PL 구현체를 위한 새로운 커버리지를 제안하기까지의 여정

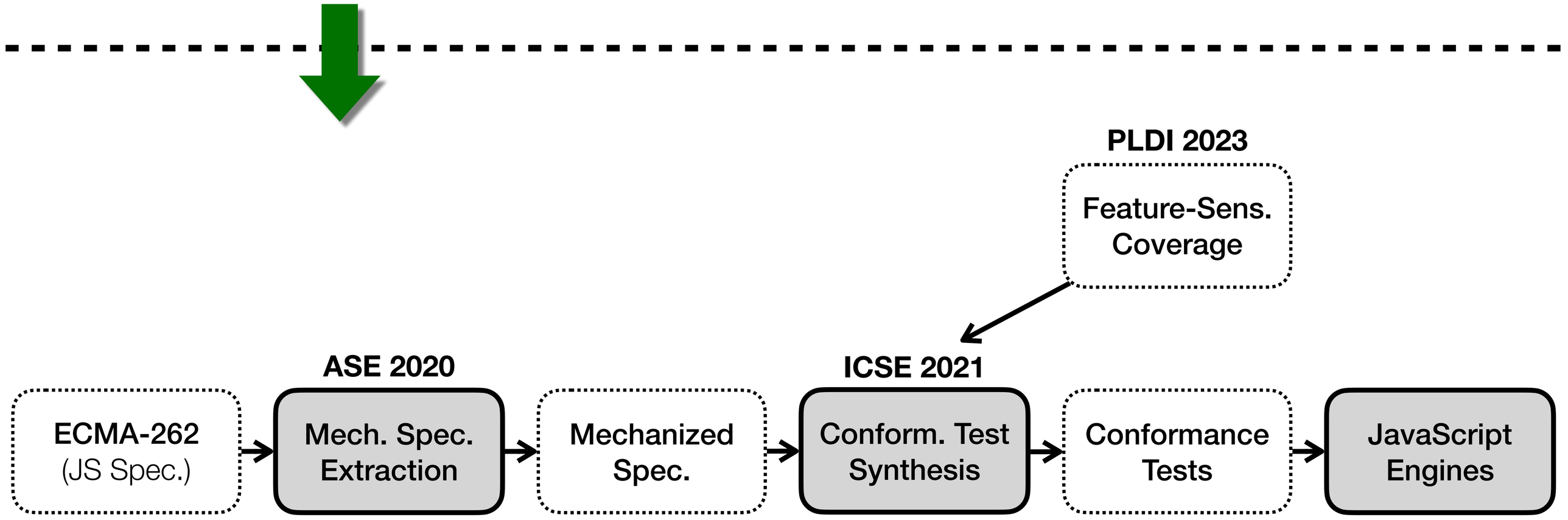
박지혁
고려대학교 정보대학 컴퓨터학과

(with 안승민, 윤동준, 박지희, 김경원, 이강욱, 류석영 교수님)

