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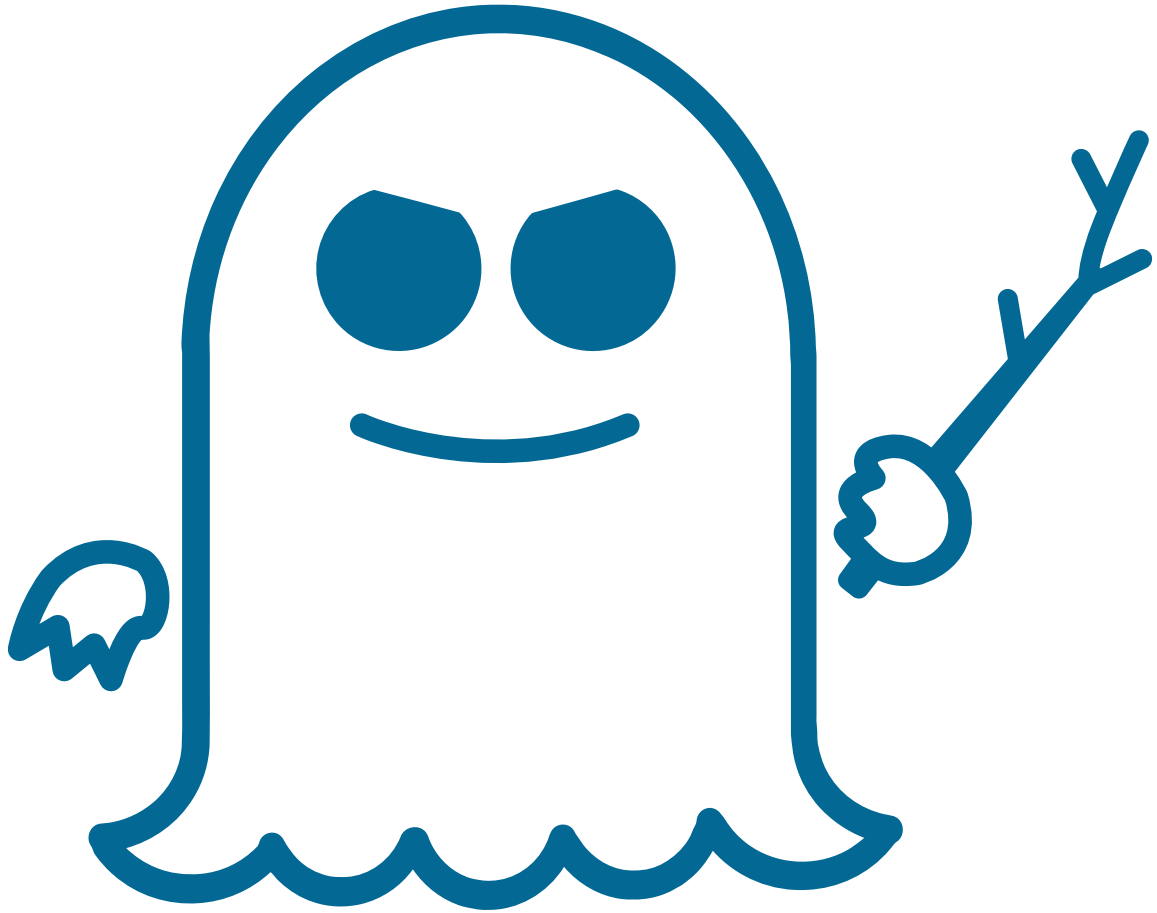
Automatic Detection of Speculative Execution Combinations

Xaver Fabian[1], Marco Guarnieri[2], Marco Patrignani[3]

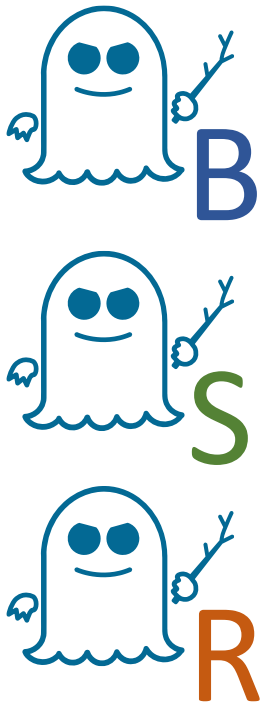
1 CISPA Helmholtz Center for Information Security
2 IMDEA Software Institute
3 University of Trento

Spectre

- Vulnerability exploiting Speculative execution in modern processors
- Uses multiple prediction mechanisms
- Mispredictions are rolled back
- Leave footprint in the microarchitectural state (e.g., cache)



Different Versions of Spectre



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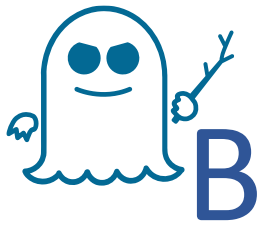

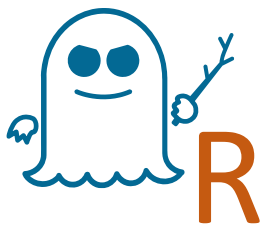

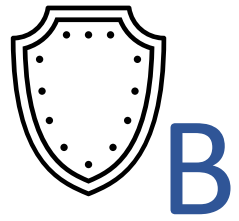

SoK: Practical Foundations for Software Spectre Defenses, Cauligi et al., IEEE S&P, 2022

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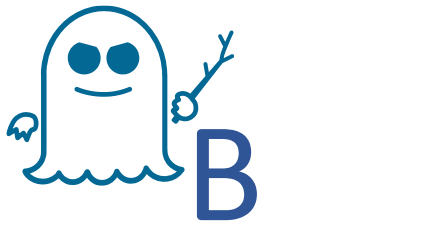

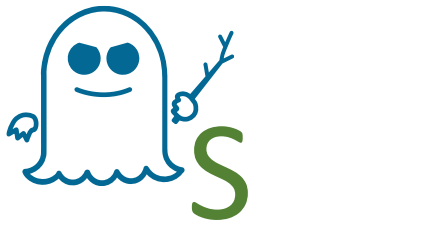

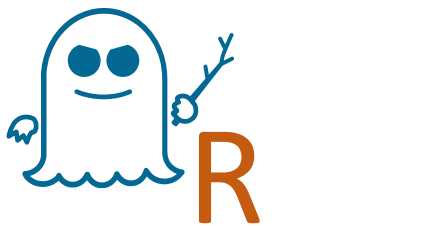

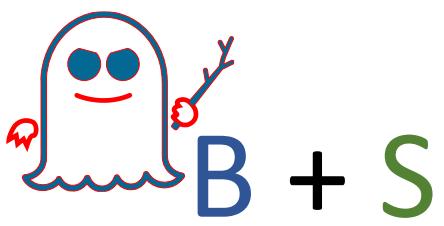

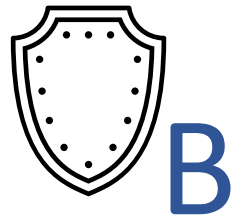

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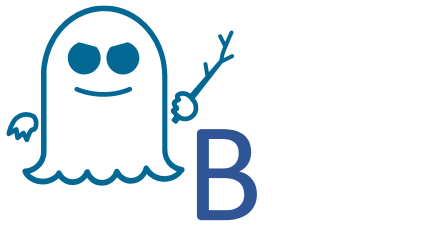

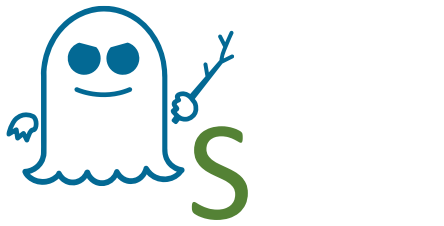

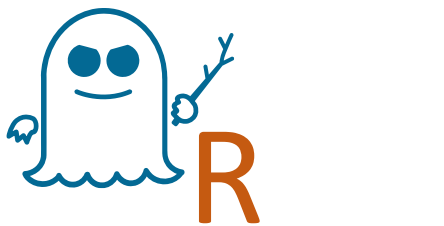

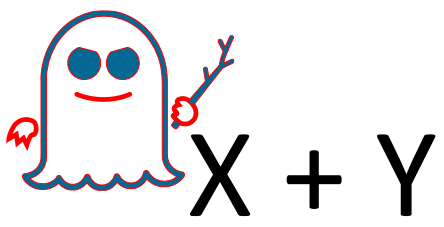

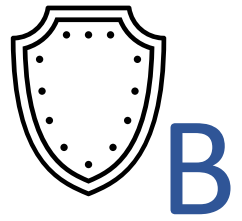

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Detecting a Combination

$$\frac{p(\sigma(\mathbf{pc})) \notin [\mathbf{store}\ x, e;\ \boxed{\mathrm{Z}}\ ] \qquad \sigma \xrightarrow{\tau} \sigma'}{\langle p, ctr, \sigma, n+1\rangle \overset{\tau}{\dashrightarrow}_{\mathrm{S}} \langle p, ctr, \sigma', n\rangle}\ (\mathrm{S}\text{:AM-NoSpec})$$

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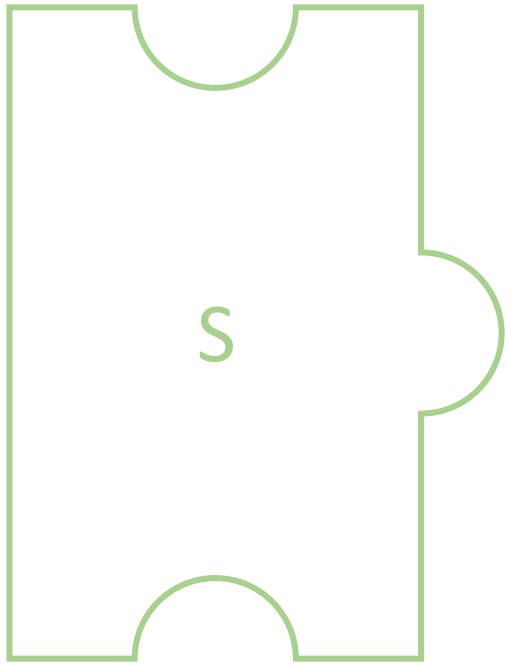

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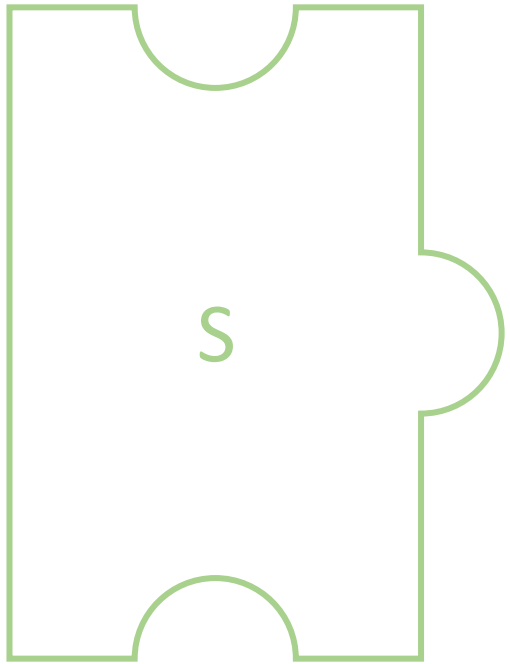

