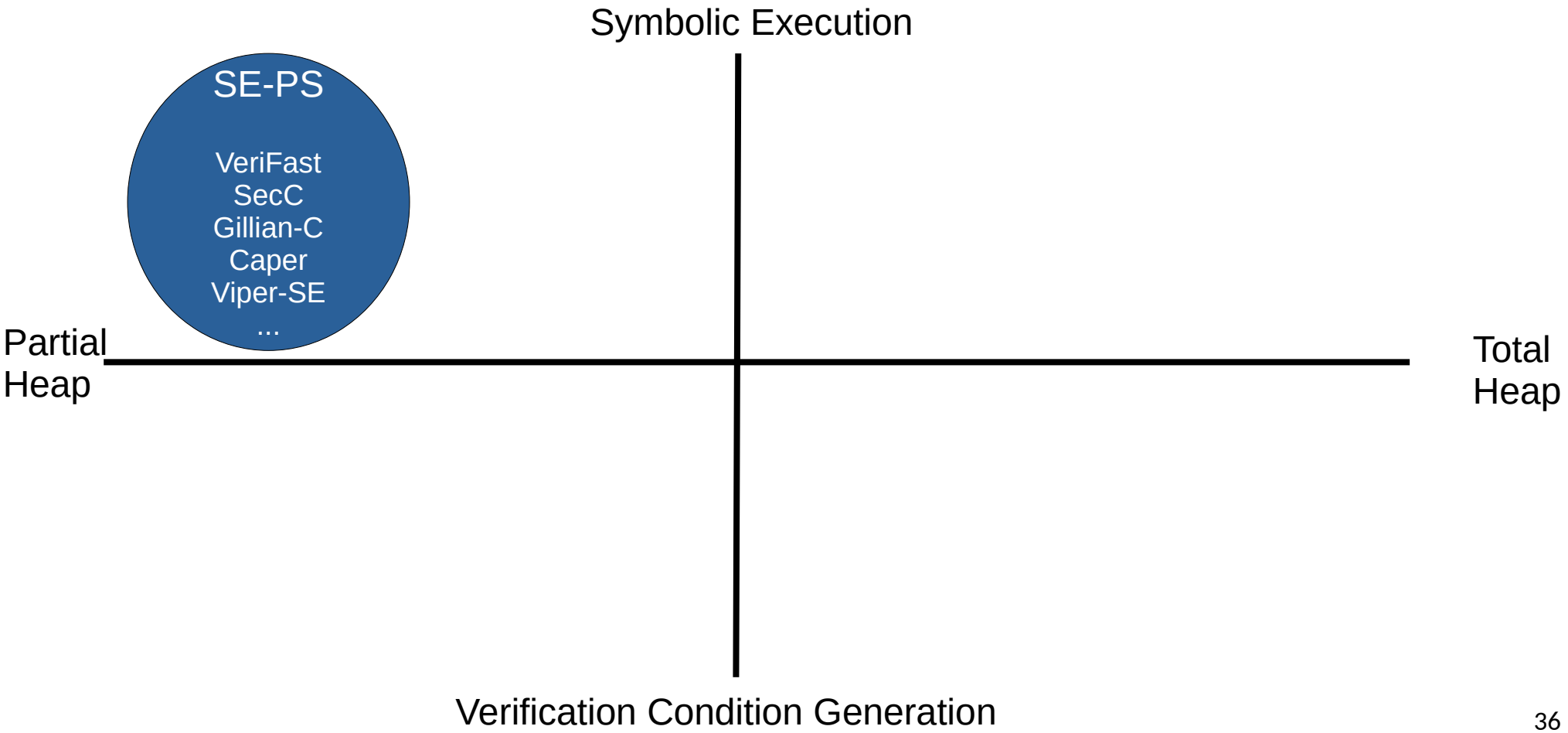

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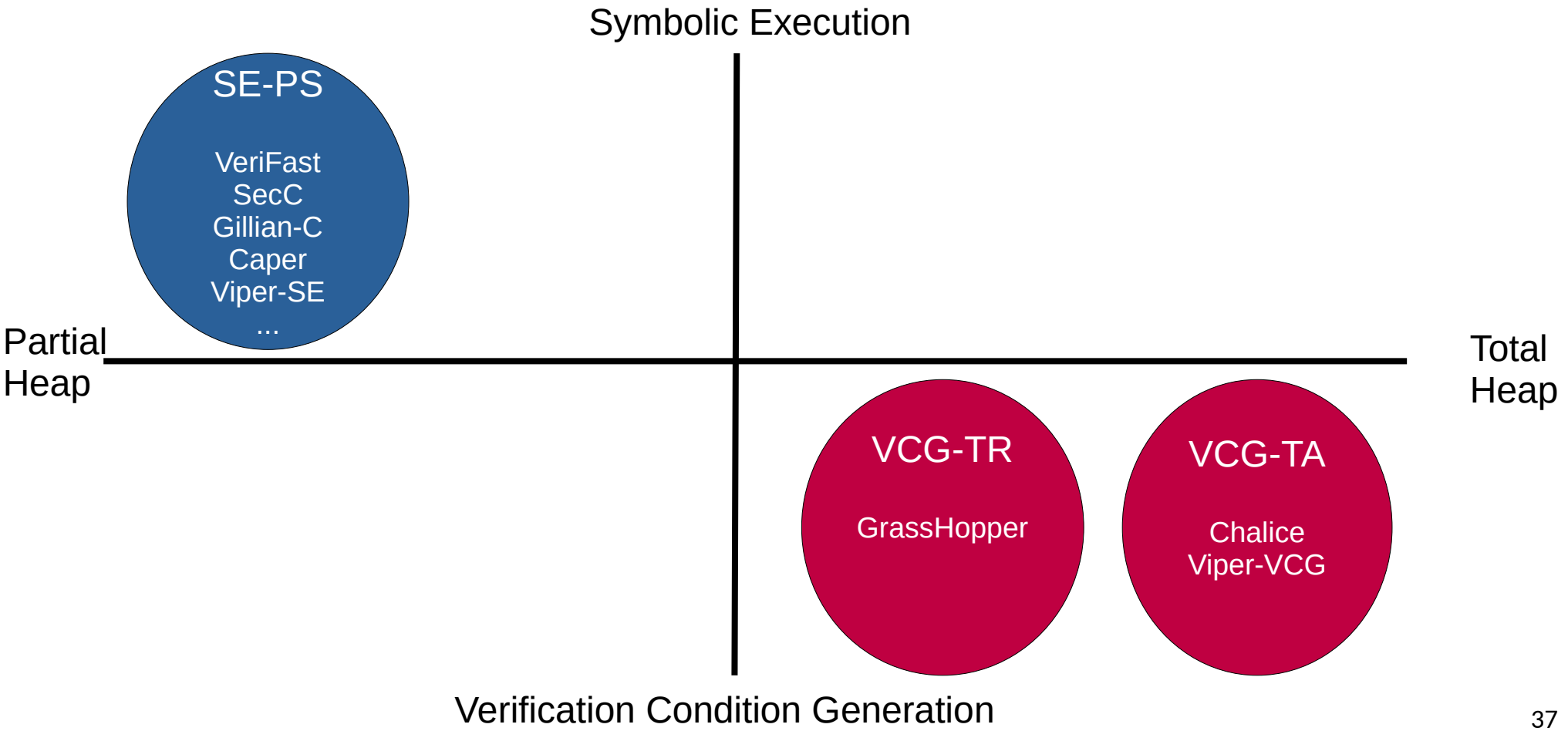