KOREA UNIVERSITY

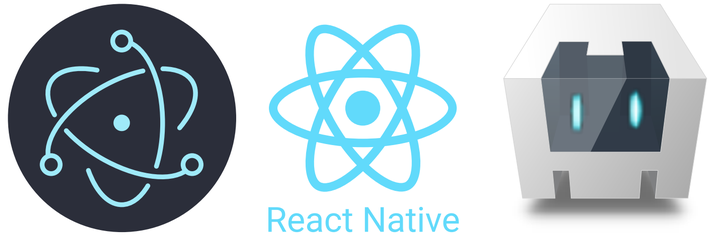
SIGPL Summer School 2023
2023.08.24

Background + Problem



JavaScript is Everywhere

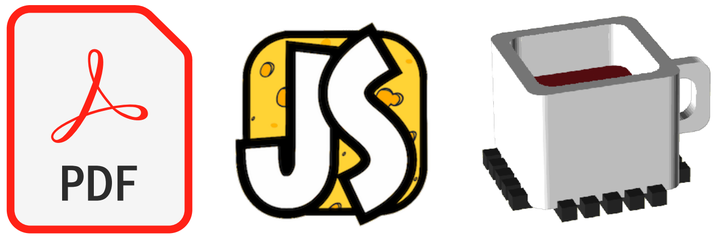
Client-Side Programming



Mobile/Desktop Applications

JS

Sever-Side Programming

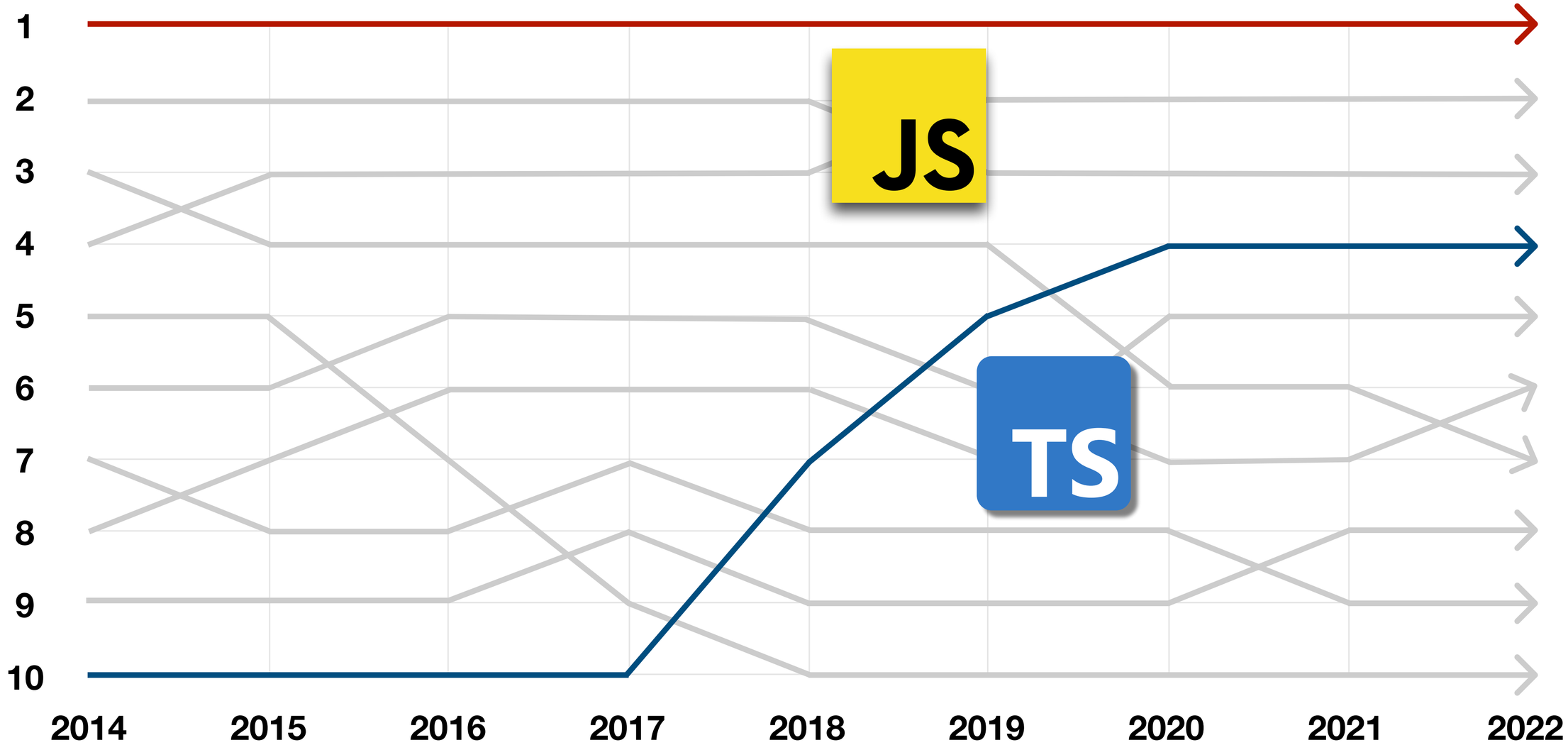


Others (PDF, IoT, Microcontrollers, etc.)

PLRG

JavaScript is Everywhere

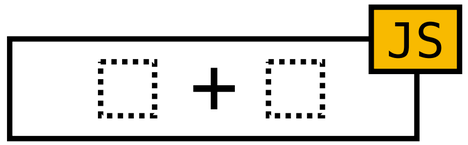
GitHub

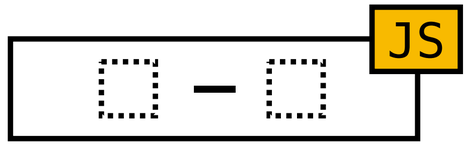


https://octoverse.github.com/

PLRG

But, **JavaScript** is Complicated





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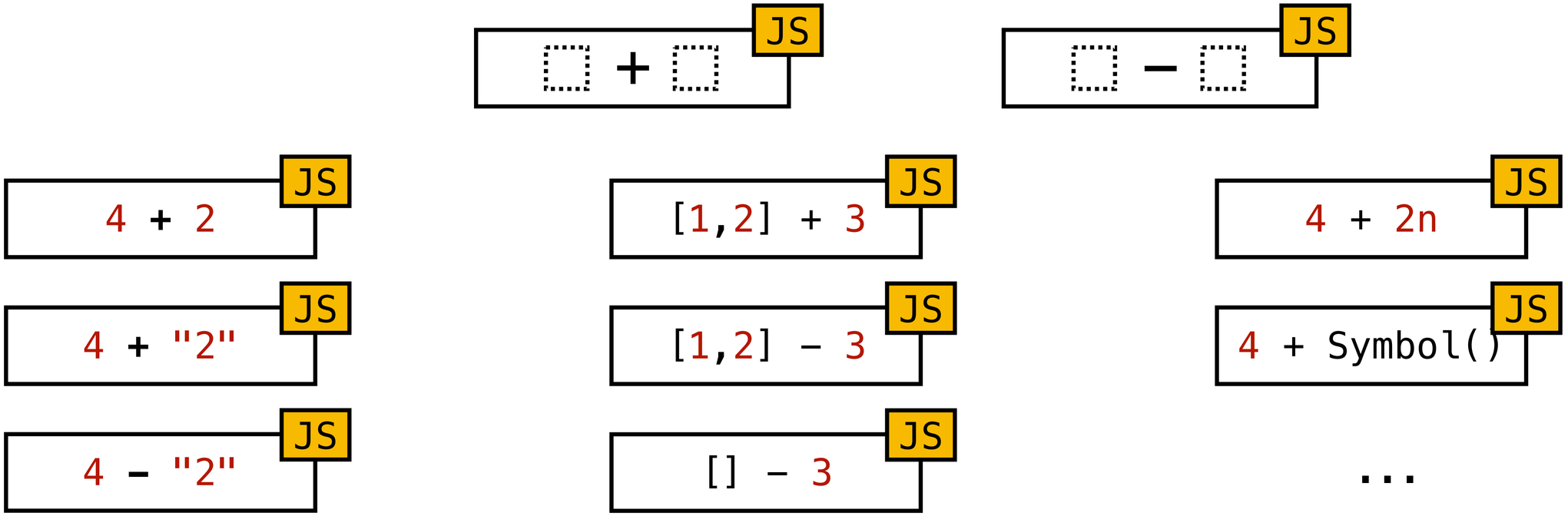