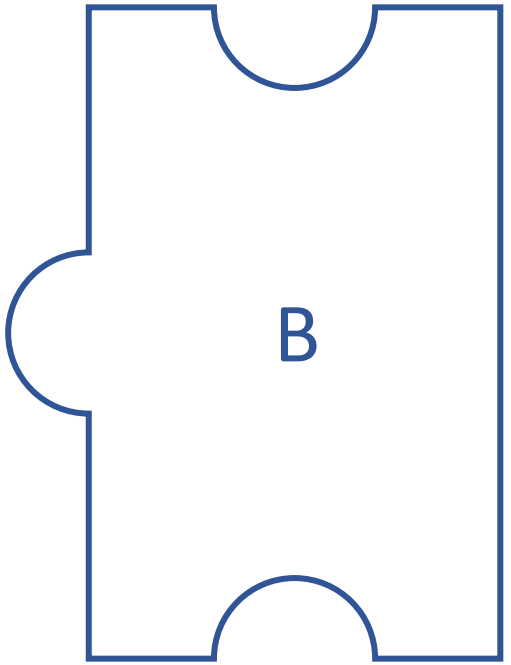

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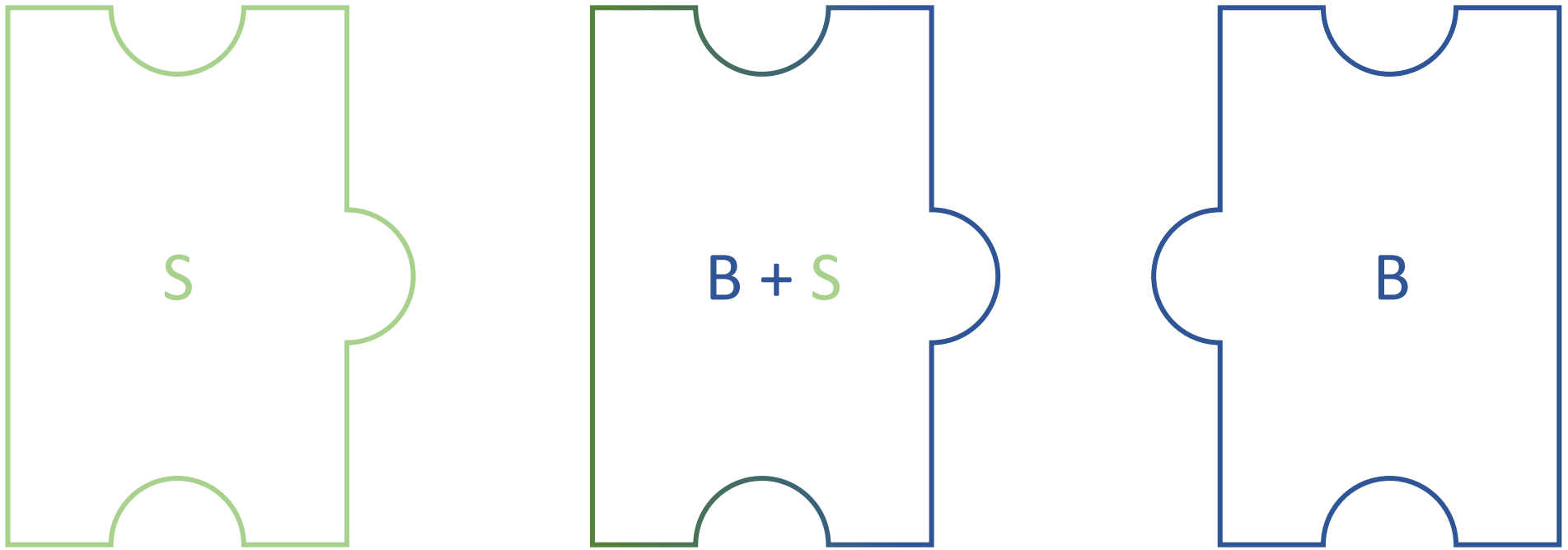

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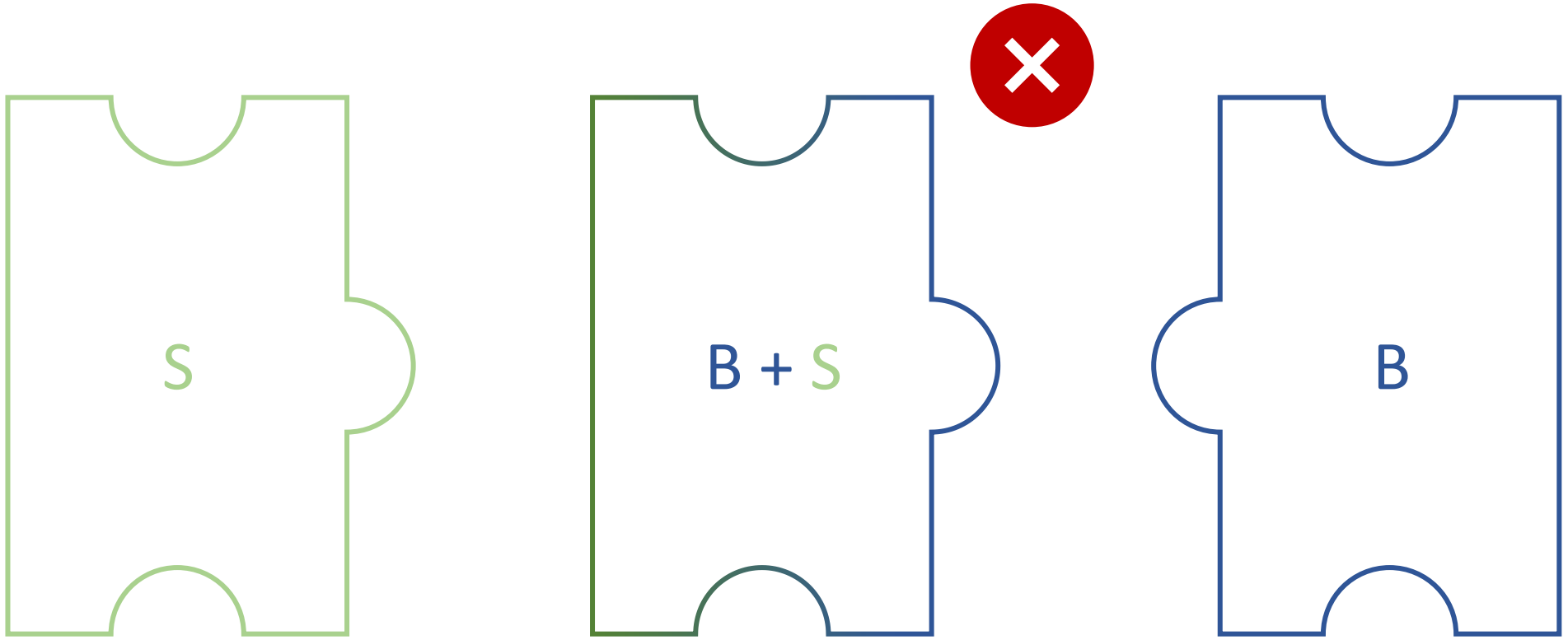

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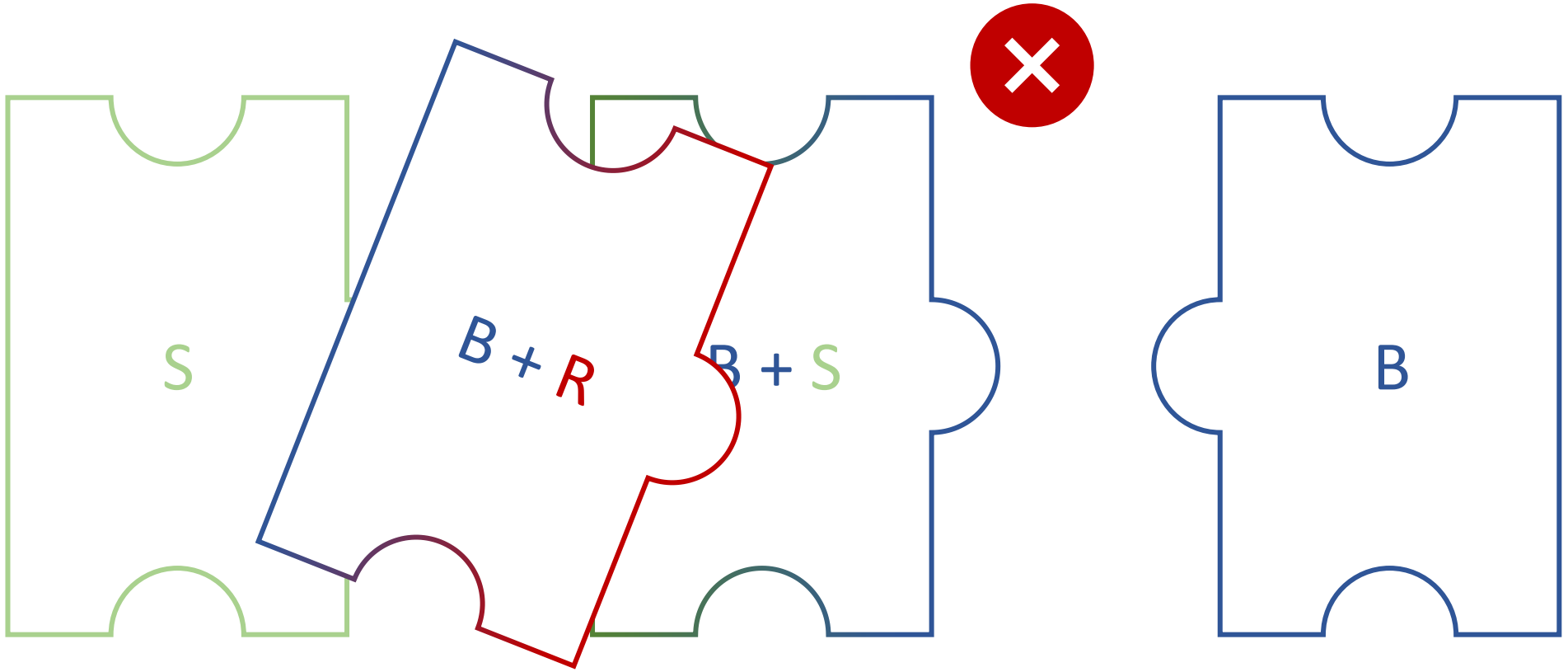

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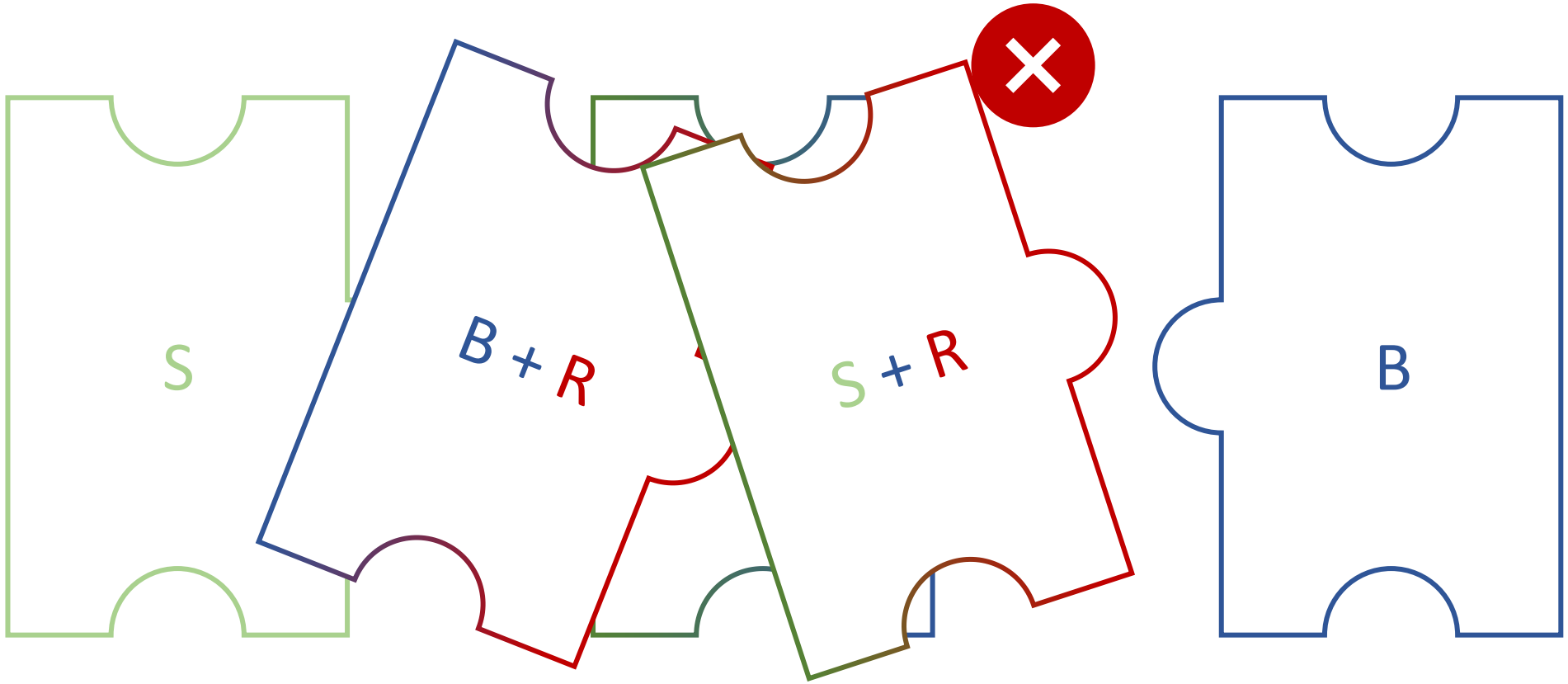