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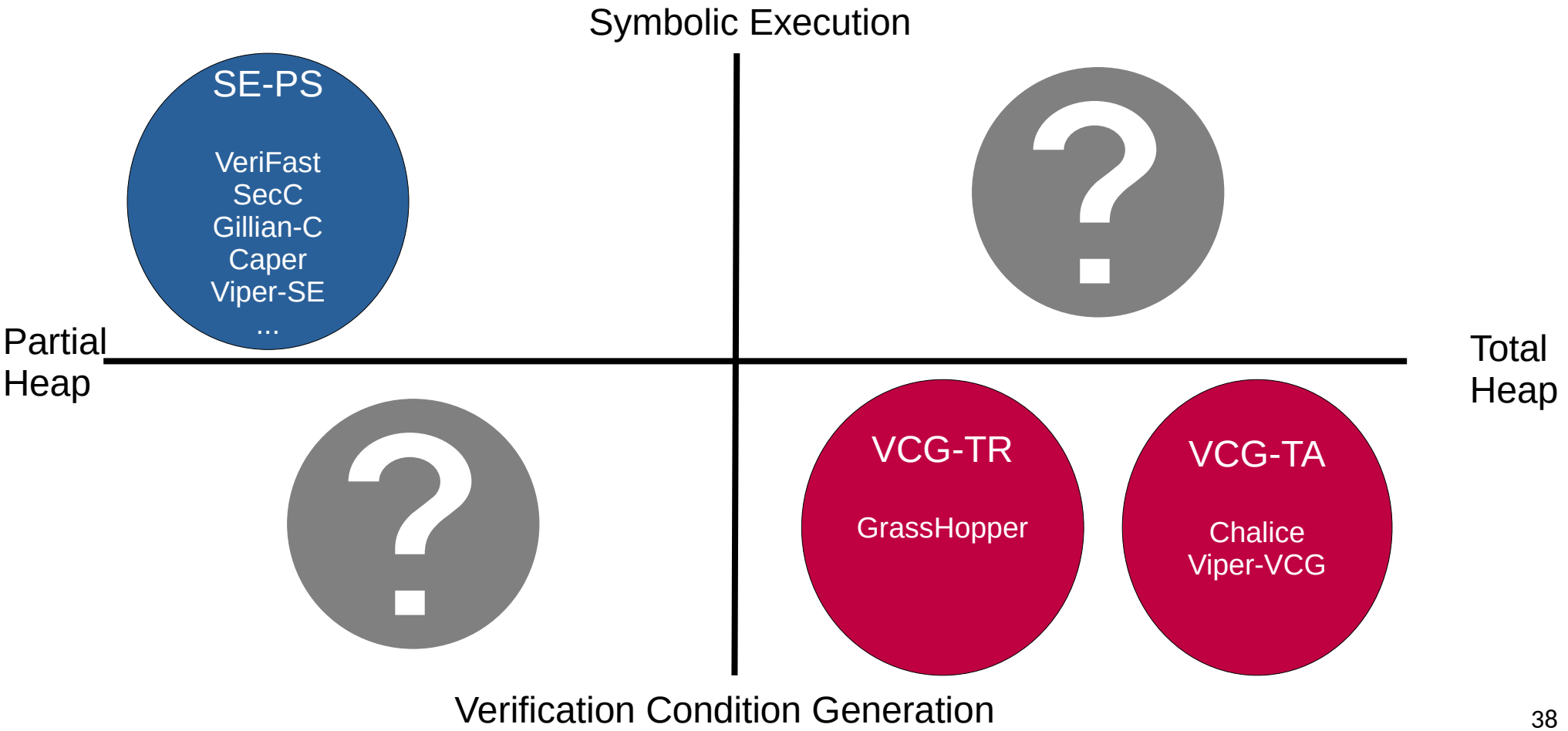

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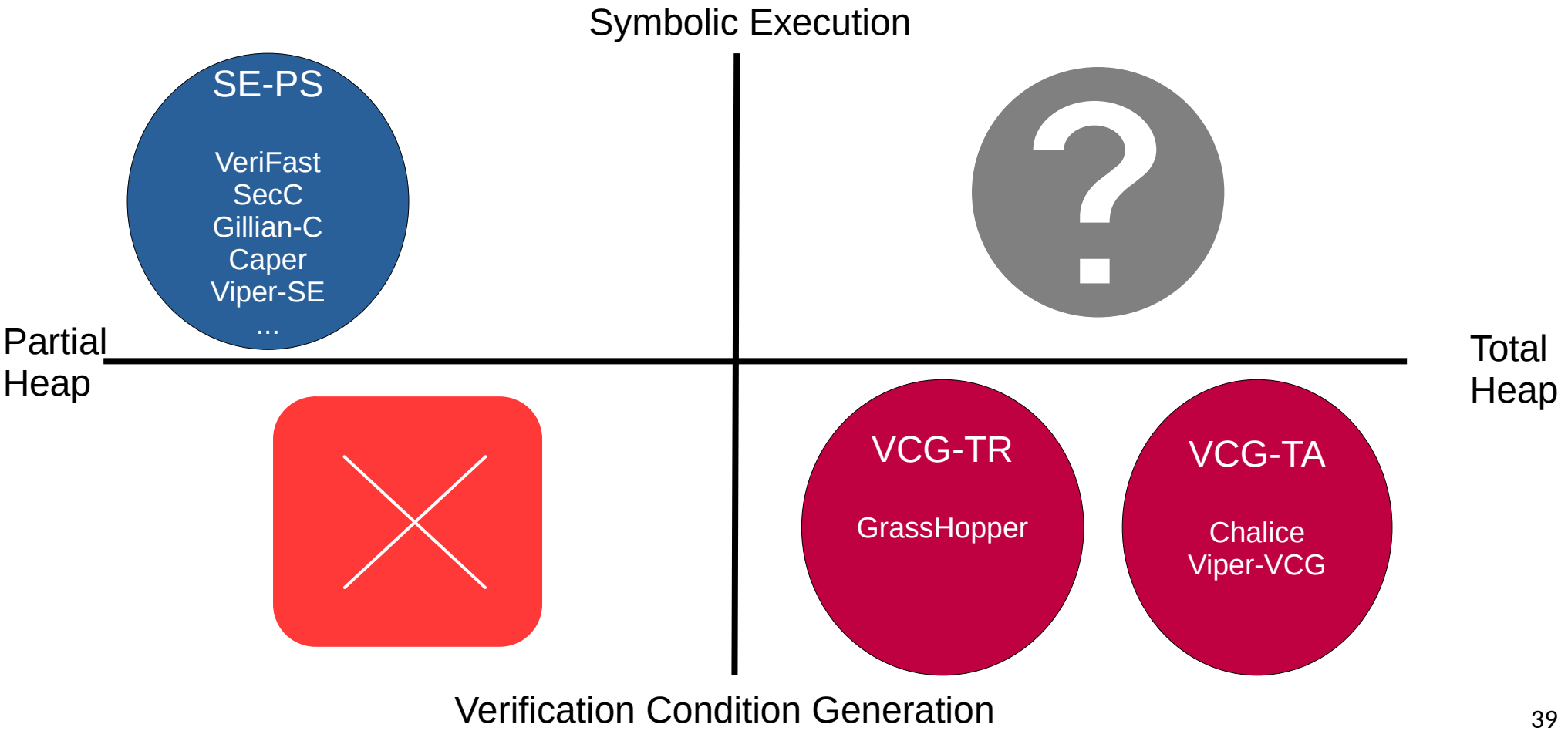