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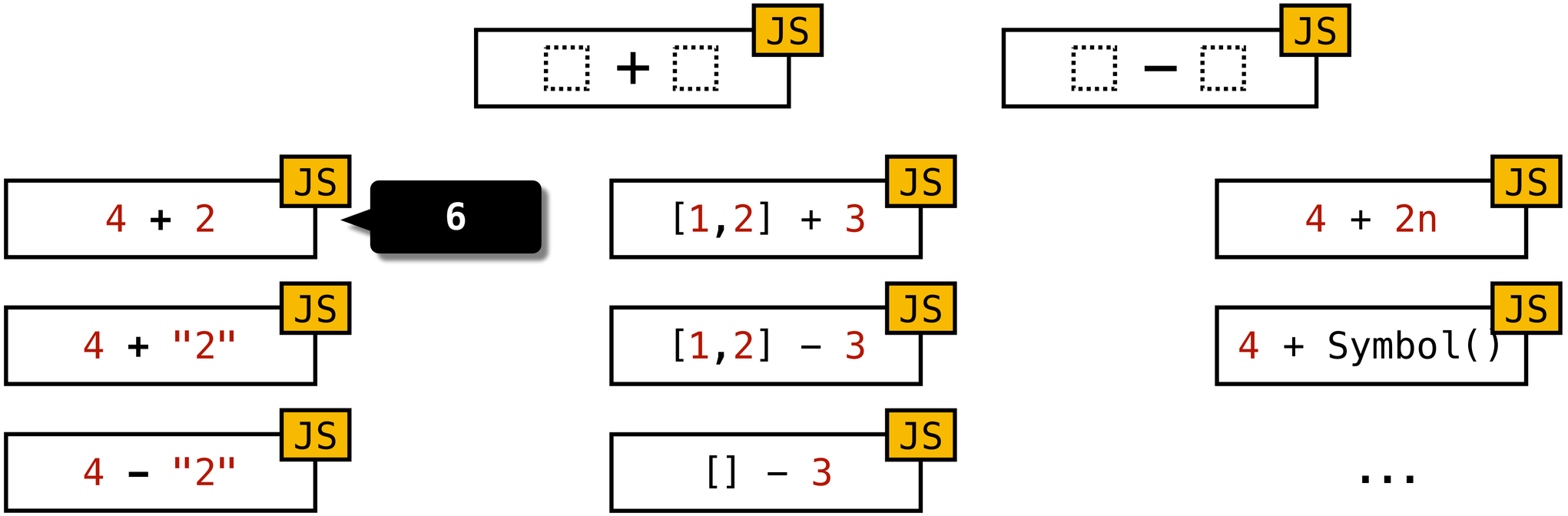

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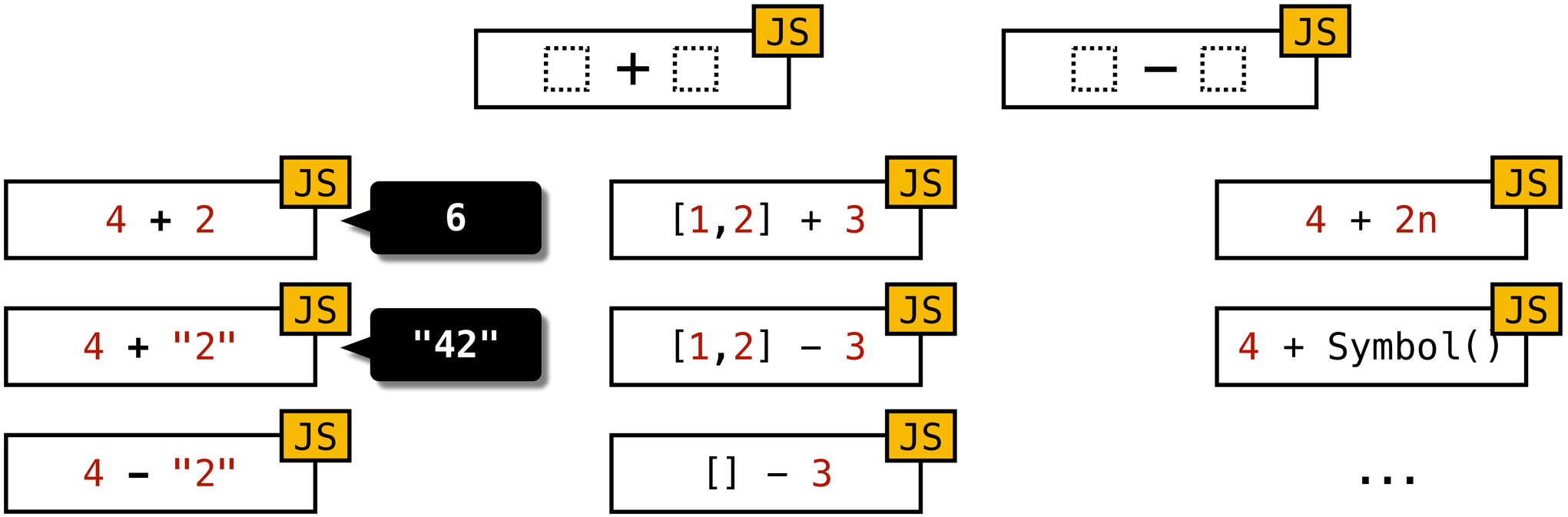