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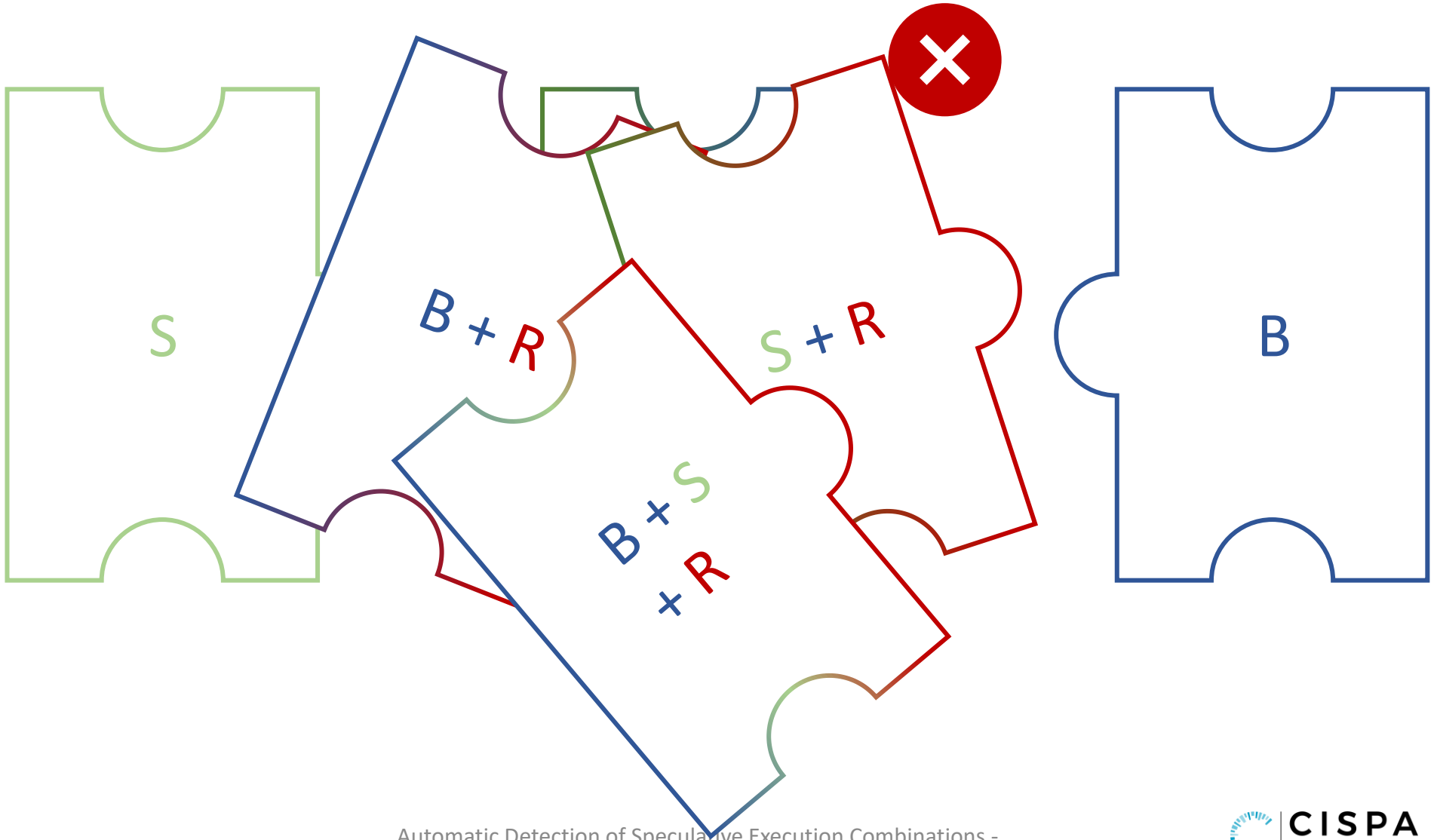

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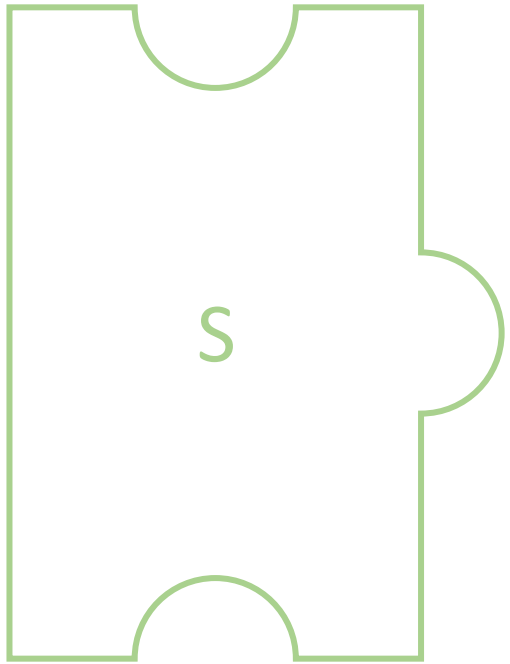

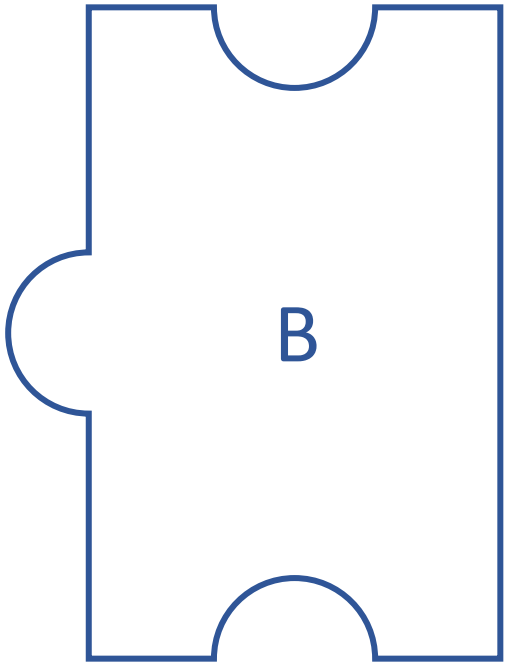

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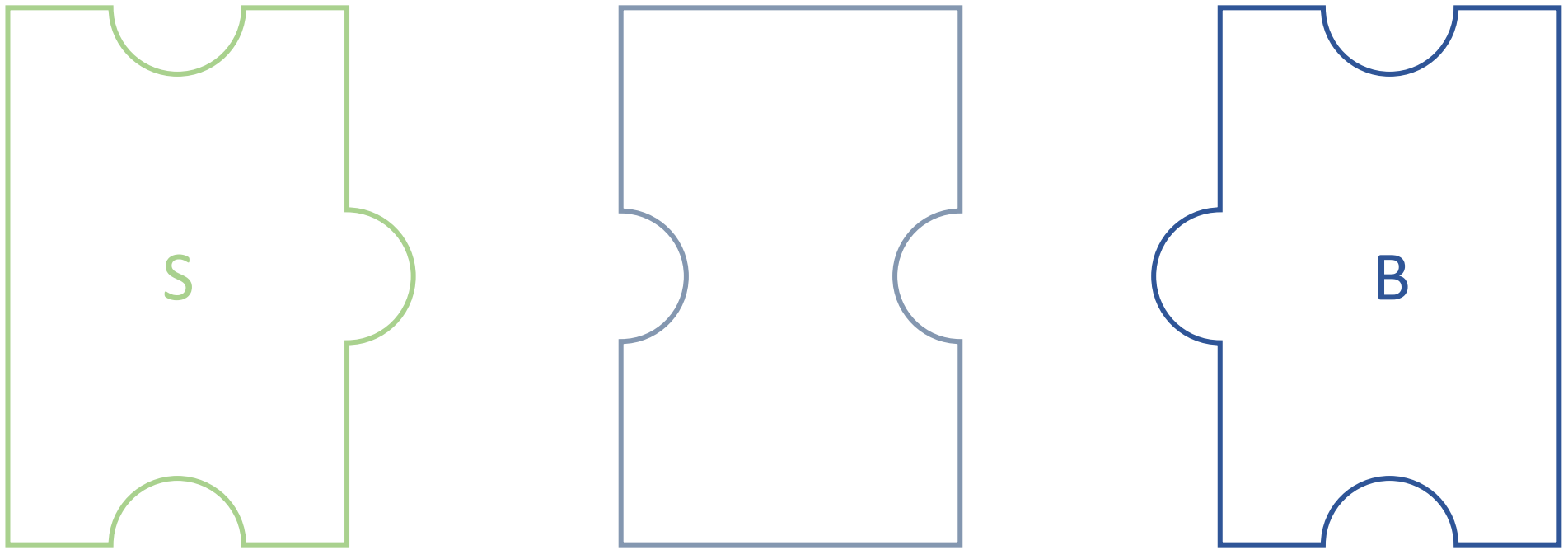

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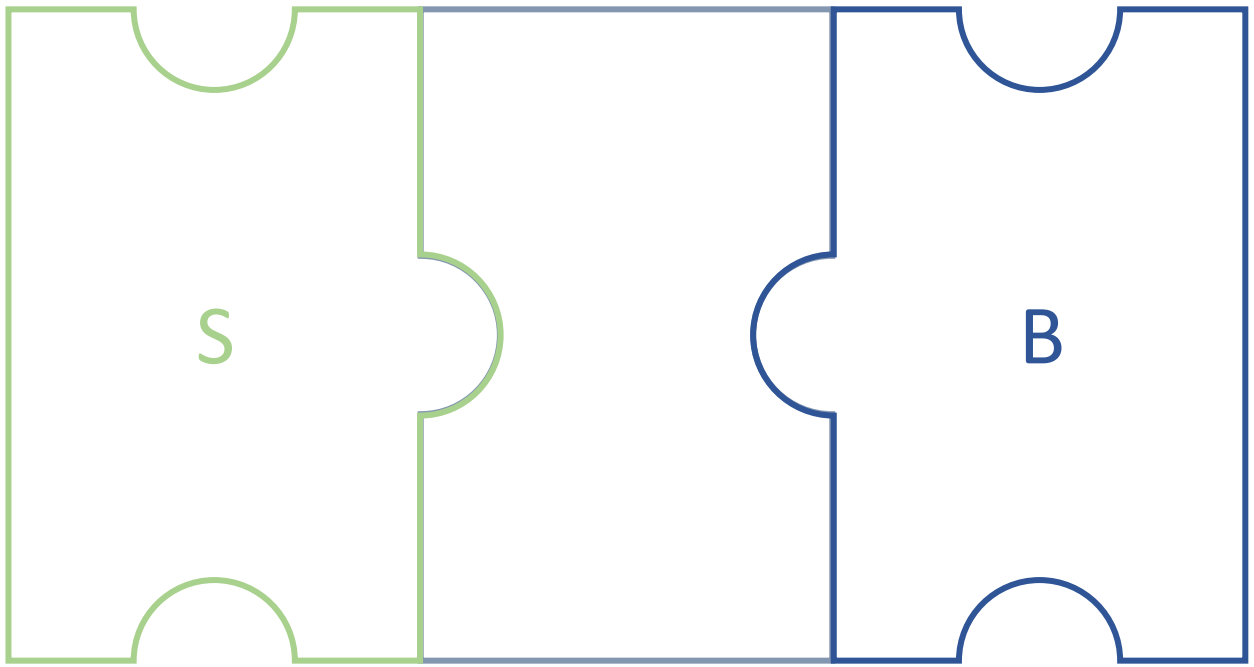

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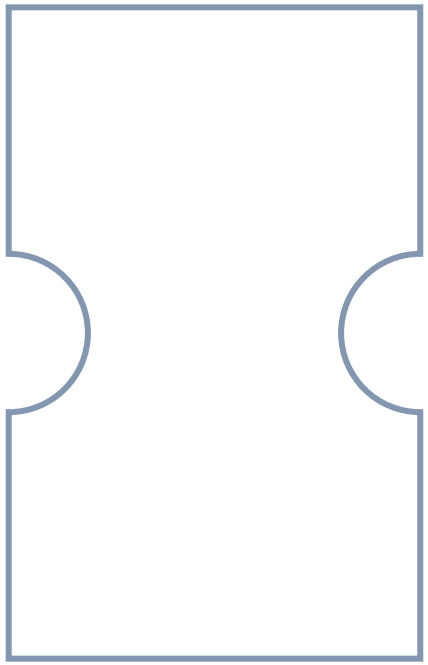

Detecting a Combination

$$\frac{\Phi_{xy}\restriction^{x}_{xy} \overset{\tau}{\dashrightarrow} x \qquad \overline{\Phi}'_{xy}\restriction^{x}_{xy}}{\Phi_{xy} \overset{\tau}{\dashrightarrow} xy \quad \overline{\Phi}'_{xy}}\ \text{(AM-x-step)}$$

$$\frac{\Phi_{xy}\restriction^{y}_{xy} \overset{\tau}{\dashrightarrow} y \qquad \overline{\Phi}'_{xy}\restriction^{y}_{xy}}{\Phi_{xy} \overset{\tau}{\dashrightarrow} xy \quad \overline{\Phi}'_{xy}}\ \text{(AM-y-step)}$$