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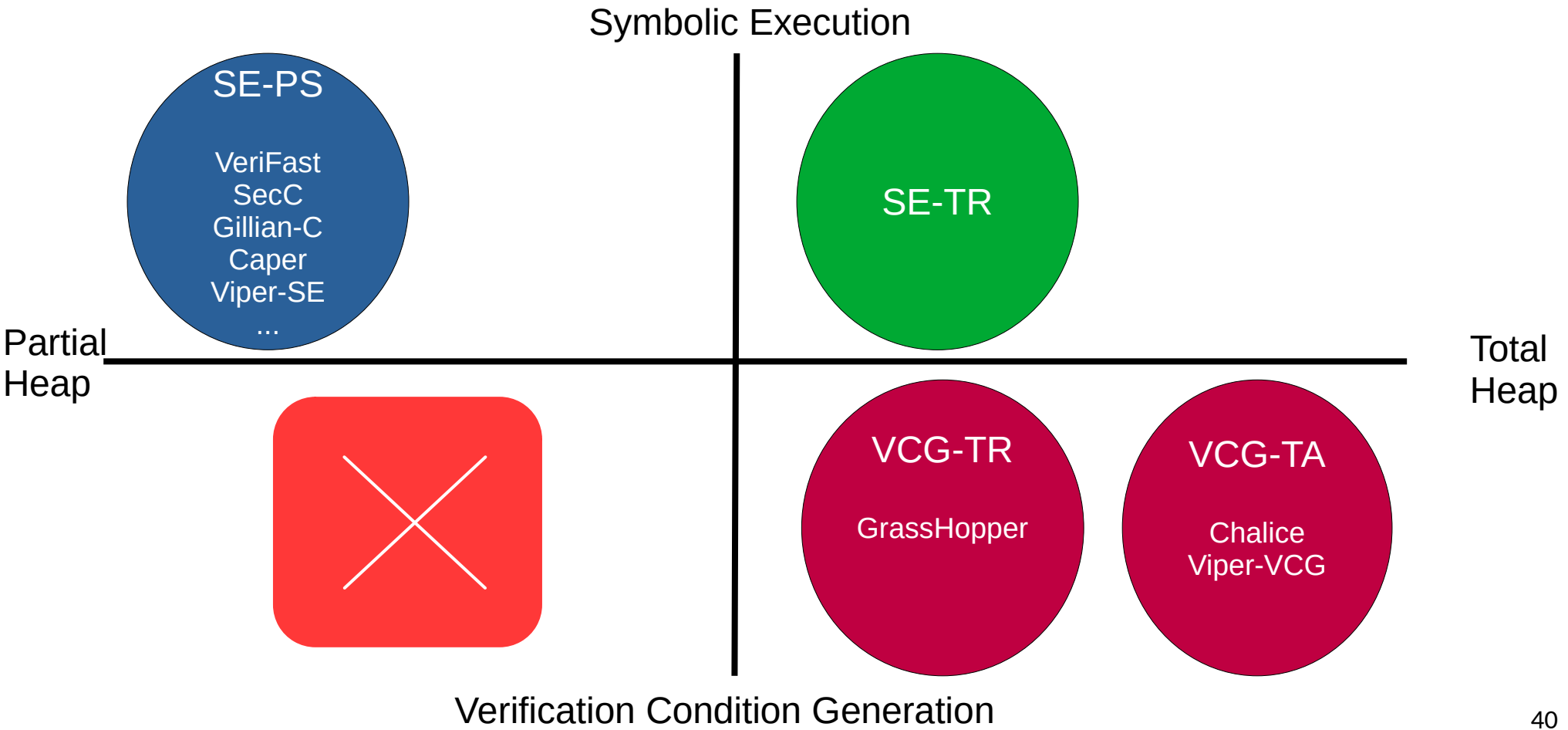
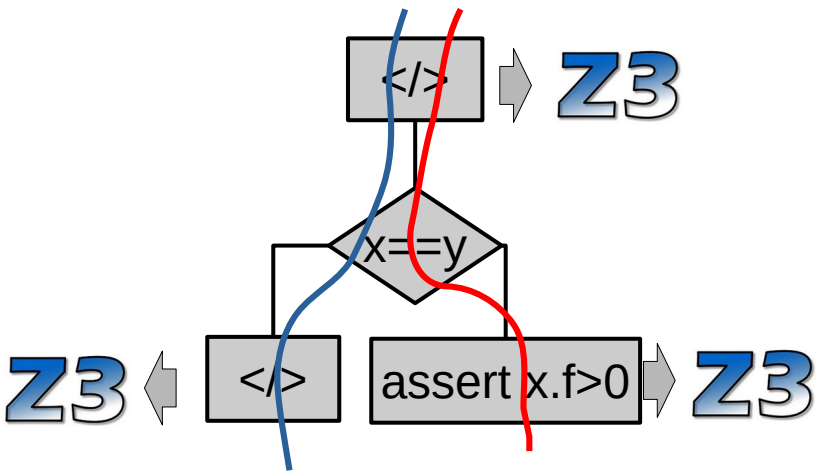


Symbolic Execution with Total Heaps



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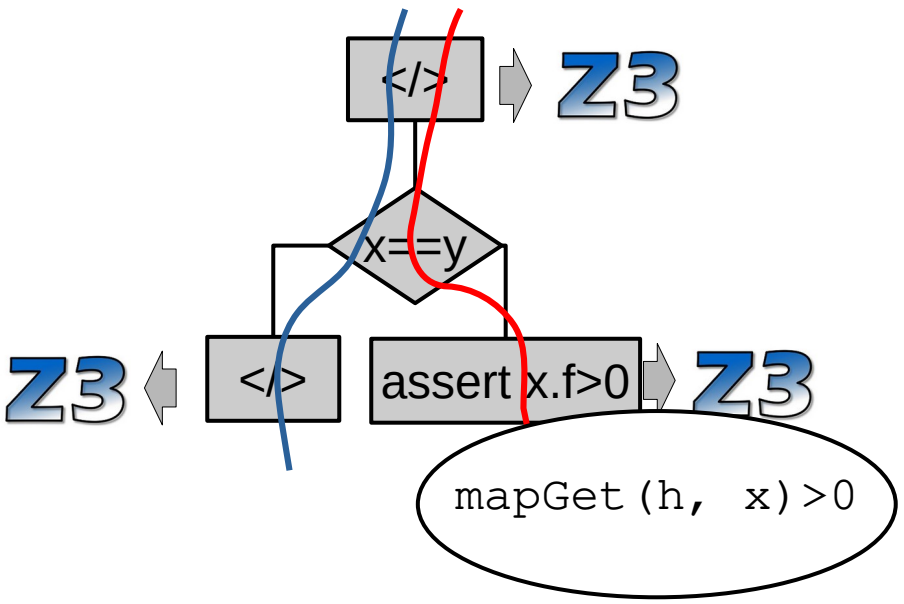

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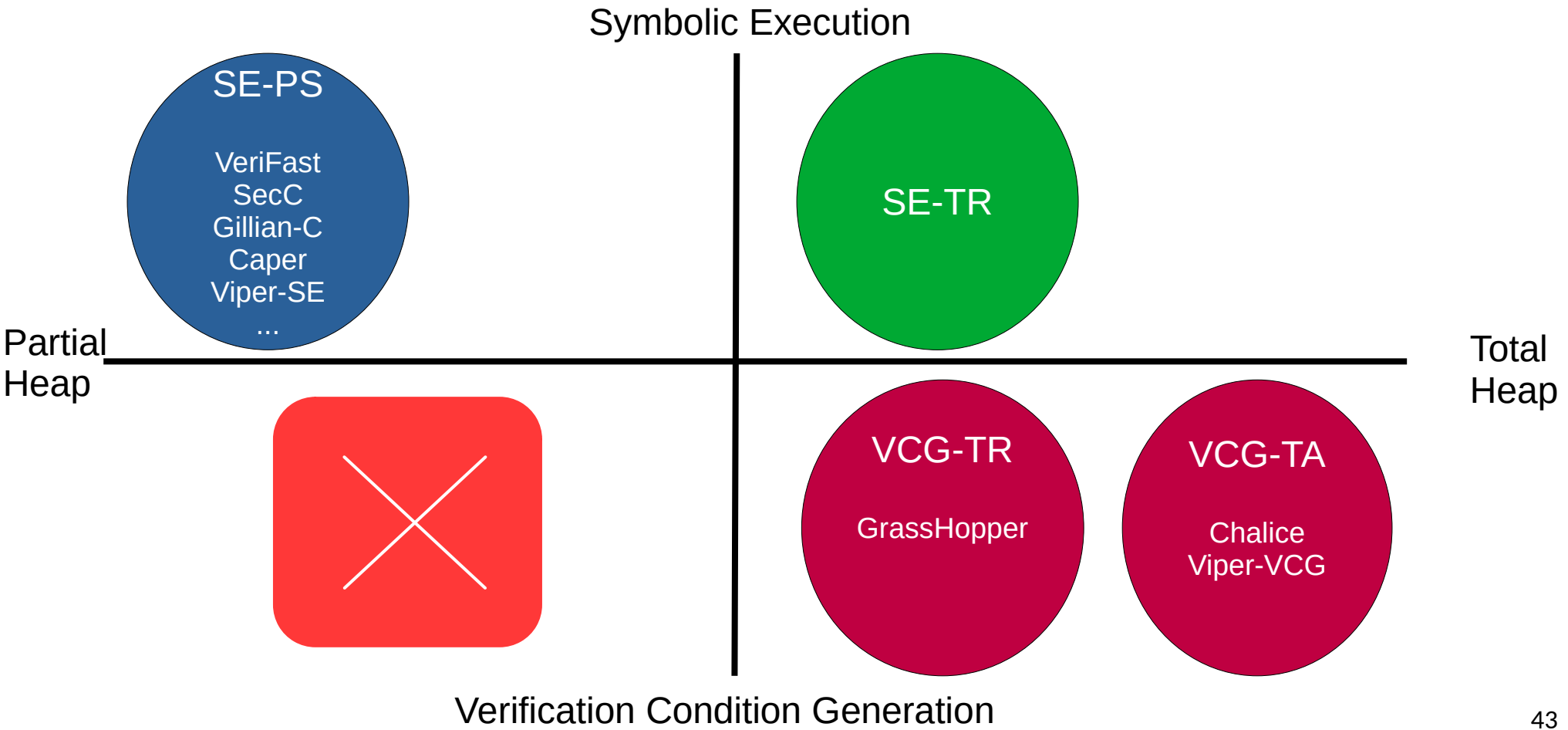