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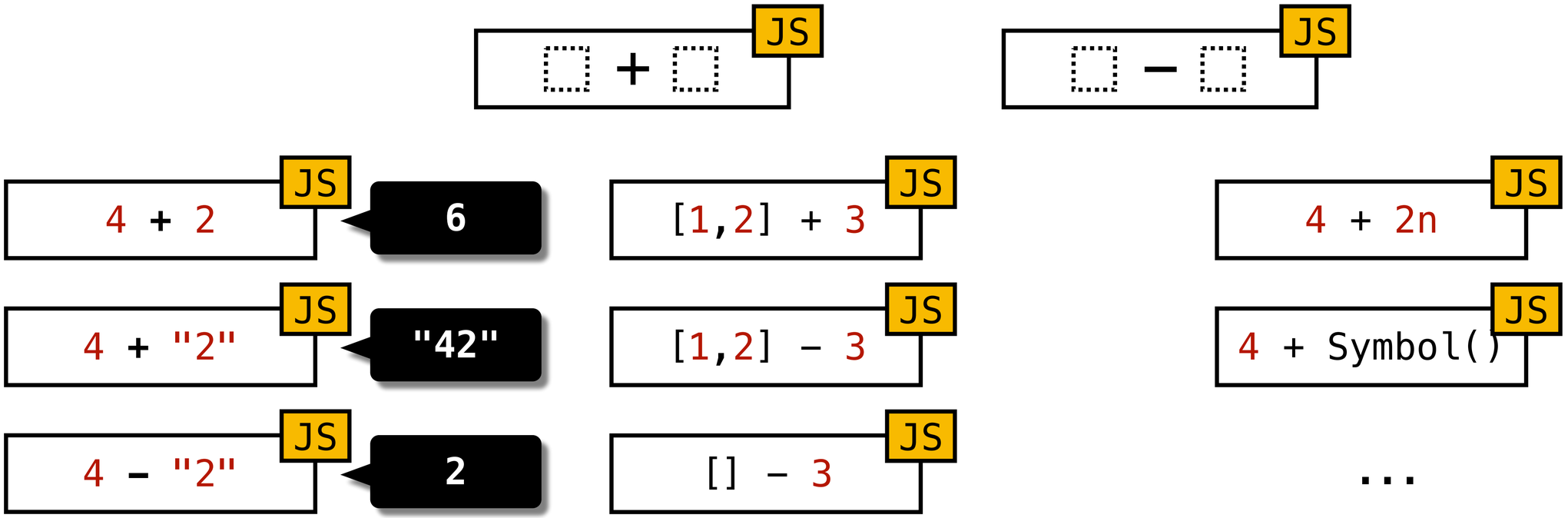

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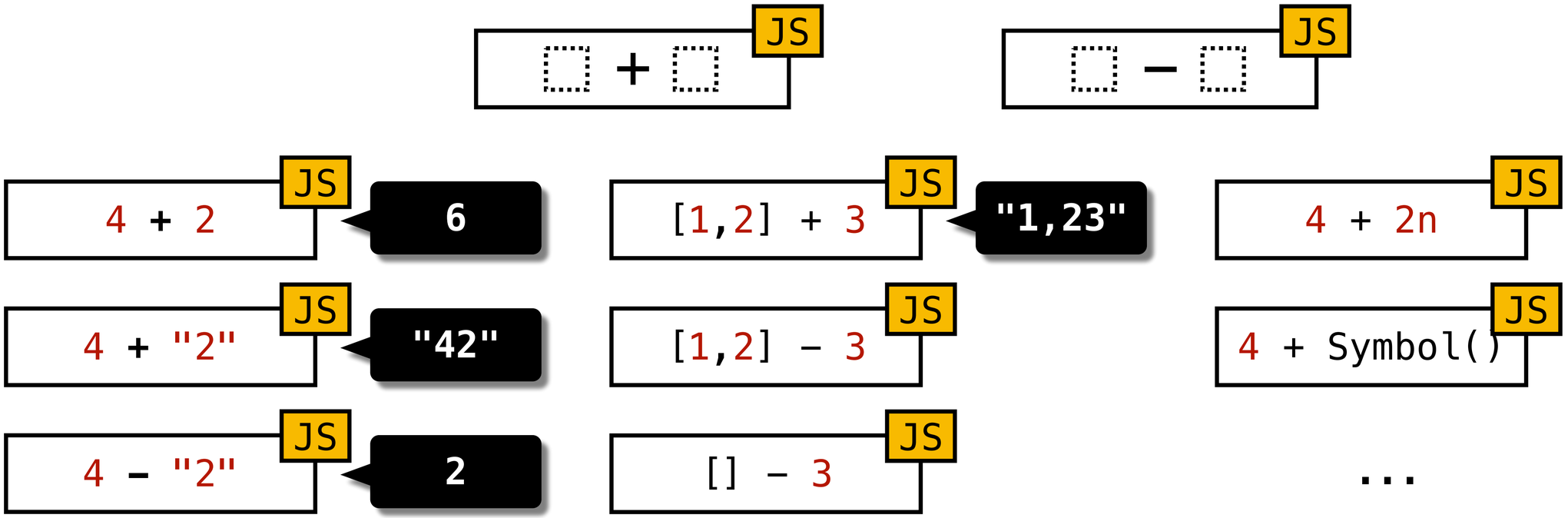

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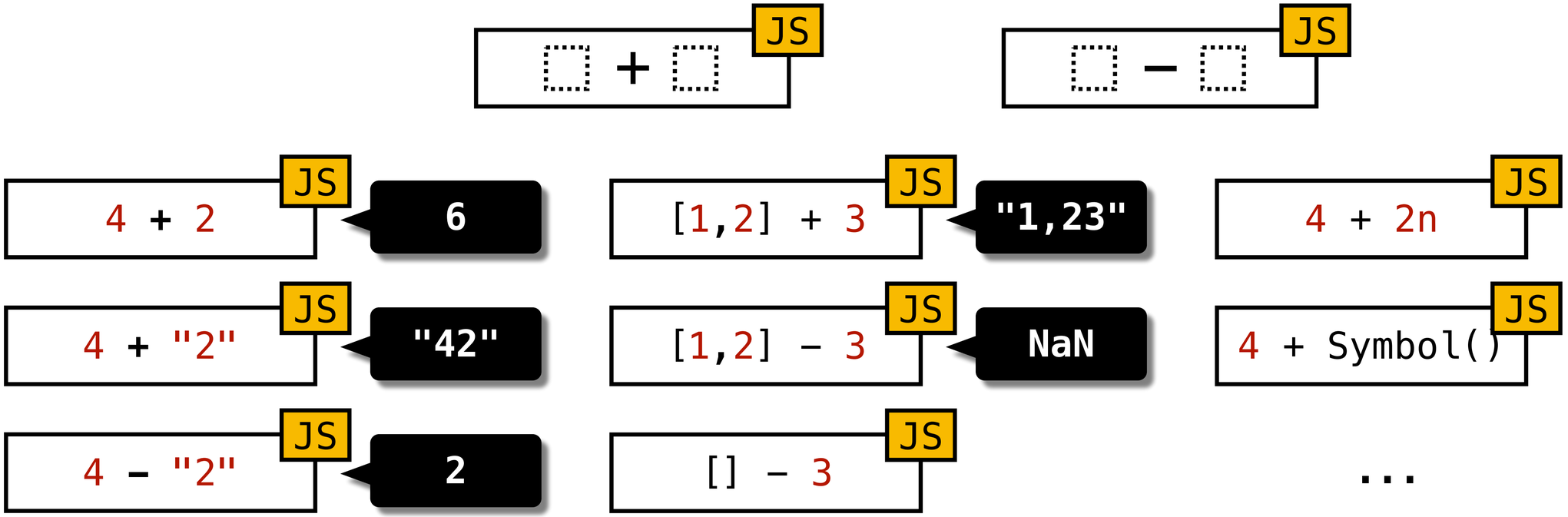