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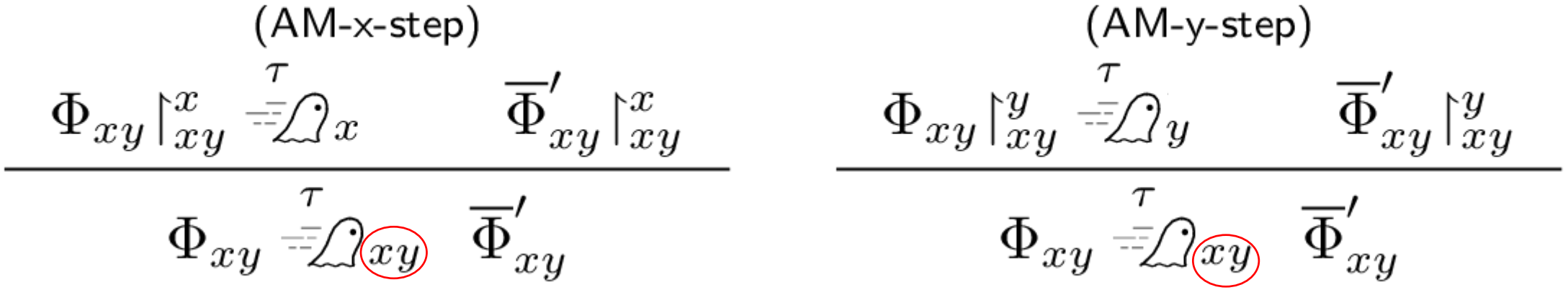
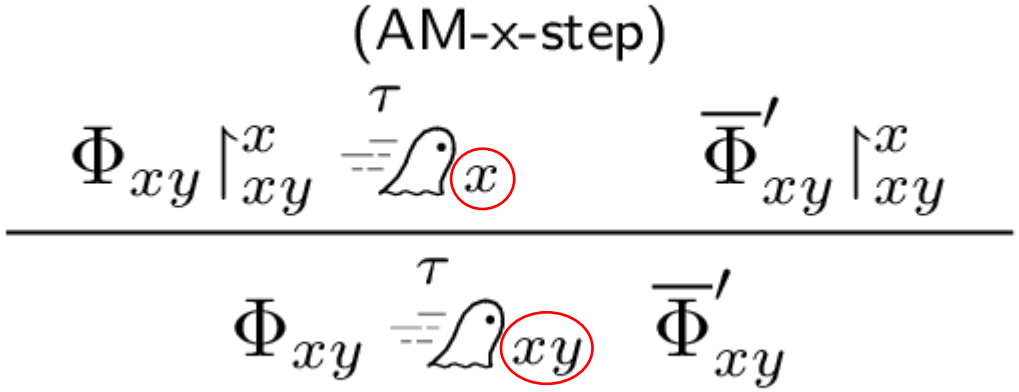


Detecting a Combination

(AM-x-step)



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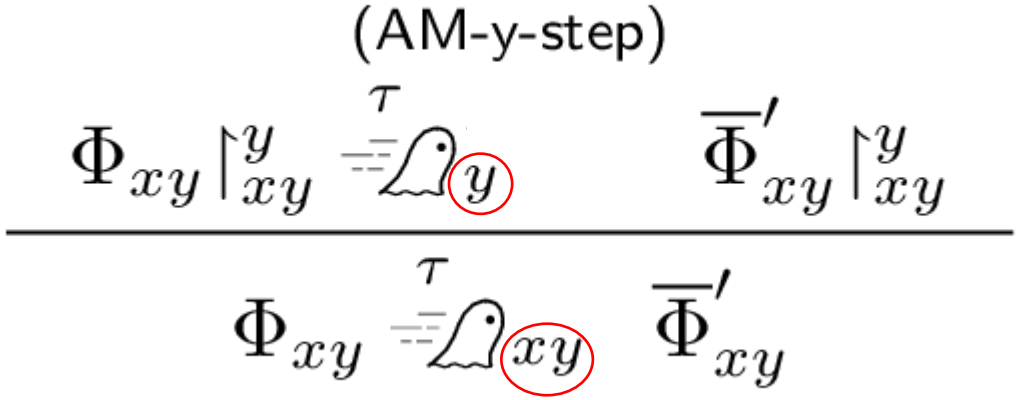

Well Formed Composition (WFC)

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- Recovering the behaviour of the source semantics

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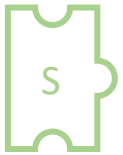
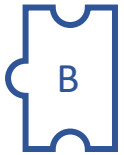
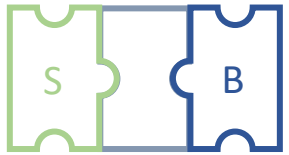
- Secure (

and 

) and WFC (

) -> Secure (

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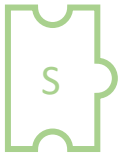
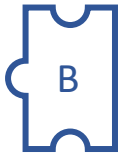
- Secure (

and 

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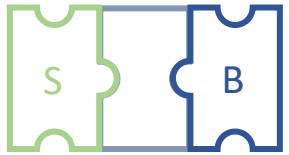
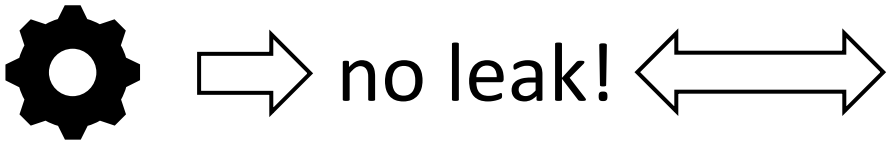
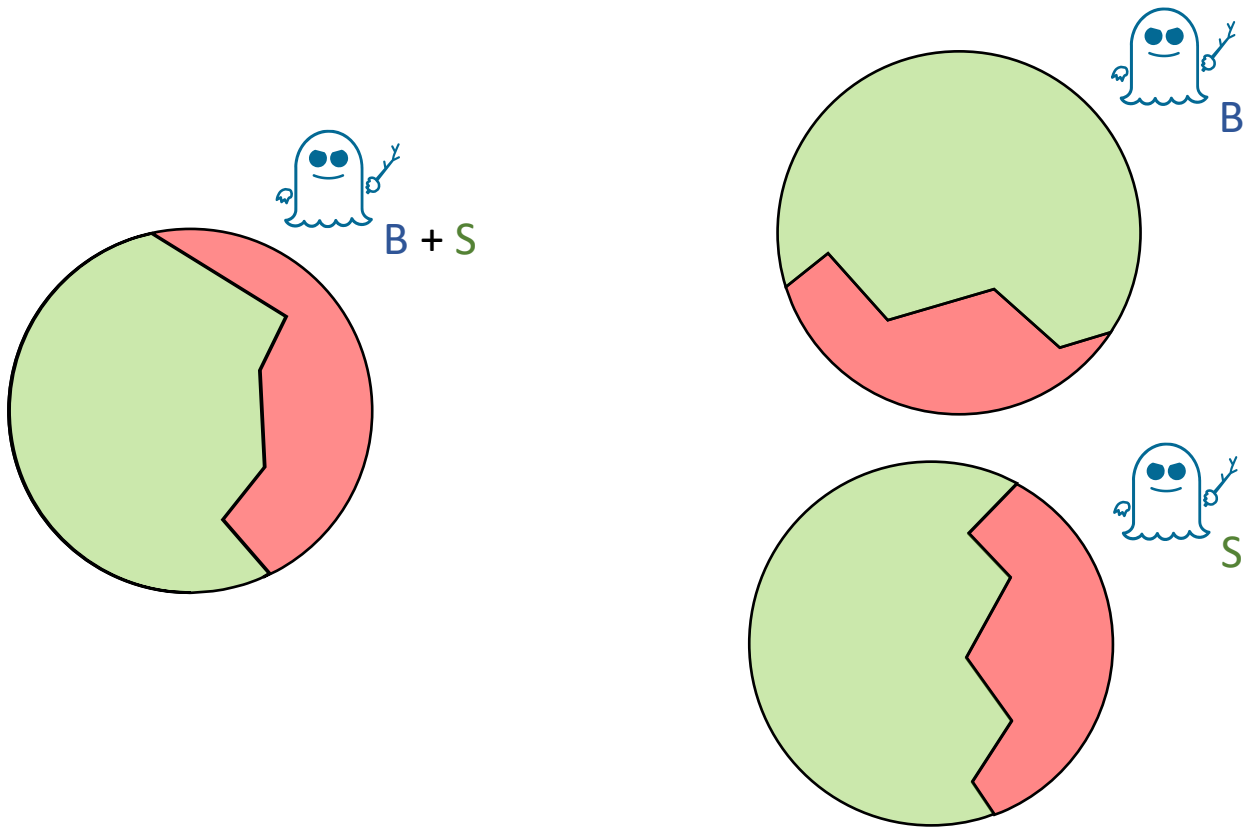
) -> Secure (

)
- Correctness of the Spectector algorithm



Relationship source and Composition



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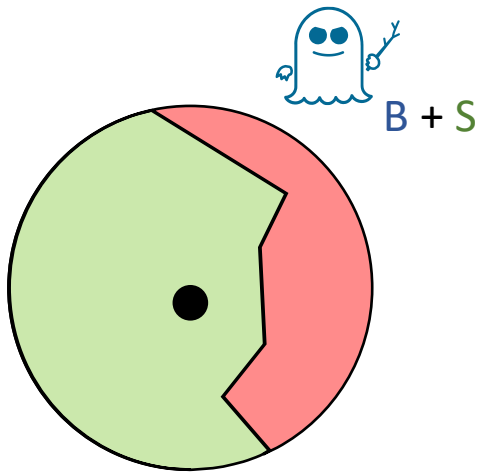