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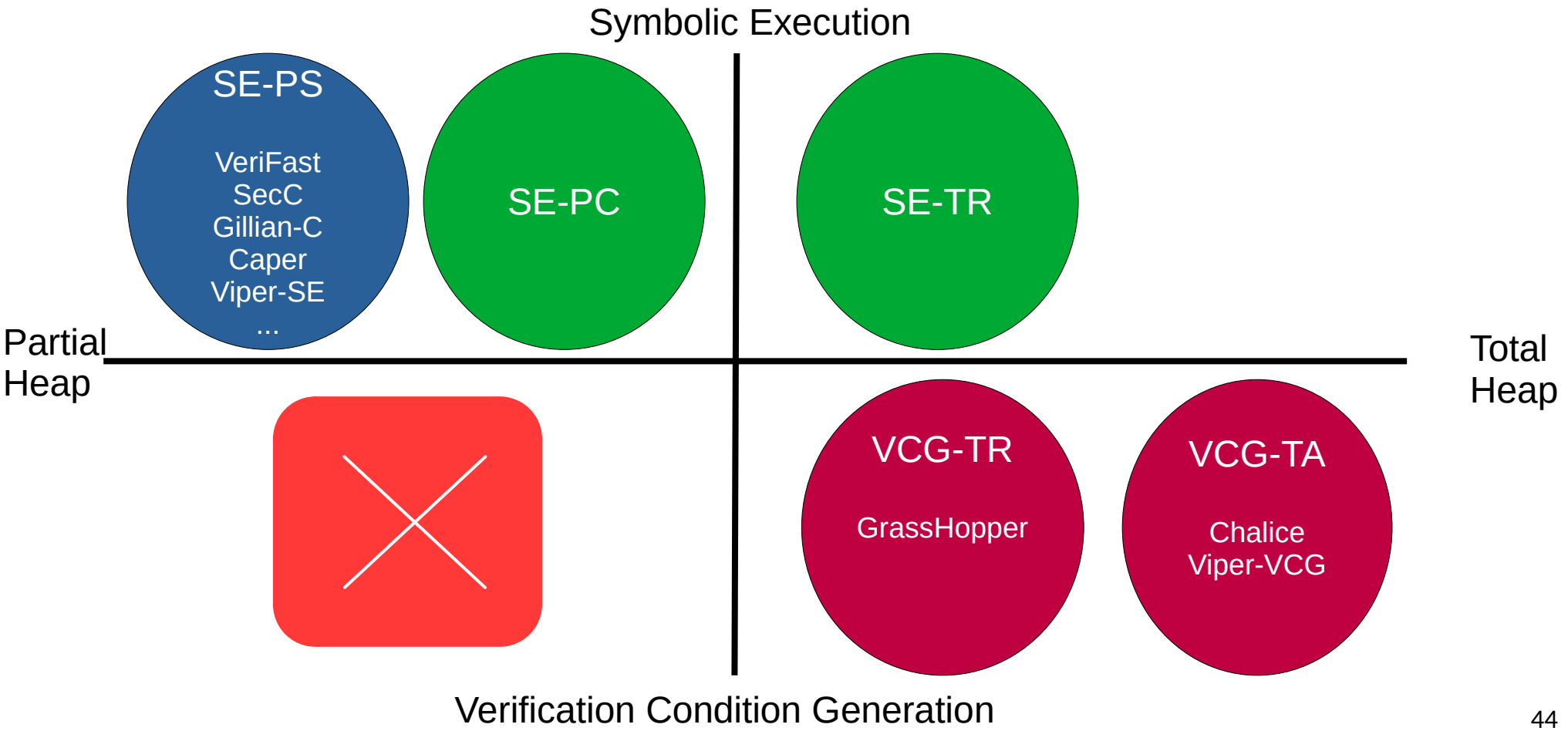

We implemented all five algorithms in Viper
and
benchmarked on large number of examples

Benchmark Example Groups

- Source language verifiers
  - Rust, Java, Go, Python, CUDA, smart contracts
- Program logics
  - Concurrent separation logic, RSL, TaDA
- Properties
  - Information flow security, hyperproperties, reachability
- Applications
  - Verification tutorials, competitions, complex case studies

- 537 examples of various sizes overall

Completeness Results

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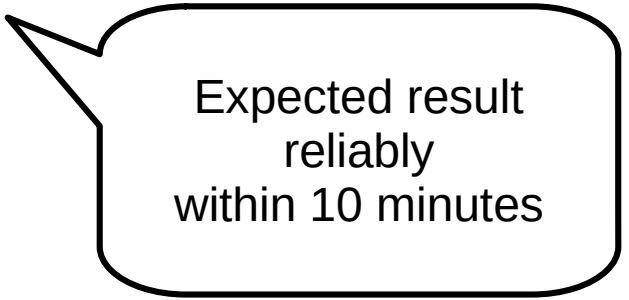

Completeness Results

	Σ	SE-PS	SE-PC	SE-TR	VCG-TR	VCG-TA
All	537	5.4	5.4	7.4	8.8	13.8
Ru_1	156	0.0	0.6	3.8	9.0	18.6
Ru_2	11	0.0	0.0	45.5	54.5	63.6
Go	11	18.2	0.0	18.2	0.0	0.0
Go_C	17	5.9	0.0	17.6	29.4	35.3
RSL	21	19.0	19.0	0.0	38.1	33.3
SC	8	0.0	0.0	0.0	0.0	0.0
SC_R	13	0.0	0.0	0.0	0.0	0.0
PP	38	0.0	0.0	0.0	0.0	0.0
Py	23	8.7	13.0	4.3	13.0	21.7
Py_P	18	16.7	11.1	11.1	5.6	5.6
Rea	16	93.8	93.8	37.5	12.5	18.8
Vi	46	2.2	2.2	4.3	4.3	8.7
Ve_C	19	0.0	10.5	42.1	10.5	10.5
Ve_V	5	0.0	0.0	20.0	20.0	0.0
Da_G	8	0.0	0.0	0.0	25.0	25.0
Da_V	41	0.0	0.0	0.0	0.0	0.0
Vo	34	2.9	2.9	11.8	0.0	20.6
Ru_3	52	0.0	0.0	0.0	1.9	1.9

Completeness Results

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Algorithms

Completeness Results

Two different Rust verifiers

					-TR	VCG-TA
A					8.8	13.8
Ru_1	15	0.0	0.6	3.8	9.0	18.6
Ru_2	11	0.0	0.0	45.5	54.5	63.6
Go	11	18.2	0.0	18.2	0.0	0.0
Go_C	17	5.9	0.0	17.6	29.4	35.3
RSL	21	19.0	19.0	0.0	38.1	33.3
SC	8	0.0	0.0	0.0	0.0	0.0
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Vo	34	2.9	2.9	11.8	0.0	20.6
Ru_3	52	0.0	0.0	0.0	1.9	1.9