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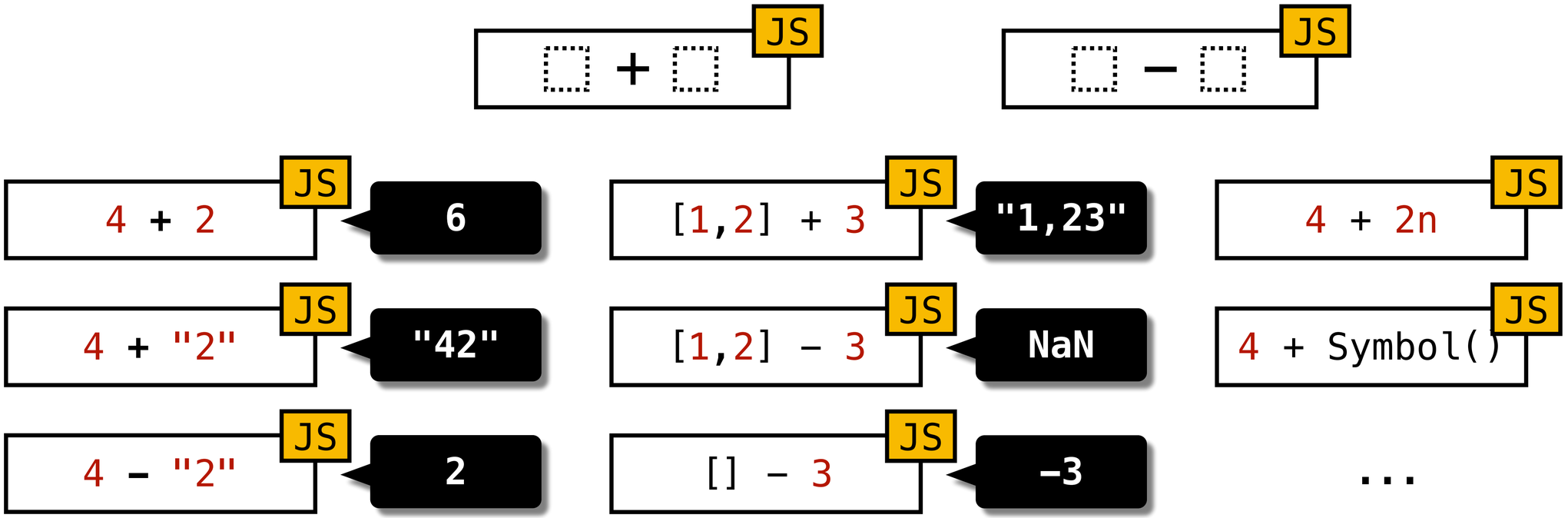

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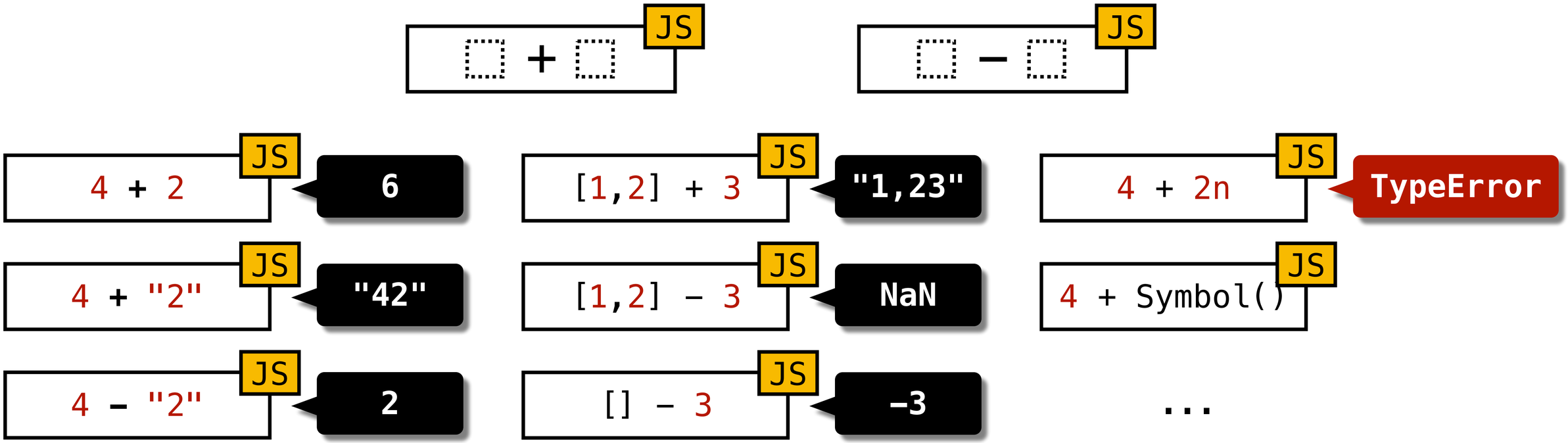