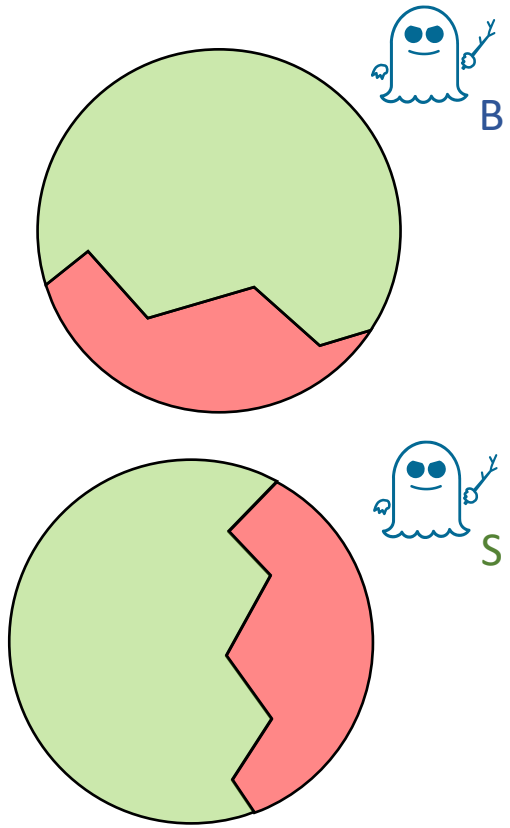

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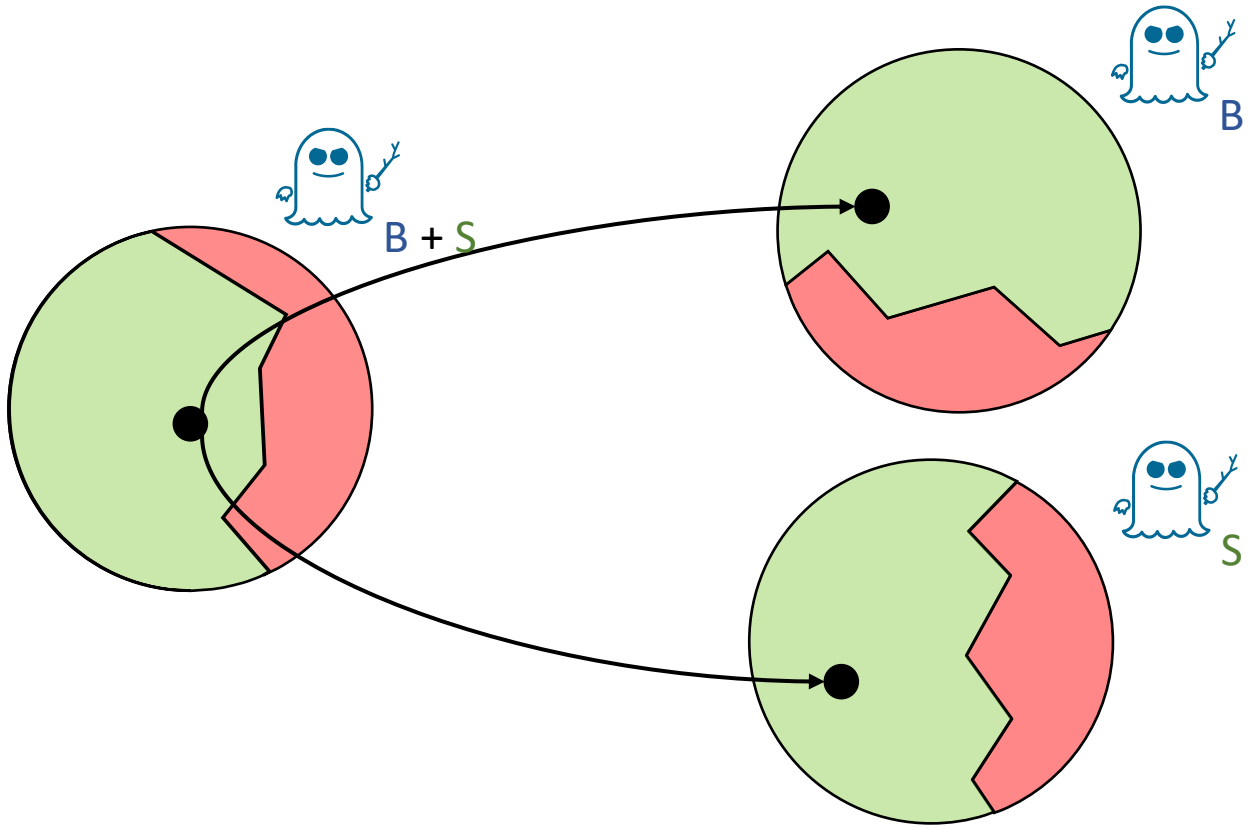

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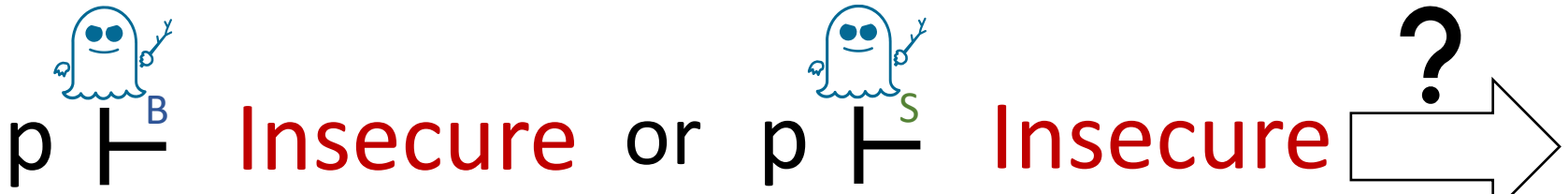

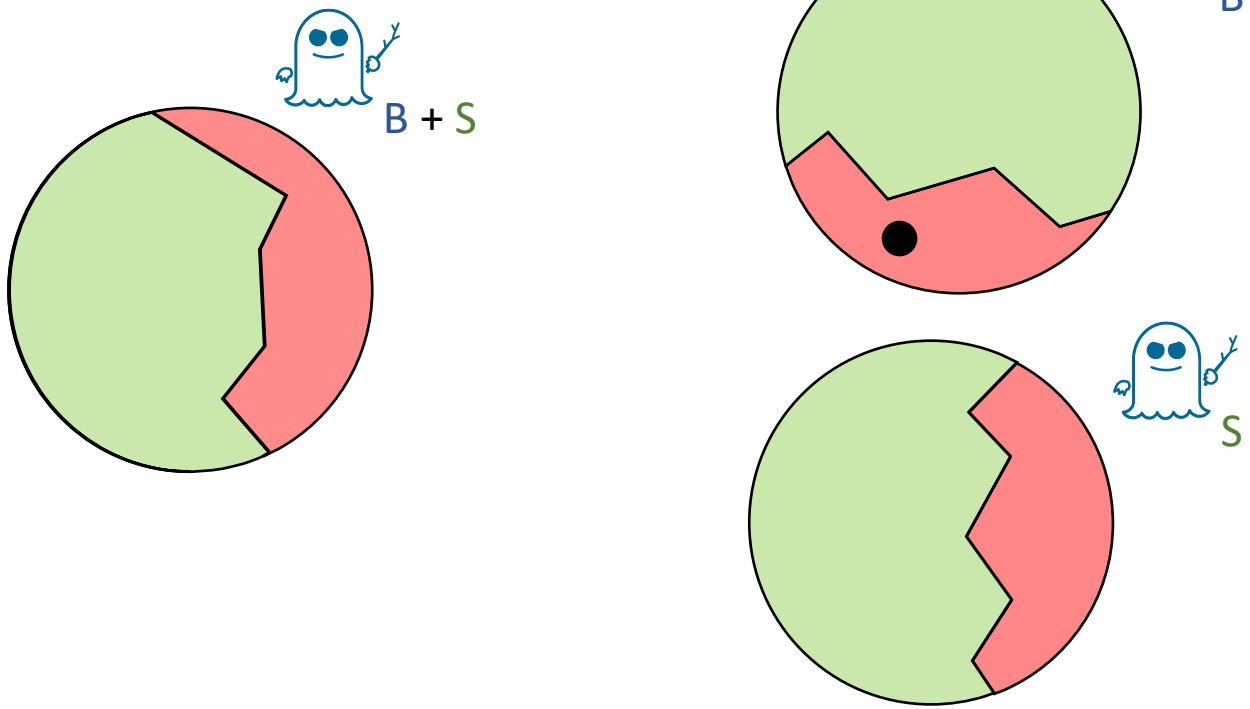

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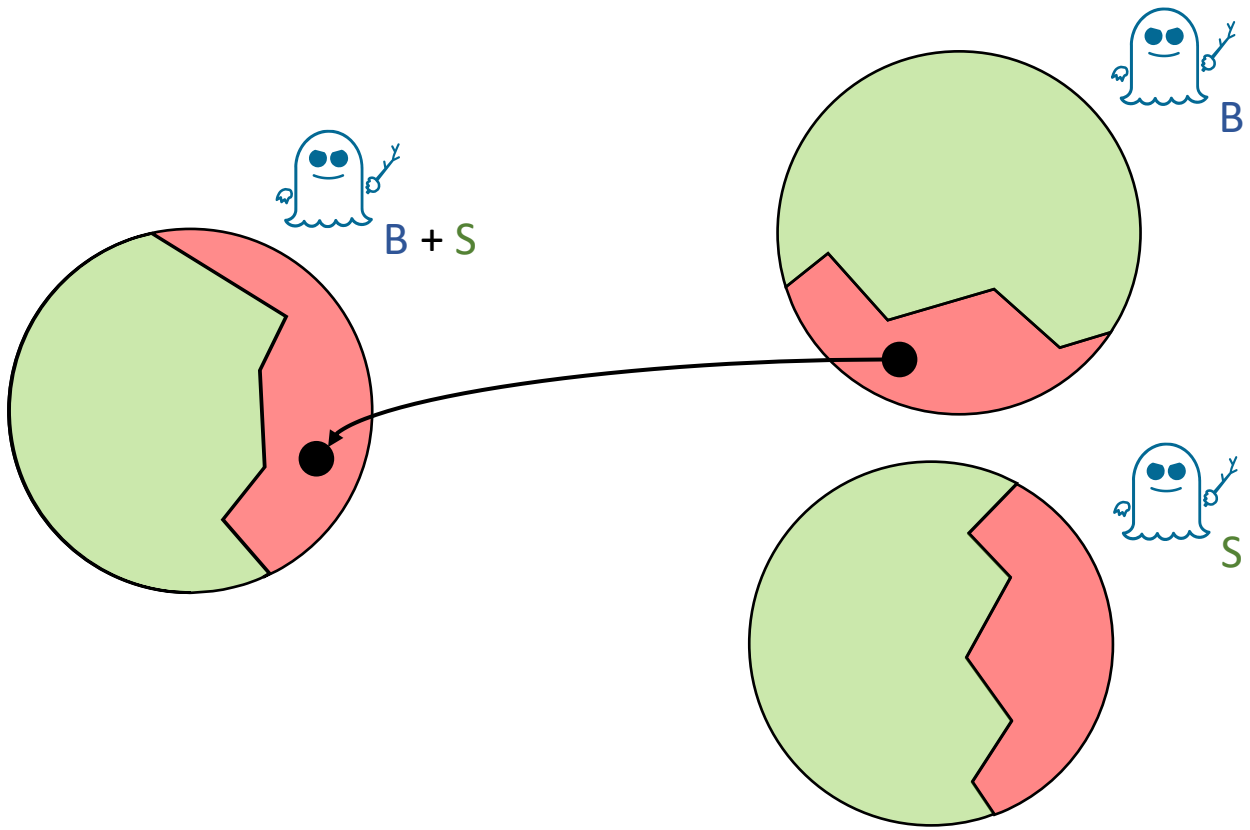