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SC_R	13	0.0	0.0	0.0	0.0	0.0
PP	38	0.0	0.0	0.0	0.0	0.0
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Py_P	18	16.7	11.1	11.1	5.6	5.6
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Da_G	8	0.0	0.0	0.0	25.0	25.0
Da_V	41	0.0	0.0	0.0	0.0	0.0
Vo	34	2.9	2.9	11.8	0.0	20.6
Ru_3	52	0.0	0.0	0.0	1.9	1.9

Percentage of Ru2 examples for which SE-TR was incomplete

Completeness Results

	Σ	SE-PS	SE-PC	SE-TR	VCG-TR	VCG-TA
All	537	5.4	5.4	7.4	8.8	13.8
Ru_1	156	0.0	0.6	3.8	9.0	18.6
Ru_2	11	0.0	0.0	45.5	54.5	63.6
Go	11	18.2	0.0	18.2	0.0	0.0
Go_C	17	5.9	0.0	17.6	29.4	35.3
RSL	21	19.0	19.0	0.0	38.1	33.3
SC	8	0.0	0.0	0.0	0.0	0.0
SC_R	13	0.0	0.0	0.0	0.0	0.0
PP	38	0.0	0.0	0.0	0.0	0.0
Py	23	8.7	13.0	4.3	13.0	21.7
Py_P	18	16.7	11.1	11.1	5.6	5.6
Rea	16	93.8	93.8	37.5	12.5	18.8
Vi	46	2.2	2.2	4.3	4.3	8.7
Ve_C	19	0.0	10.5	42.1	10.5	10.5
Ve_V	5	0.0	0.0	20.0	20.0	0.0
Da_G	8	0.0	0.0	0.0	25.0	25.0
Da_V	41	0.0	0.0	0.0	0.0	0.0
Vo	34	2.9	2.9	11.8	0.0	20.6
Ru_3	52	0.0	0.0	0.0	1.9	1.9

SE-algorithms perform best overall

Completeness Results

	Σ	SE-PS	SE-PC	SE-TR	VCG-TR	VCG-TA
All	537	5.4	5.4	7.4	8.8	13.8
Ru_1	156	0.0	0.6	3.8	9.0	18.6
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Go_C	17	5.9	0.0	17.6	29.4	35.3
RSL	21	19.0	19.0	0.0	38.1	33.3
SC	8	0.0	0.0	0.0	0.0	0.0
SC_R	13	0.0	0.0	0.0	0.0	0.0
PP	38	0.0	0.0	0.0	0.0	0.0
Py	23	8.7	13.0	4.3	13.0	21.7
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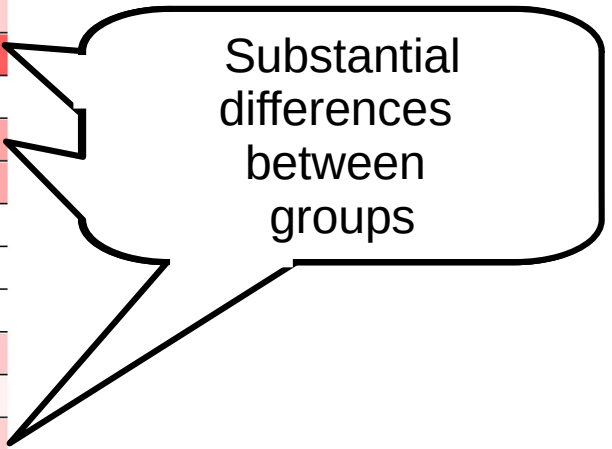
Da_G	8	0.0	0.0	0.0	25.0	25.0
Da_V	41	0.0	0.0	0.0	0.0	0.0
Vo	34	2.9	2.9	11.8	0.0	20.6
Ru_3	52	0.0	0.0	0.0	1.9	1.9



Completeness Tendencies

	Σ	SE-PS	SE-PC	SE-TR	VCG-TR	VCG-TA
All	537	5.4	5.4	7.4	8.8	13.8
Ru_1	156	0.0	0.6	3.8	9.0	18.6
Ru_2	11	0.0	0.0	45.5	54.5	63.6
Go	11	18.2	0.0	18.2	0.0	0.0
Go_C	17	5.9	0.0	17.6	29.4	35.3
RSL	21	19.0	19.0	0.0	38.1	33.3
SC	8	0.0	0.0	0.0	0.0	0.0
SC_R	13	0.0	0.0	0.0	0.0	0.0
PP	38	0.0	0.0	0.0	0.0	0.0
Py	23	8.7	13.0	4.3	13.0	21.7
Py_P	18	16.7	11.1	11.1	5.6	5.6
Rea	16	93.8	93.8	37.5	12.5	18.8
Vi	46	2.2	2.2	4.3	4.3	8.7
Ve_C	19	0.0	10.5	42.1	10.5	10.5
Ve_V	5	0.0	0.0	20.0	20.0	0.0
Da_G	8	0.0	0.0	0.0	25.0	25.0
Da_V	41	0.0	0.0	0.0	0.0	0.0
Vo	34	2.9	2.9	11.8	0.0	20.6
Ru_3	52	0.0	0.0	0.0	1.9	1.9

- Partial heap better:
  - Many simple heap operations
- Total heap better:
  - Heavy quantifier use
  - Lots of iterated separating conjunctions
- VCG struggles with large examples
- Future work: Predict best algorithm?