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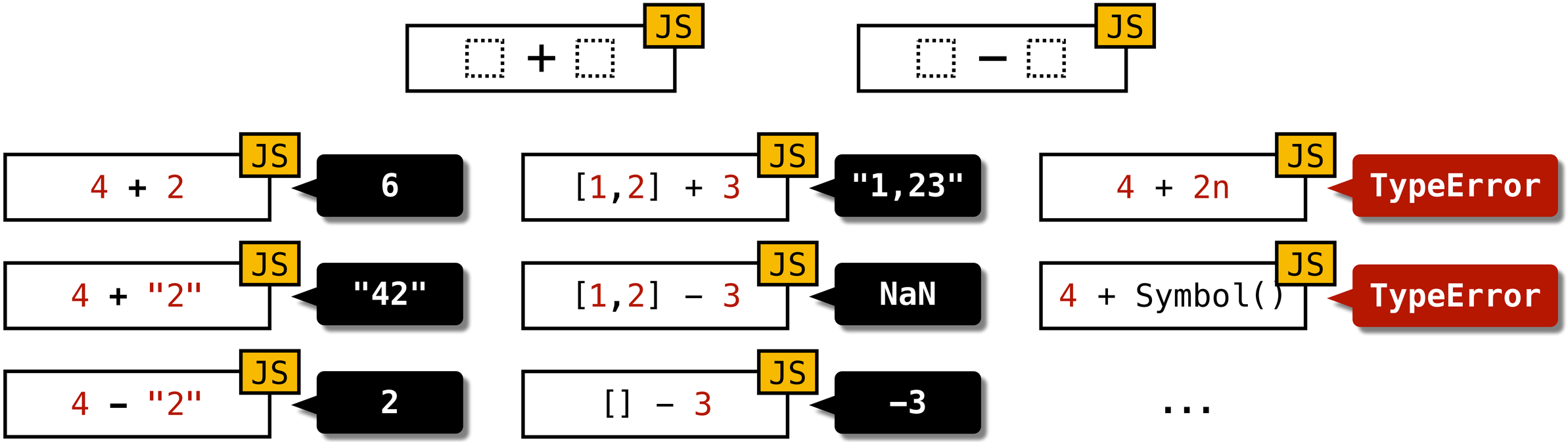

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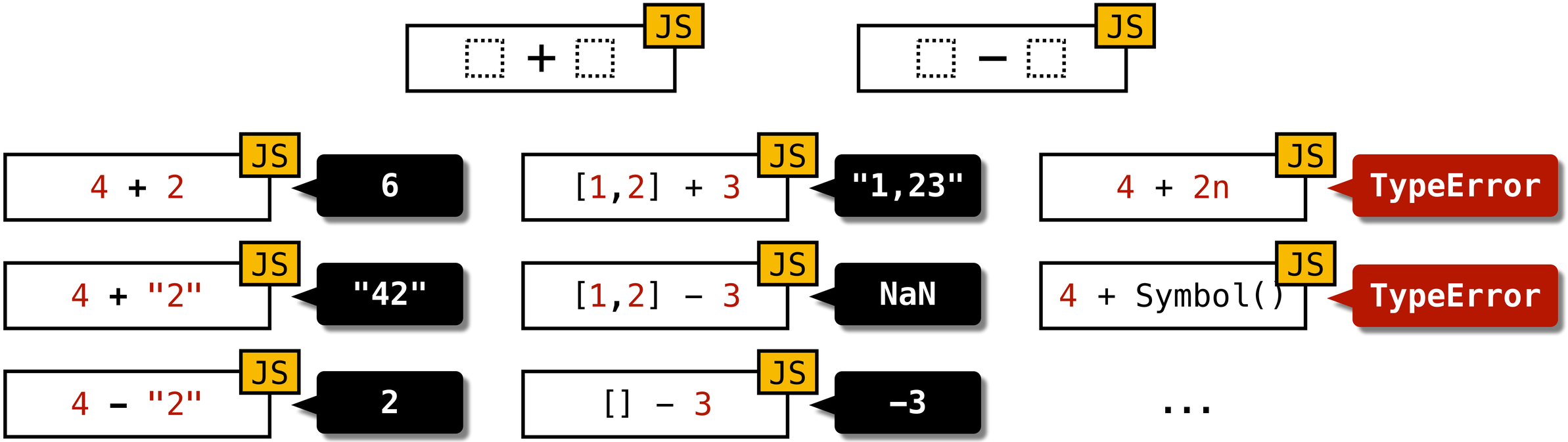
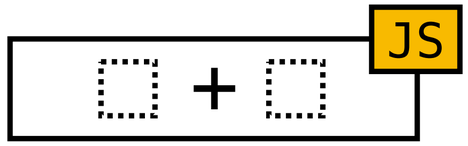



```
(![]+[])[+[]]                    +   // "f"
(![]+[])[+!+[]]                  +   // "a"
([![]]+[][[]])[+!+[]+[+[]]] +   // "i"
(![]+[])[!+[]+!+[]]                  // "l"
```

"fail"

Language Specification (ECMA-262) of JavaScript



TC 39

ECMA-262
(JavaScript Spec.)