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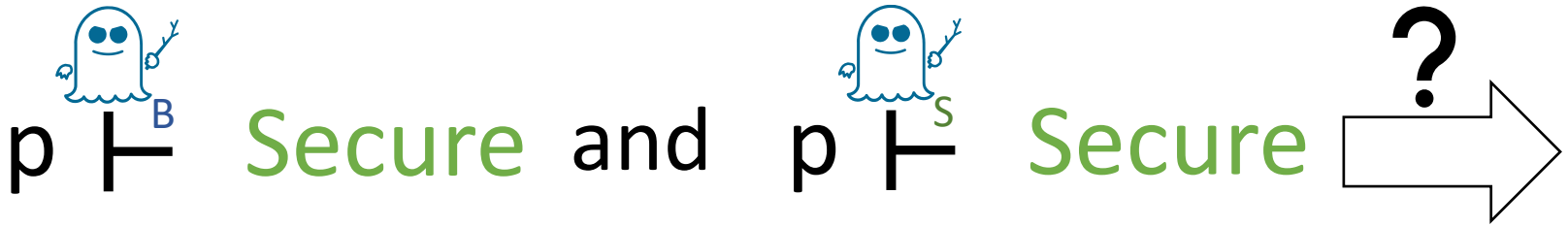
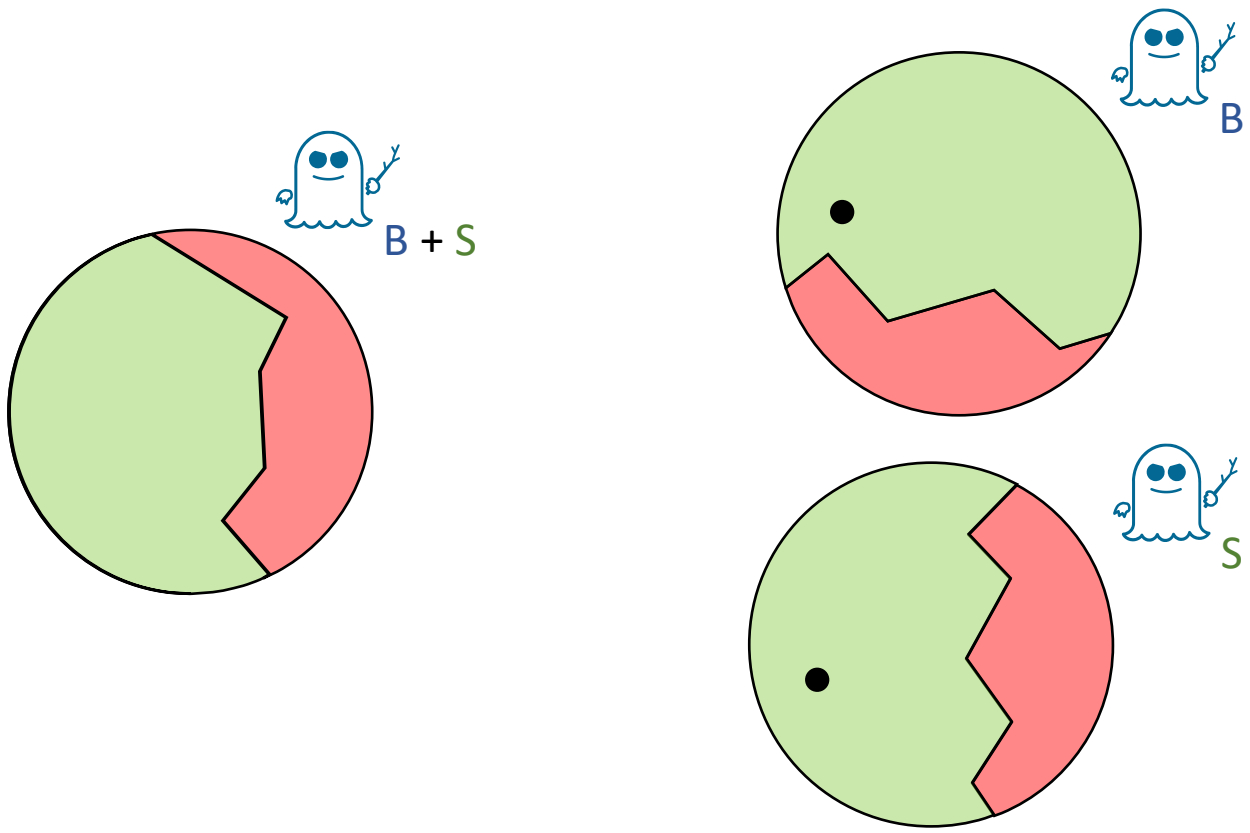
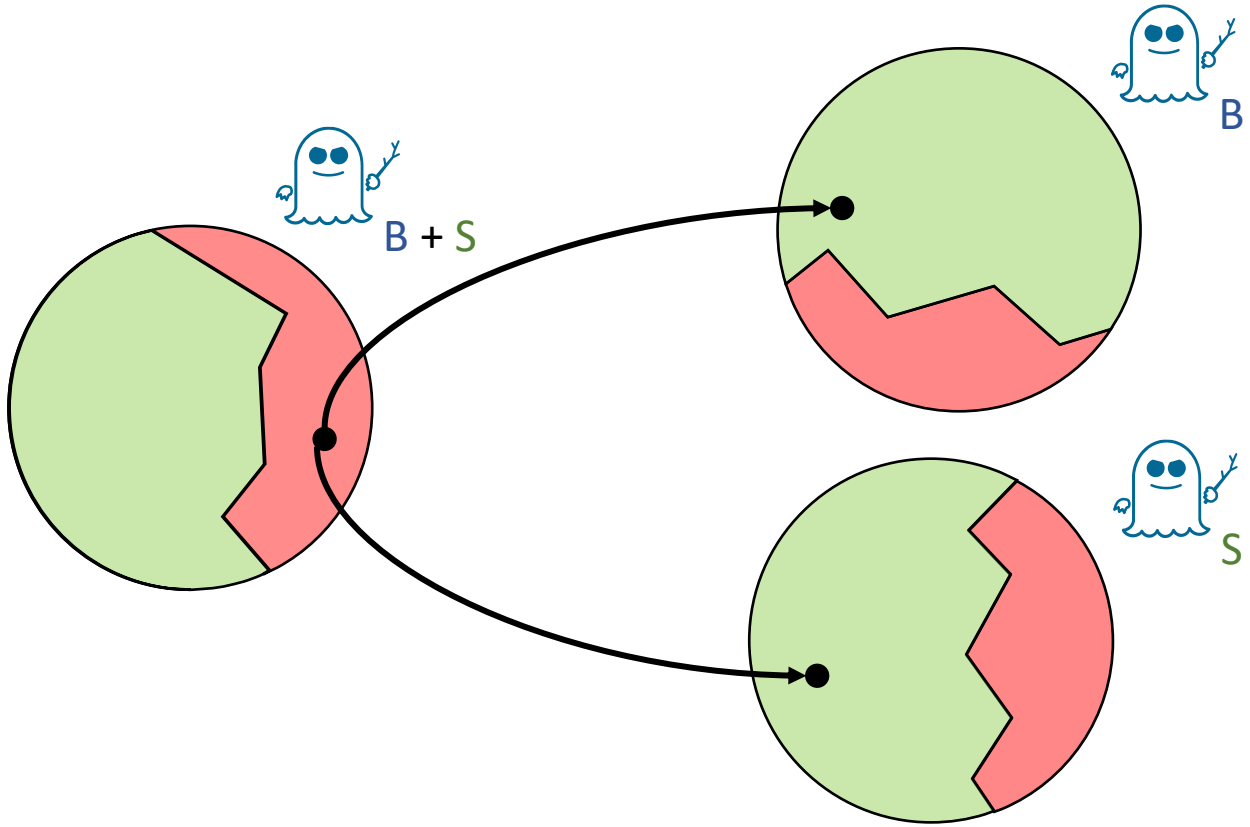




Relationship source and Composition

$p \vdash_{B}$ Secure and $p \vdash_{S}$ Secure $\not\Rightarrow$ $p \vdash_{B+S}$ Secure