Portfolios

	Σ	SE-PS	SE-PC	SE-TR	VCG-TR	VCG-TA
All	537	5.4	5.4	7.4	8.8	13.8
Ru_1	156	0.0	0.6	3.8	9.0	18.6
Ru_2	11	0.0	0.0	45.5	54.5	63.6
Go	11	18.2	0.0	18.2	0.0	0.0
Go_C	17	5.9	0.0	17.6	29.4	35.3
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Py	23	8.7	13.0	4.3	13.0	21.7
Py_P	18	16.7	11.1	11.1	5.6	5.6
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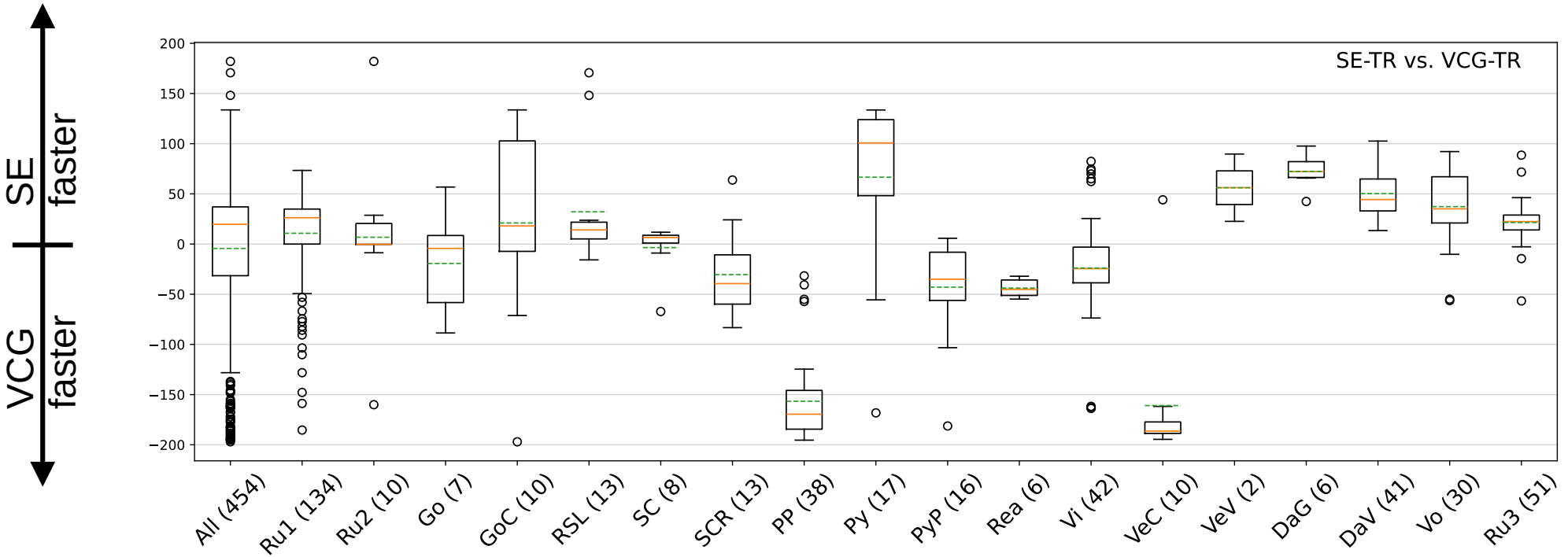
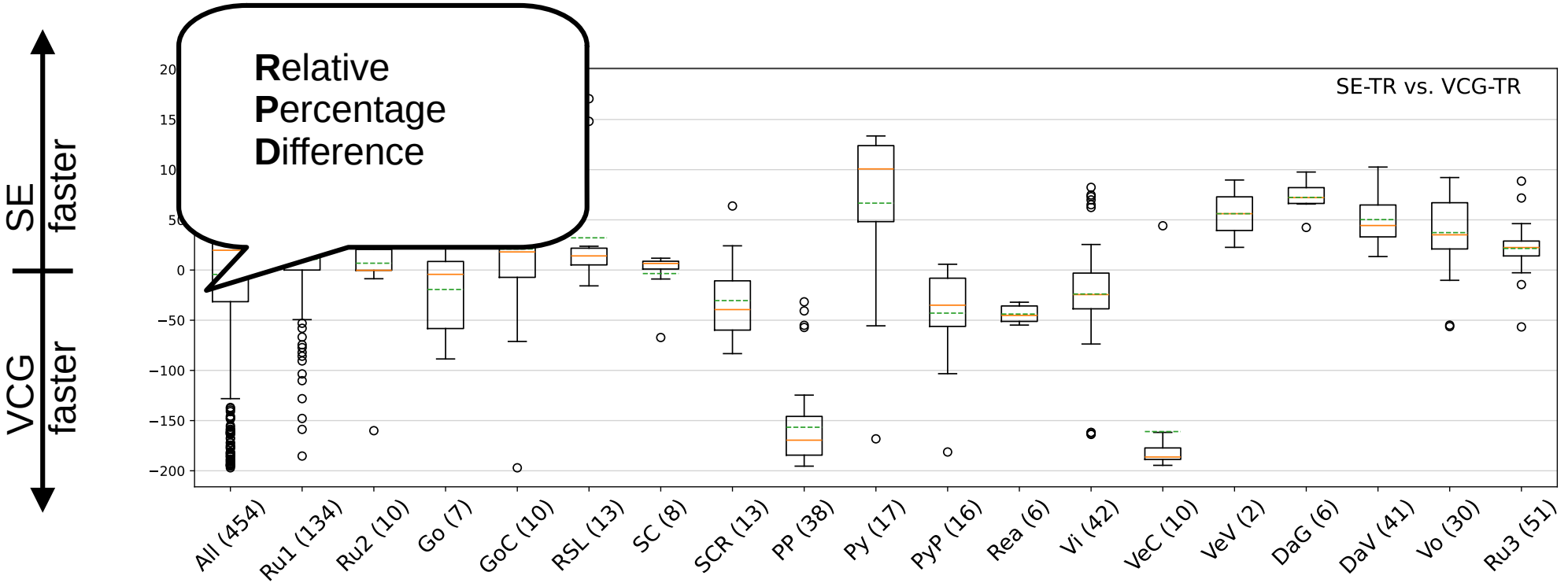
Da_G	8	0.0	0.0	0.0	25.0	25.0
Da_V	41	0.0	0.0	0.0	0.0	0.0
Vo	34	2.9	2.9	11.8	0.0	20.6
Ru_3	52	0.0	0.0	0.0	1.9	1.9

- No single algorithm can do everything
  - Portfolio recommended
- Four needed to cover all examples
- Three needed for all but one
  - SE-PS, SE-TR, any VCG
- SE-PS, VCG-TR for all but six
- SE-PS, SE-TR for all but ten
  - Easy to implement SE-TR in existing SE-PS

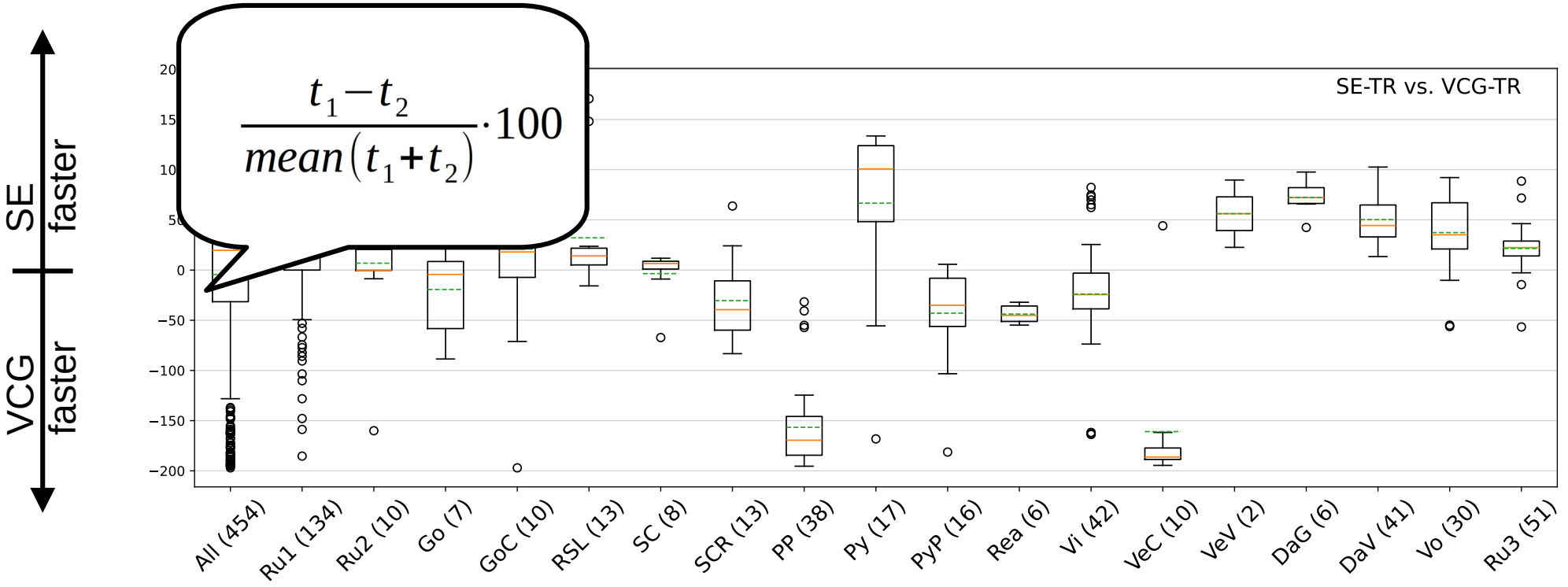
Performance Benchmark Example: SE vs. VCG with Total Heap