Syntax

AdditiveExpression`[Yield, Await]` :

MultiplicativeExpression`[?Yield, ?Await]`

AdditiveExpression`[?Yield, ?Await]` **+** *MultiplicativeExpression*`[?Yield, ?Await]`

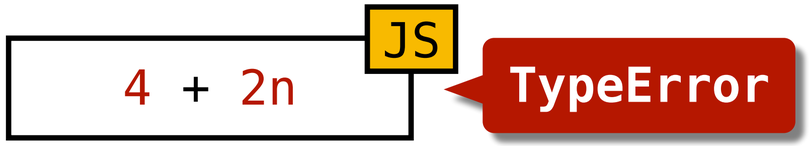
AdditiveExpression`[?Yield, ?Await]` **–** *MultiplicativeExpression*`[?Yield, ?Await]`

Semantics

AdditiveExpression **:** *AdditiveExpression* **+** *MultiplicativeExpression*

1. Return ? EvaluateStringOrNumericBinaryExpression(*AdditiveExpression*, **+**, *MultiplicativeExpression*).

Language Specification (ECMA-262) of JavaScript



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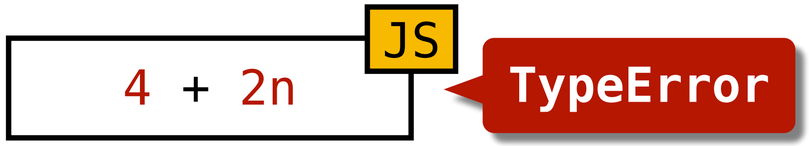
Language Specification (ECMA-262) of JavaScript



AdditiveExpression : *AdditiveExpression* **+** *MultiplicativeExpression*

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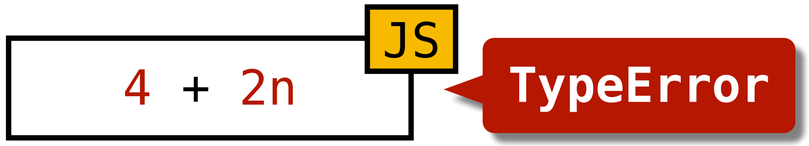
EvaluateStringOrNumericBinaryExpression (*leftOperand*, *opText*, *rightOperand*)

1. Let *lref* be ? Evaluation of *leftOperand*.
2. Let *lval* be ? GetValue(*lref*).
3. Let *rref* be ? Evaluation of *rightOperand*.
4. Let *rval* be ? GetValue(*rref*).
5. Return ? ApplyStringOrNumericBinaryOperator(*lval*, *opText*, *rval*).

Language Specification (ECMA-262) of JavaScript



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Expr **4** | **+** | Expr **2n**

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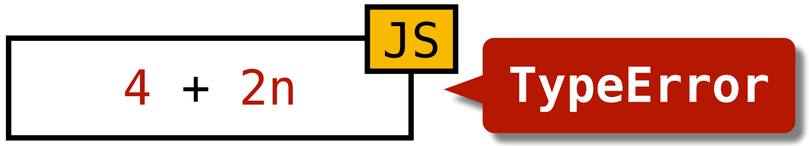
Language Specification (ECMA-262) of JavaScript



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ApplyStringOrNumericBinaryOperator (*lval*, *opText*, *rval*)

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    c. If *lprim* is a String or *rprim* is a String, then
        i. Let *lstr* be ? ToString(*lprim*).
        ii. Let *rstr* be ? ToString(*rprim*).
        iii. Return the string-concatenation of *lstr* and *rstr*.
    d. Set *lval* to *lprim*.
    e. Set *rval* to *rprim*.
2. NOTE: At this point, it must be a numeric operation.
3. Let *lnum* be ? ToNumeric(*lval*).
4. Let *rnum* be ? ToNumeric(*rval*).
5. If Type(*lnum*) is not Type(*rnum*), throw a **TypeError** exception.

...

Language Specification (ECMA-262) of JavaScript

```
4 + 2n
```
JS

TypeError

AdditiveExpression : *AdditiveExpression* **+** *MultiplicativeExpression*

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ApplyStringOrNumericBinaryOperator (*lval*, *opText*, *rval*)

Number **4** | **+** | BigInt **2n**

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Language Specification (ECMA-262) of JavaScript

JS

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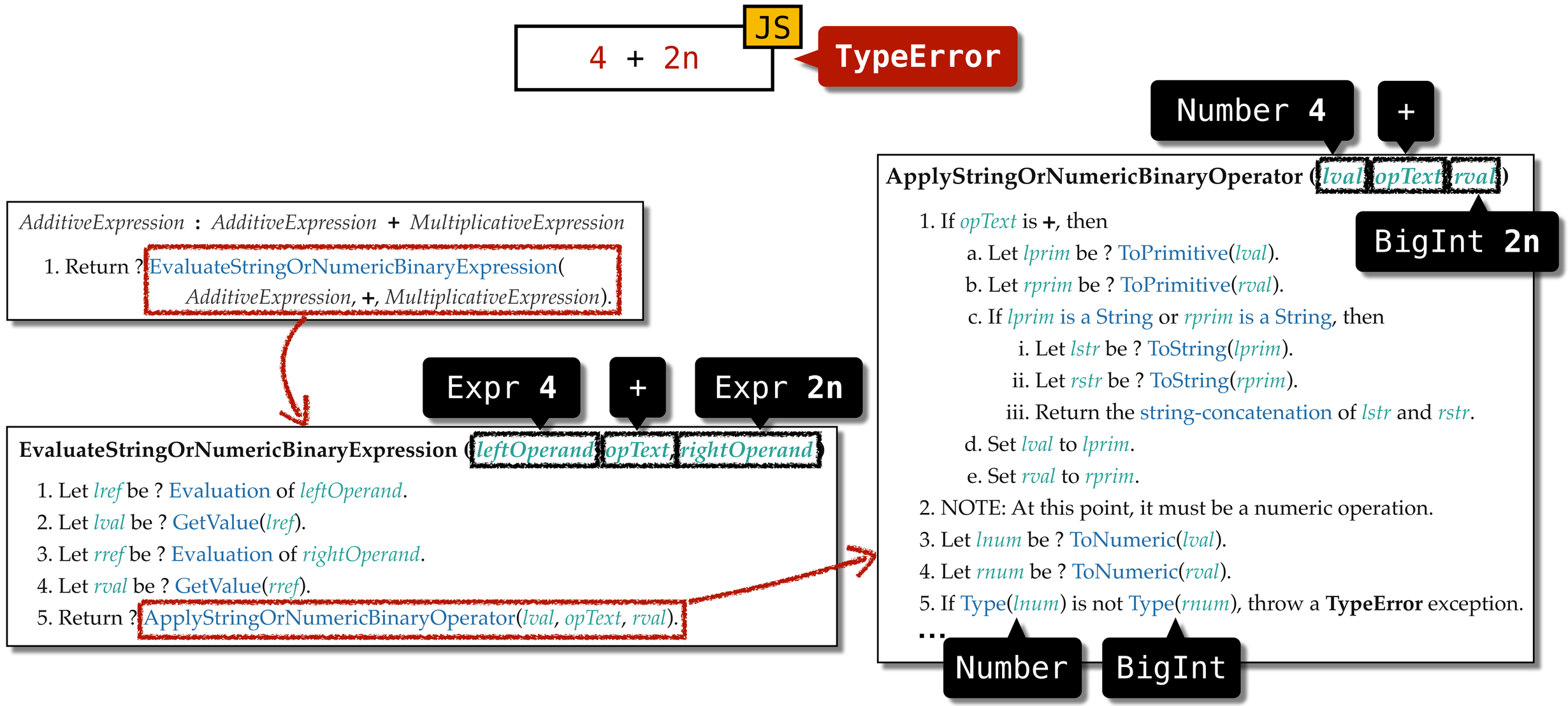
Number