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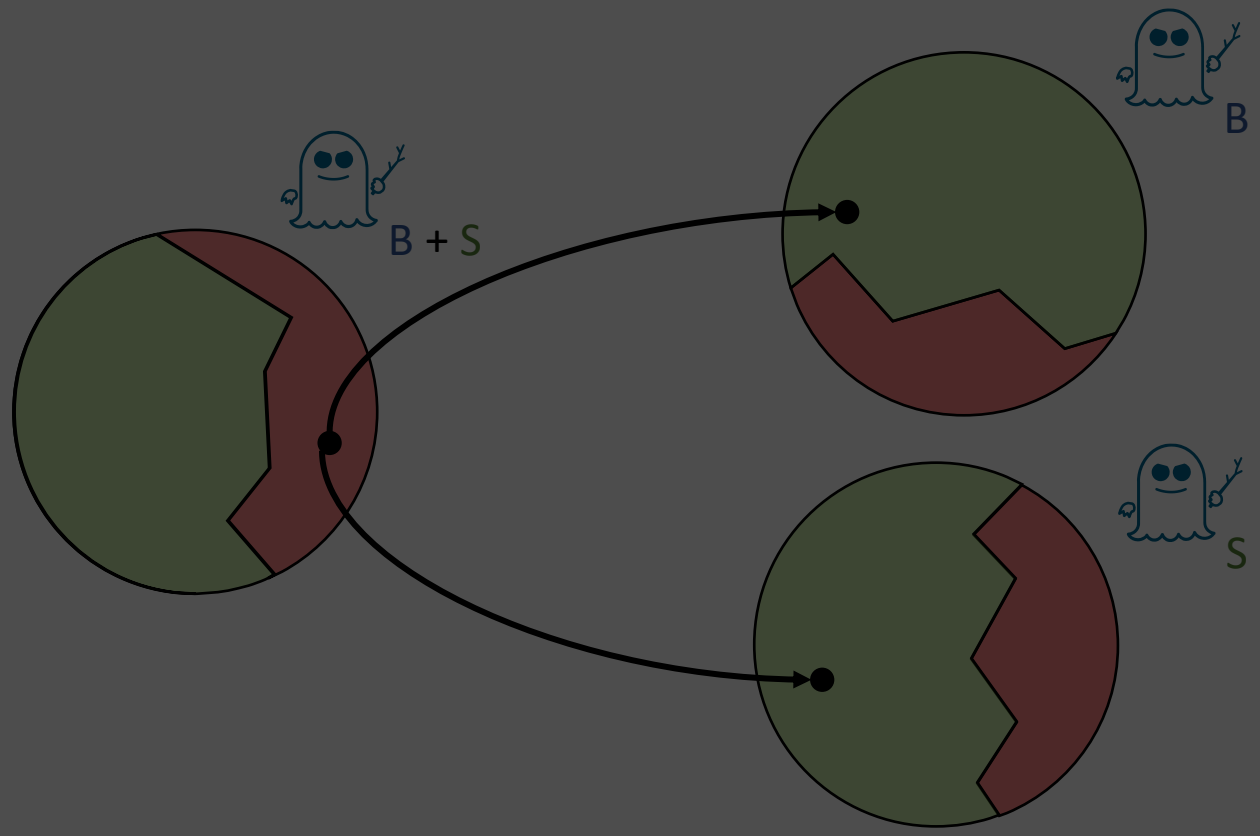


```
1. x = 0
2. p = &secret
3. p = &public
4. if x != 0
5.     y = A[*p]
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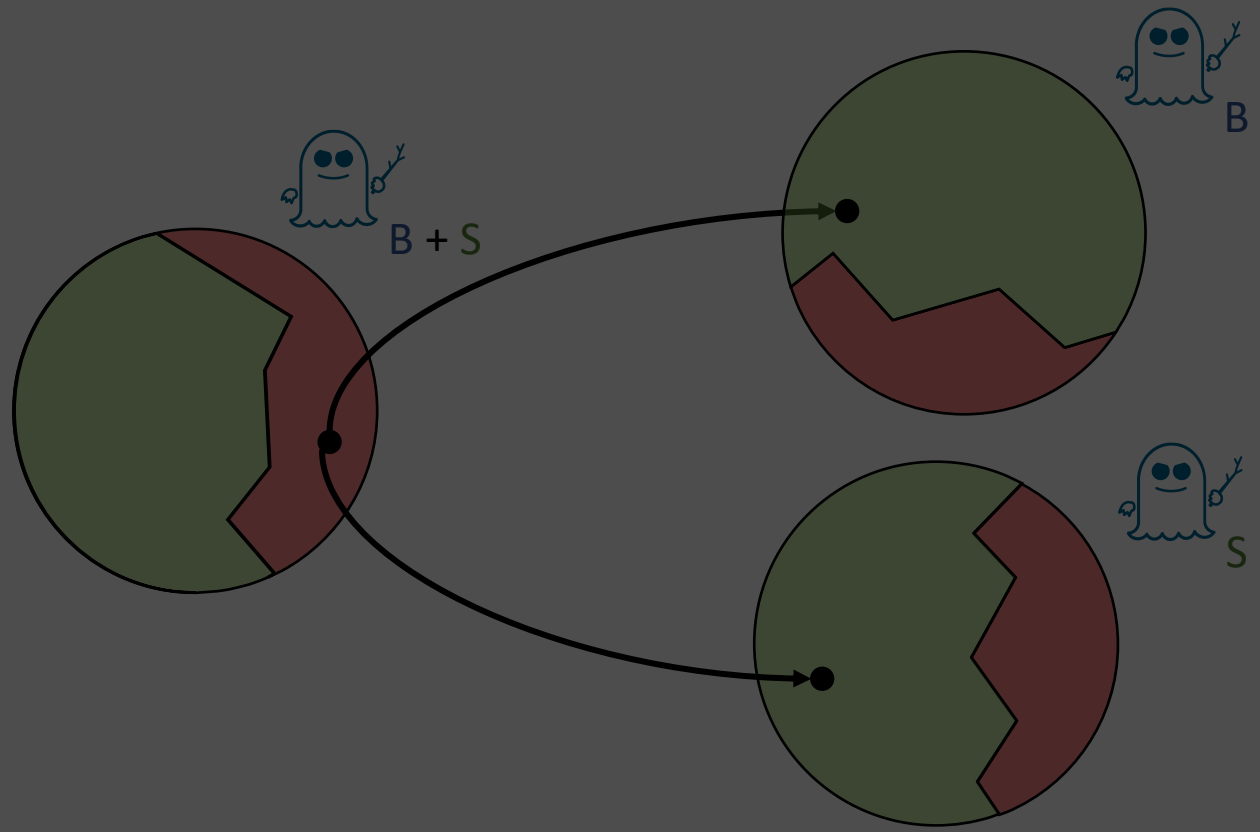


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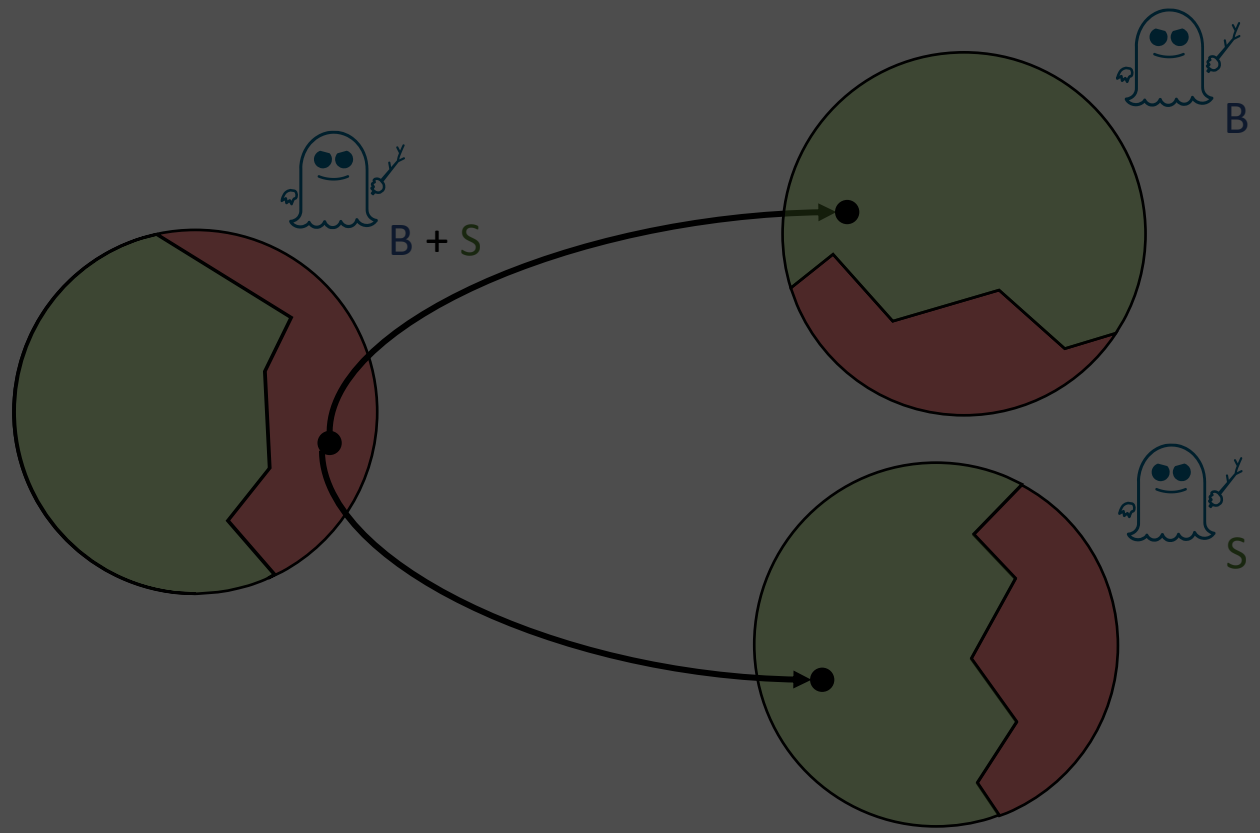


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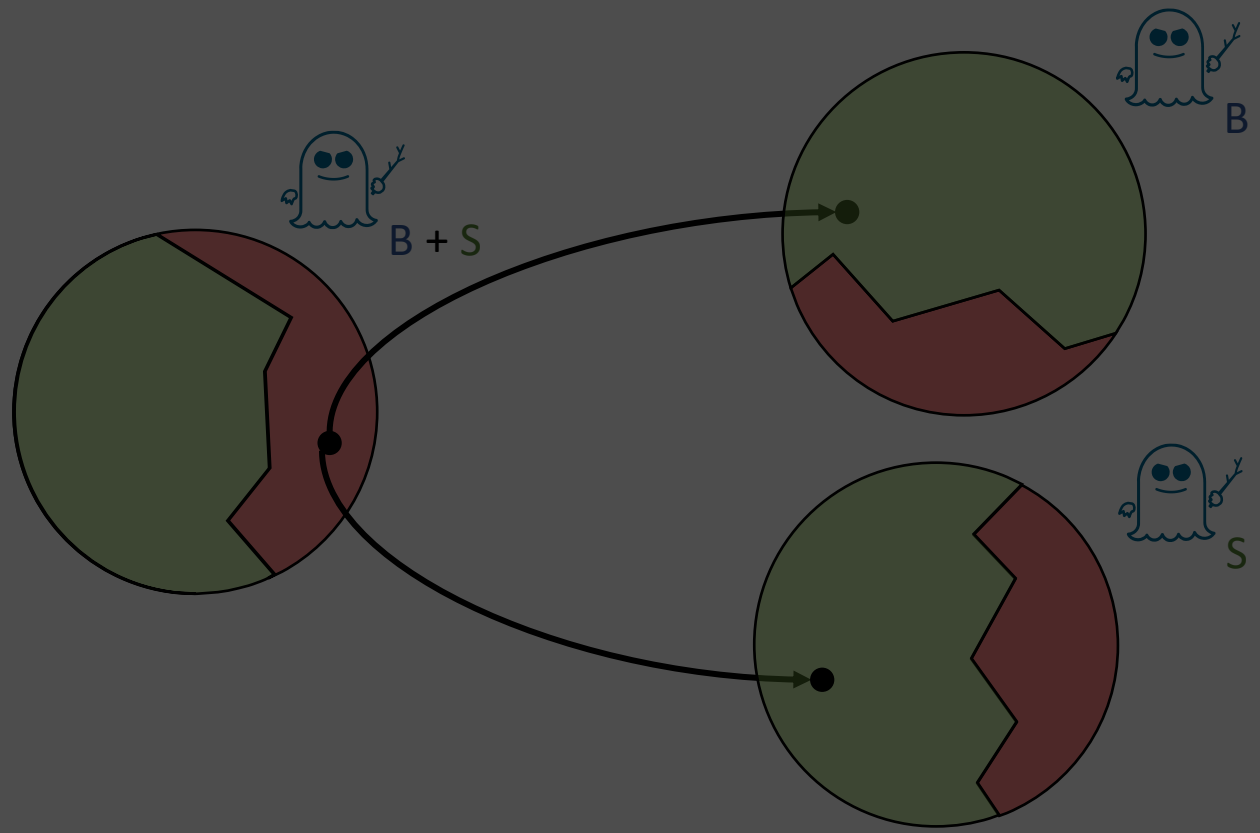


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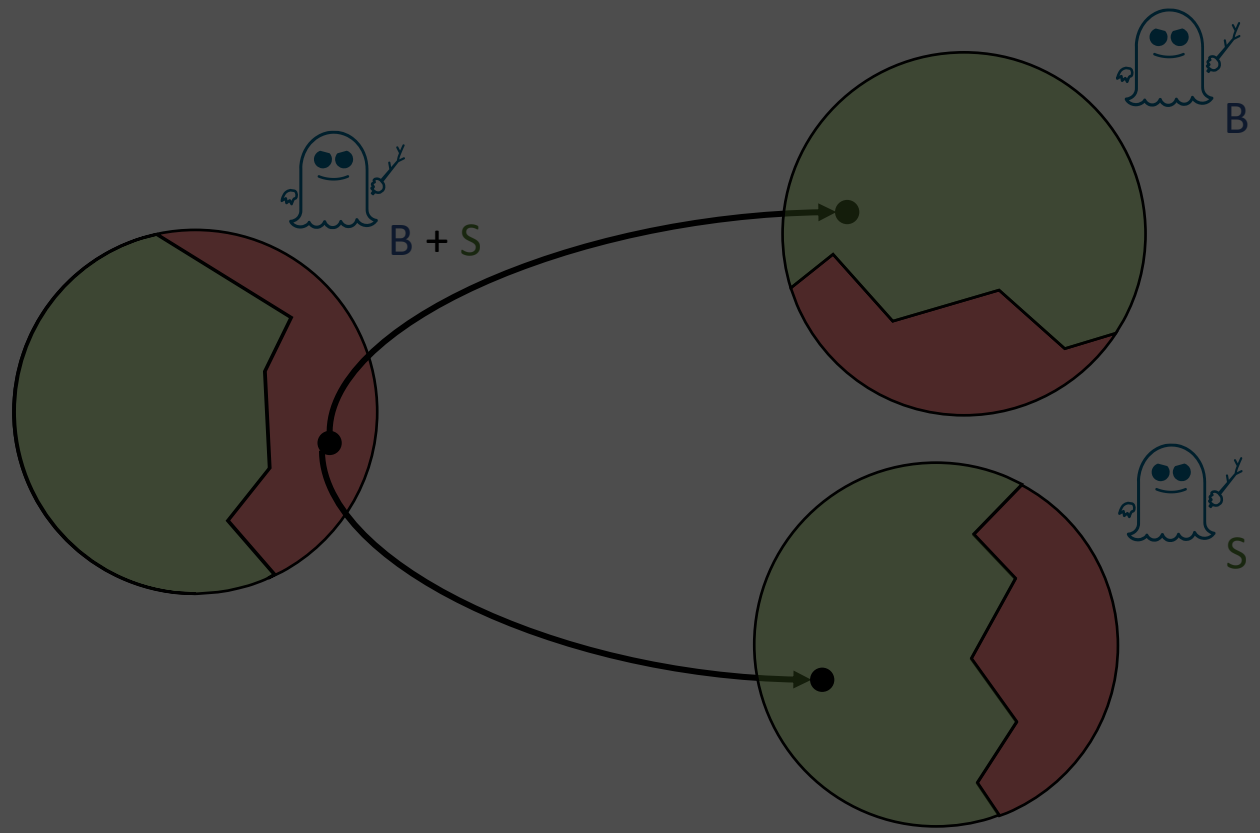


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```
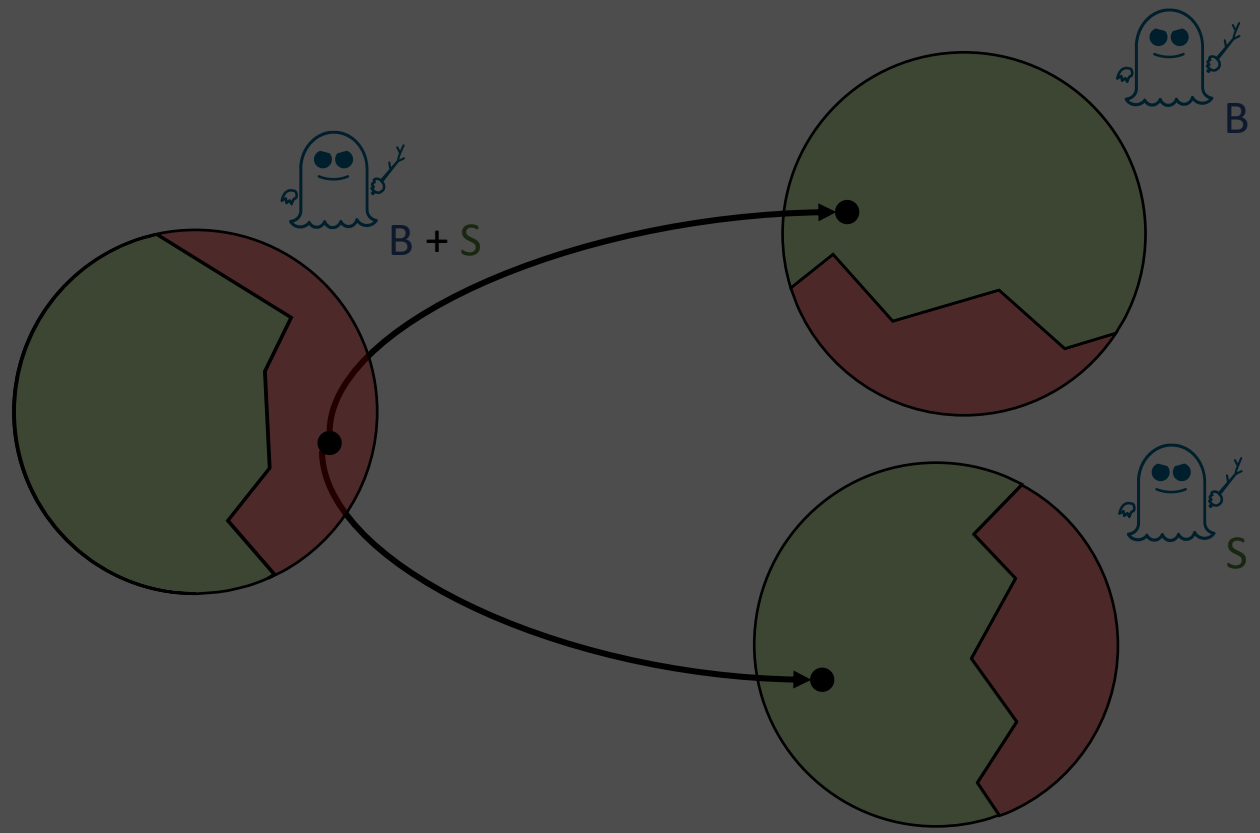

Relationship source and Composition

$p \vdash_{B}$ Secure and $p \vdash_{S}$ Secure $\not\Rightarrow$ $p \vdash_{B+S}$ Secure

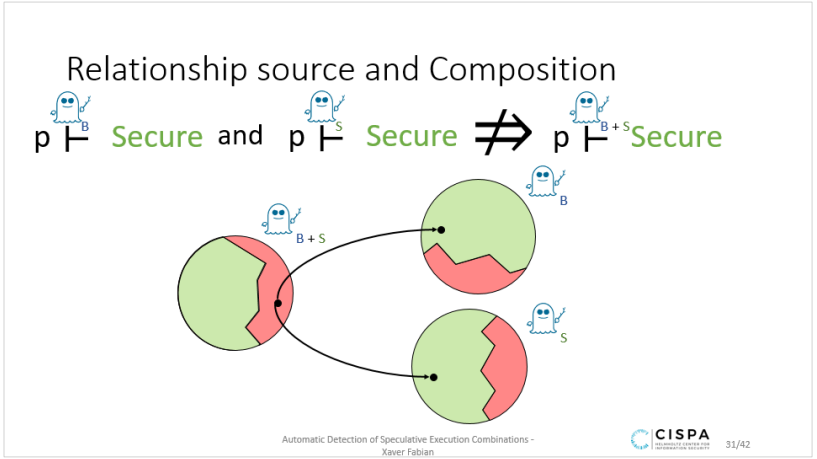