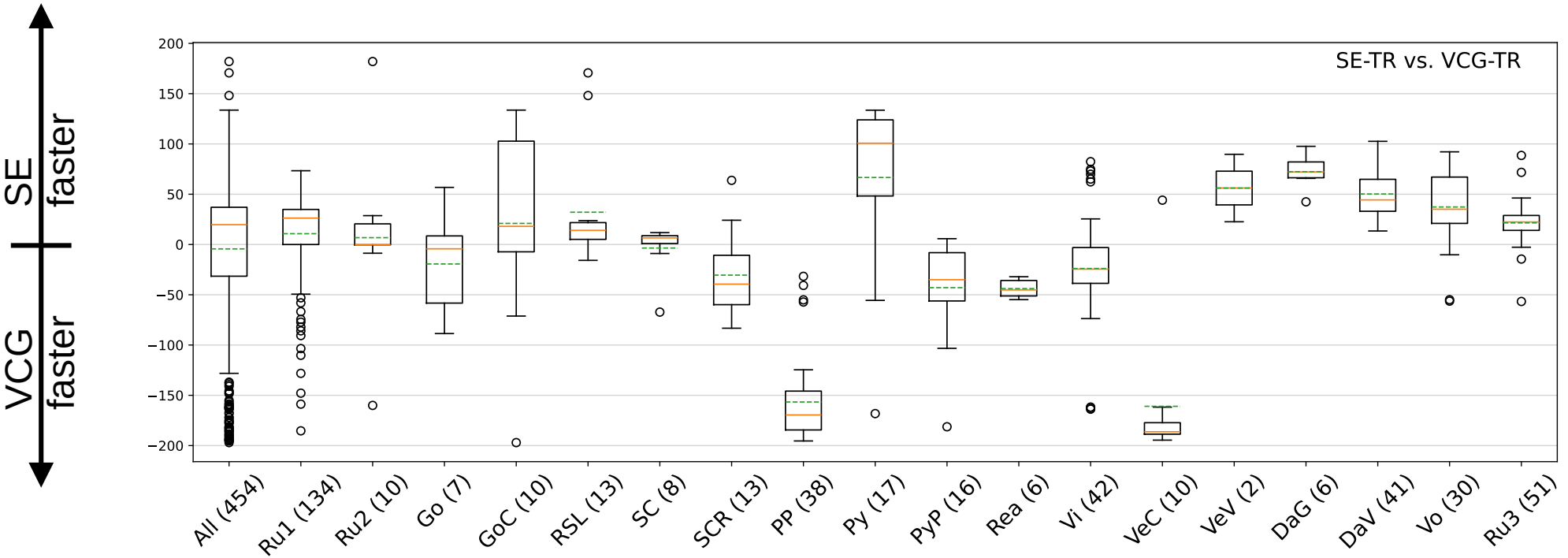
Performance Benchmark Example: SE vs. VCG with Total Heap



Performance Benchmark Example: SE vs. VCG with Total Heap



Performance Benchmark Example: SE vs. VCG with Total Heap



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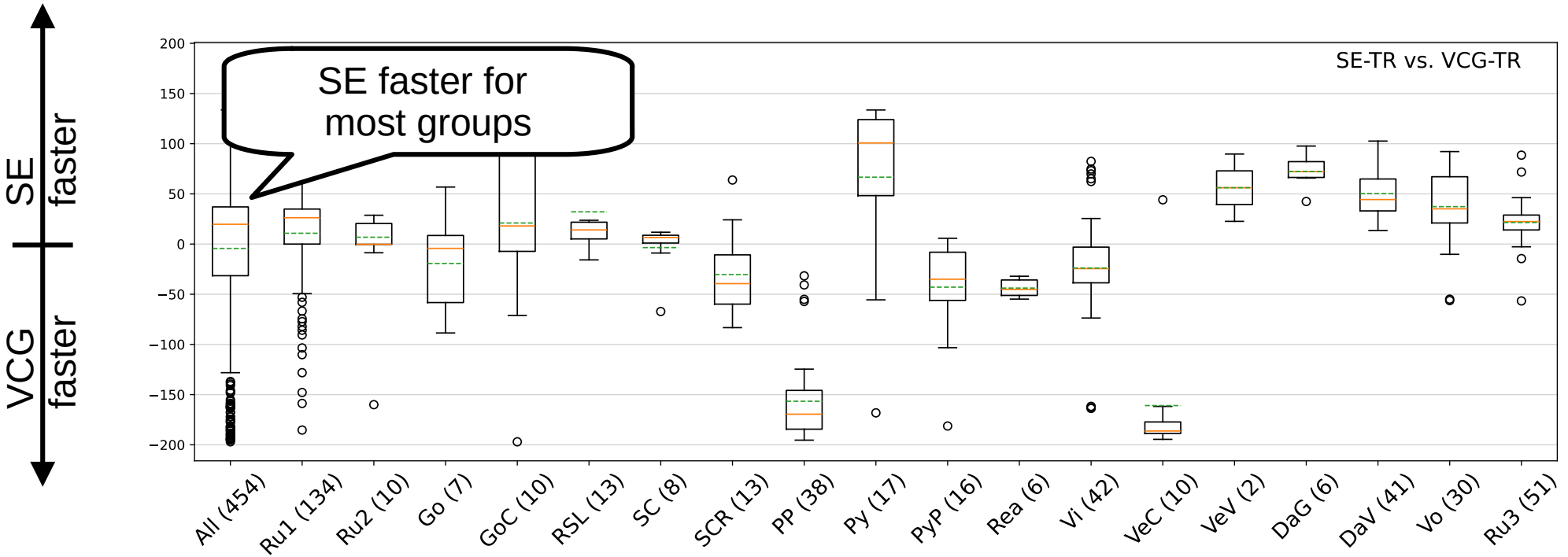
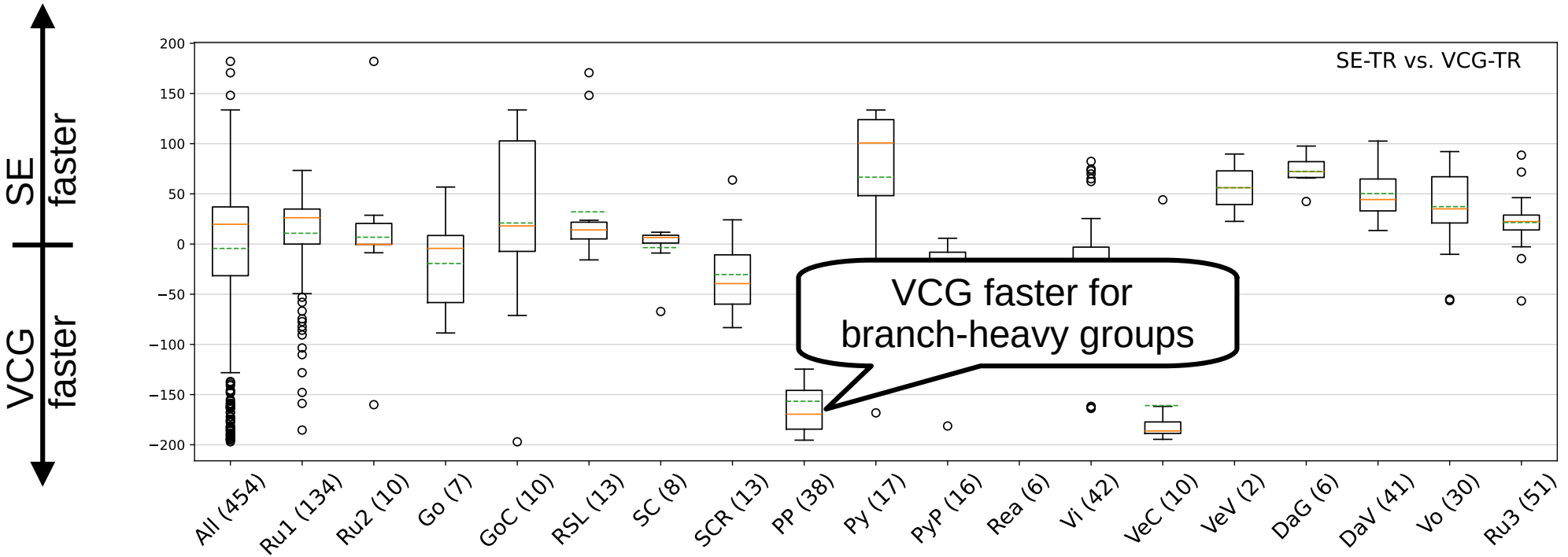
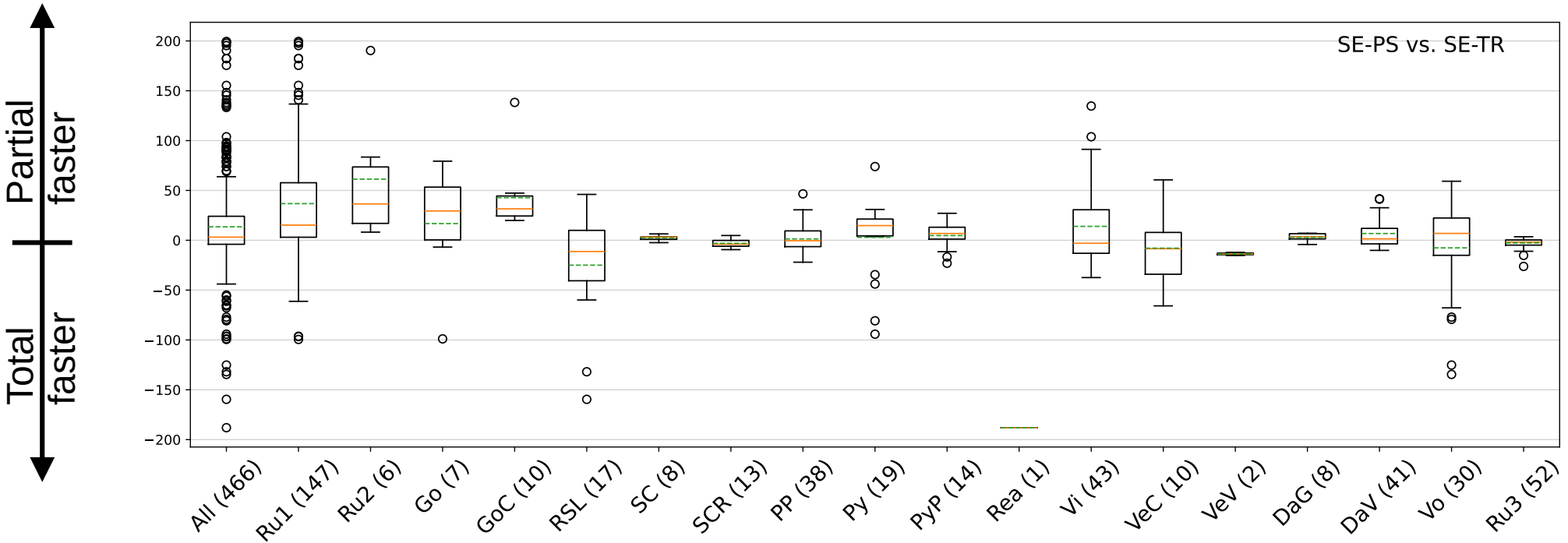


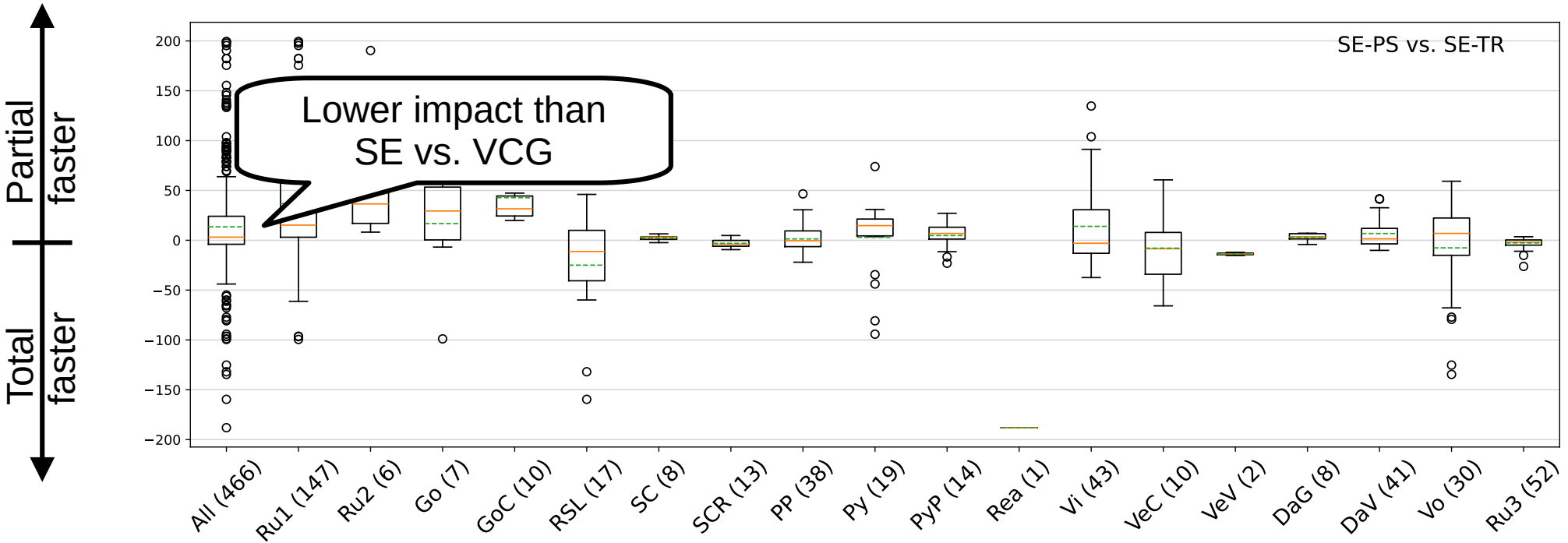
Performance Benchmark Example: SE vs. VCG with Total Heap



Performance Benchmark Example: SE with Partial vs. Total Heap

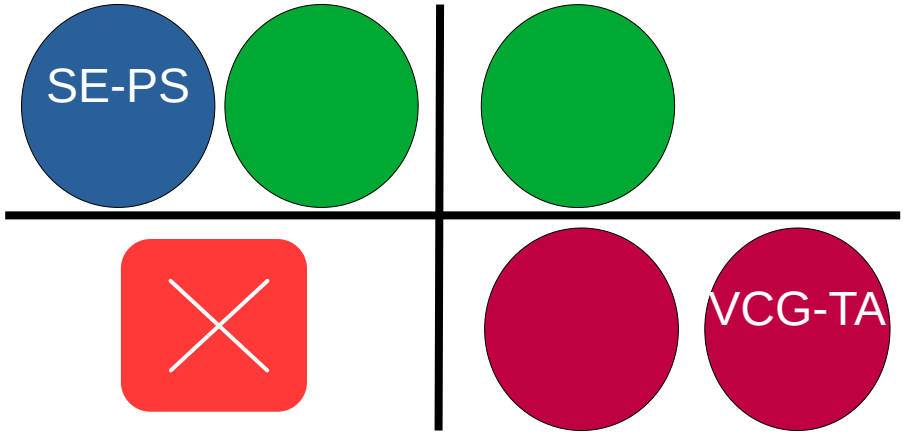


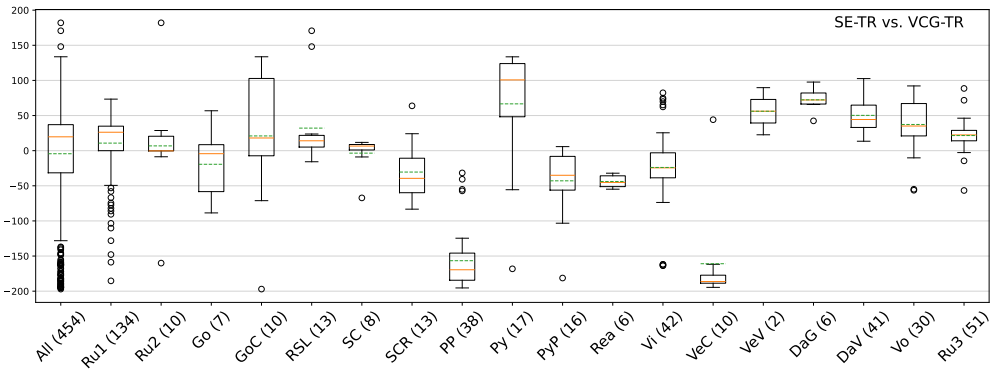
Performance Benchmark Example: SE with Partial vs. Total Heap



Conclusion

- SE + partial heap combinations perform best overall
  - Best overall completeness and performance
  - Most existing tools made a good choice
- Other algorithms are needed to cover all cases
  - Some example groups require total heaps
- Portfolio approach useful
- VCG-TR strictly better than VCG-TA
- Two new algorithms
  - SE-TR offers unique tradeoff
  - SE-PC is best overall along with SE-PS





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