```
1. x = 0
2. p = &secret
3. p = &public
4. if x != 0
5.     y = A[*p]
6.     z = B[y]
```

Evaluation : Combinations

Test case		$\mathcal{B}$ [2]	$\mathcal{S}$	$\mathcal{R}$	$\mathcal{B}$+$\mathcal{S}$	$\mathcal{S}$+$\mathcal{R}$	$\mathcal{B}$+$\mathcal{R}$	$\mathcal{B}$+$\mathcal{S}$+$\mathcal{R}$
listing 1	(-)	●	●	●	○	●	●	○
listing 5	(-)	●	●	●	●	○	●	○
listing 4	(-)	●	●	●	●	●	○	○
listing 6	(-)	●	●	●	●	●	●	○
listing 1 Fence	(+)	●	●	●	●	●	●	●
listing 5 Fence	(+)	●	●	●	●	●	●	●
listing 4 Fence	(+)	●	●	●	●	●	●	●
listing 6 Fence	(+)	●	●	●	●	●	●	●

(c) Results for the Spectre-Comb programs where "listing x Fence" denotes the patched version (using `lfence`) of "listing x"



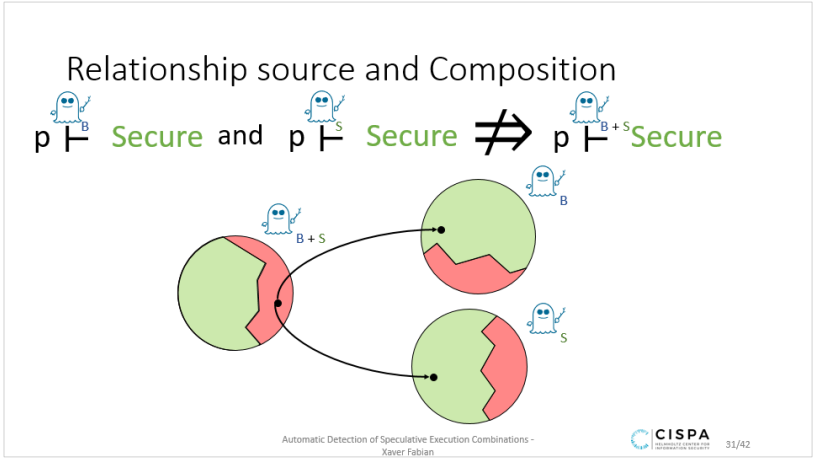
- ● : **Secure** under the resp. Semantics
- ○ : **Insecure** under the resp. Semantics

[2] Spectector, Guarnieri et al., IEEE S&P, 2020

Evaluation : Combinations

Test case		[2] B	S	R	$B+S$	$S+R$	$B+R$	$B+S+R$
listing 1	(-)	●	●	●	○	●	●	○
listing 5	(-)	●	●	●	●	○	●	○
listing 4	(-)	●	●	●	●	●	○	○
listing 6	(-)	●	●	●	●	●	●	○
listing 1 Fence	(+)	●	●	●	●	●	●	●
listing 5 Fence	(+)	●	●	●	●	●	●	●
listing 4 Fence	(+)	●	●	●	●	●	●	●
listing 6 Fence	(+)	●	●	●	●	●	●	●

(c) Results for the Spectre-Comb programs where "listing x Fence" denotes the patched version (using `lfence`) of "listing x"



- ● : **Secure** under the resp. Semantics
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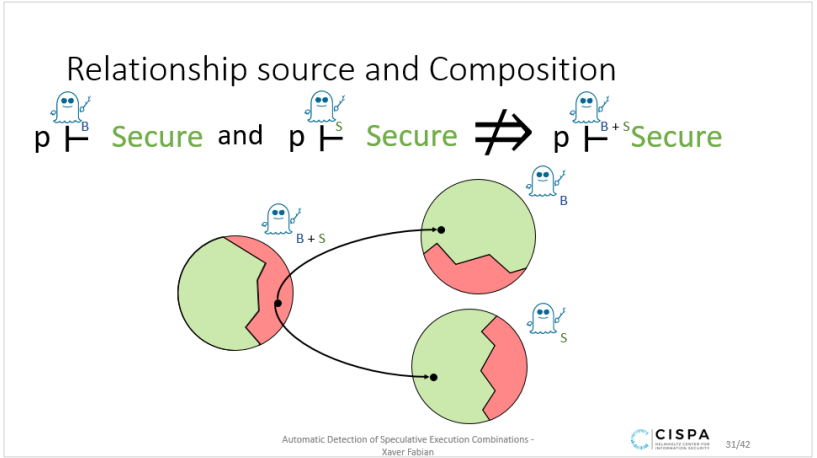
[2] Spectector, Guarnieri et al., IEEE S&P, 2020

Evaluation : Combinations

Test case		B [2]	S	R	B+S	S+R	B+R	B+S+R
listing 1	(-)	●	●	●	○	●	●	○
listing 5	(-)	●	●	●	●	○	●	○
listing 4	(-)	●	●	●	●	●	○	○
listing 6	(-)	●	●	●	●	●	●	○
listing 1 Fence	(+)	●	●	●	●	●	●	●
listing 5 Fence	(+)	●	●	●	●	●	●	●
listing 4 Fence	(+)	●	●	●	●	●	●	●
listing 6 Fence	(+)	●	●	●	●	●	●	●

(c) Results for the Spectre-Comb programs where "listing x Fence" denotes the patched version (using `lfence`) of "listing x"



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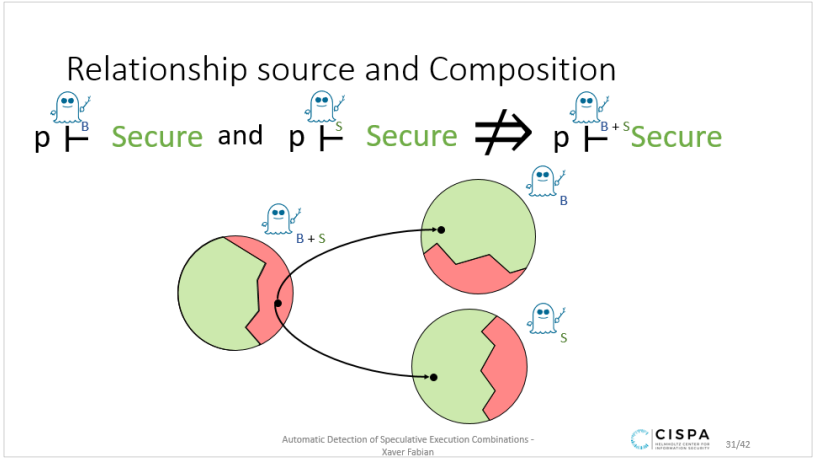
- ○ : **Insecure** under the resp. Semantics

[2] Spectector, Guarnieri et al., IEEE S&P, 2020

Evaluation : Combinations

Test case		B [2]	S	R	$B+S$	$S+R$	$B+R$	$B+S+R$
listing 1	(-)	●	●	●	○	●	●	○
listing 5	(-)	●	●	●	●	○	●	○
listing 4	(-)	●	●	●	●	●	○	○
listing 6	(-)	●	●	●	●	●	●	○
listing 1 Fence	(+)	●	●	●	●	●	●	●
listing 5 Fence	(+)	●	●	●	●	●	●	●
listing 4 Fence	(+)	●	●	●	●	●	●	●
listing 6 Fence	(+)	●	●	●	●	●	●	●

(c) Results for the Spectre-Comb programs where "listing x Fence" denotes the patched version (using `lfence`) of "listing x"



- ● : **Secure** under the resp. Semantics
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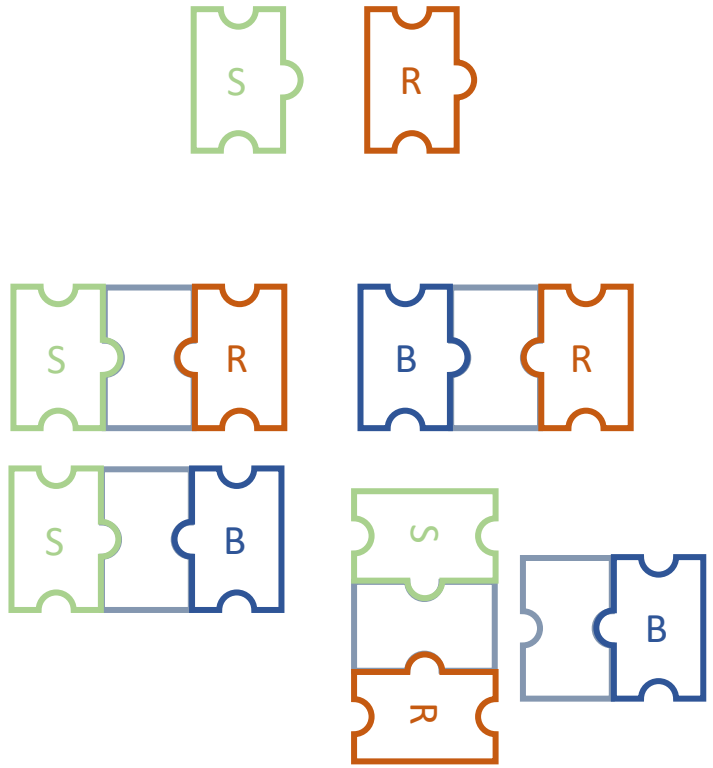
[2] Spectector, Guarnieri et al., IEEE S&P, 2020

In the paper you will find…

- Source Semantics
- A general framework for combinations
- => Derivable Lemmas from framework
- Created all combinations
- Implementation as extension of Spectector
- Evaluation



Spectre Examples


```
1. if idx < A_size
2.     y = A[idx]
3.     z = B[y]
4. end
```


```
1. p = &secret
2. p = &public
3. temp = B[*p]
```

What about this one?

```
1. x = 0
2. p = &secret
3. p = &public
4. if x != 0
5.     y = A[*p]
6.     z = B[y]
7. end
```

Evaluation

Test case		λ_S None	λ_S Fence
case01	(-)	○	●
case02	(-)	○	●
case03	(+)	●	●
case04	(-)	○	●
case05	(-)	○	●
case06	(-)	○	●
case07	(-)	○	●
case08	(-)	○	●
case09	(+)	●	●
case10	(-)	○	●
case11	(-)	○	●
case12	(+)	●	●
case13	(-)	○	●

(a) Results for the Spectre-STL programs under the λ_S semantics against unpatched programs (column "None") and programs patched with `lfence` (column "Fence")

Test case		λ_R None	λ_R Fence	λ_R Retpoline
ret2spec_c_d	(-)	○	●	●
ca_ip	(-)	○	●	●
ca_oop	(-)	○	●	●
sa_ip	(-)	○	●	●
sa_oop	(-)	○	●	●

(b) Results for the Spectre-RSB programs under the λ_R semantics against unpatched programs (column "None"), programs patched with `lfence` (column "Fence"), and programs patched with retpoline (column "Retpoline")

● : **Secure** under the resp. Semantics

○ : **Insecure** under the resp. Semantics

Evaluation

Test case		λ_S None	λ_S Fence
case01	(-)	○	●
case02	(-)	○	●
case03	(+)	●	●
case04	(-)	○	●
case05	(-)	○	●
case06	(-)	○	●
case07	(-)	○	●
case08	(-)	○	●
case09	(+)	●	●
case10	(-)	○	●
case11	(-)	○	●
case12	(+)	●	●
case13	(-)	○	●

(a) Results for the Spectre-STL programs under the λ_S semantics against unpatched programs (column "None") and programs patched with `lfence` (column "Fence")

Test case		λ_R None	λ_R Fence	λ_R Retpoline
ret2spec_c_d	(-)	○	●	●
ca_ip	(-)	○	●	●
ca_oop	(-)	○	●	●
sa_ip	(-)	○	●	●
sa_oop	(-)	○	●	●

(b) Results for the Spectre-RSB programs under the λ_R semantics against unpatched programs (column "None"), programs patched with `lfence` (column "Fence"), and programs patched with retpoline (column "Retpoline")

● : **Secure** under the resp. Semantics

○ : **Insecure** under the resp. Semantics

Stronger than sum of its parts