Language Specification (ECMA-262) of JavaScript



Language Specification (ECMA-262) of JavaScript

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4 + 2n
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Number 4 | + | BigInt 2n

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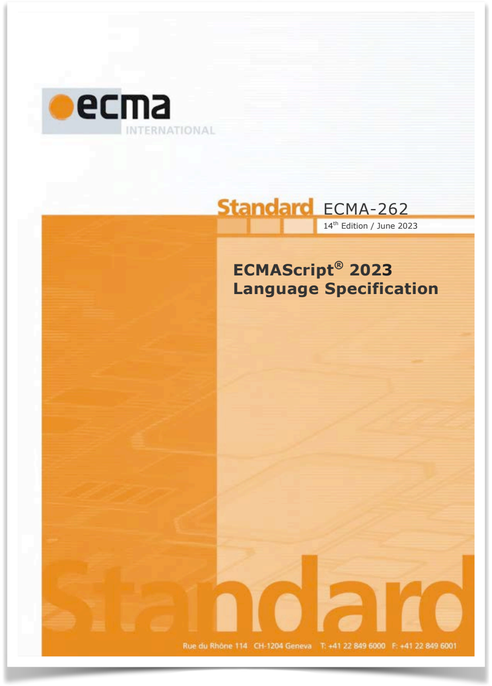
...

Number | BigInt | TypeError

Conformance of JavaScript Engines



ECMA-262
(JavaScript Spec.)

Conformance

Test262
(Official Test Suite)

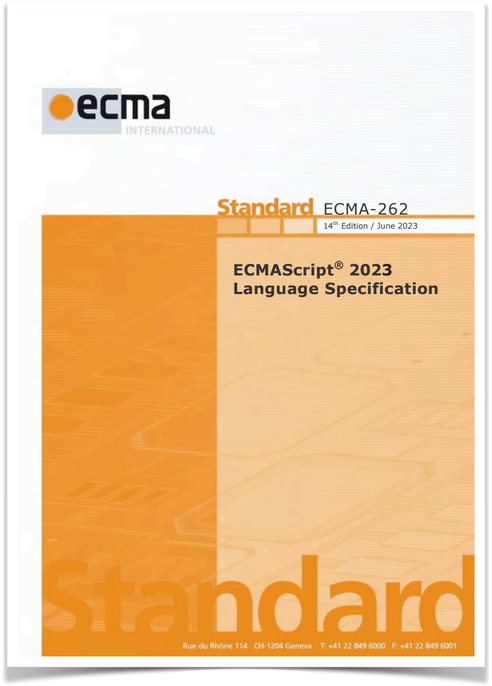
GraalVM™

QuickJS

moddable

JavaScript Engines

Conformance of JavaScript Engines



ECMA-262
(JavaScript Spec.)

How?

Conformance

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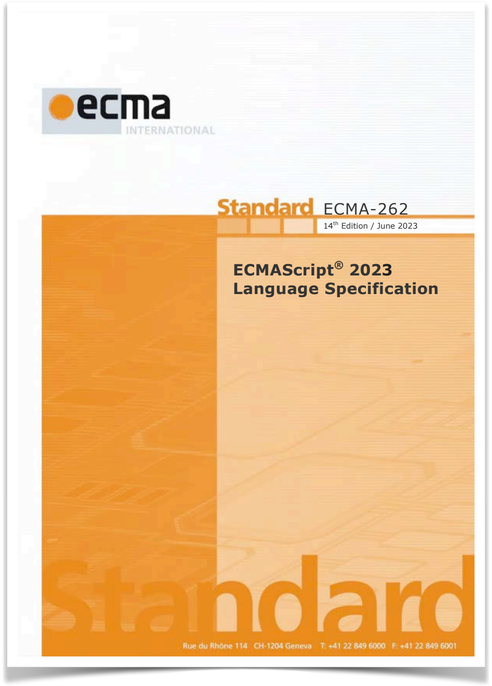
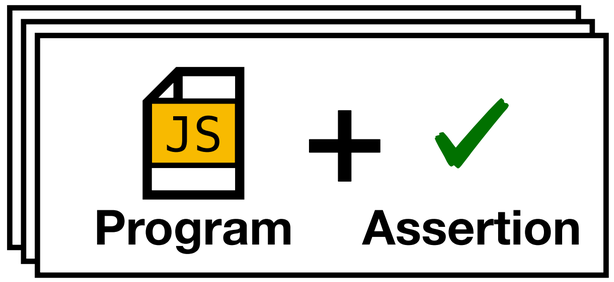
JavaScript Engines

Conformance of JavaScript Engines



ECMA-262
(JavaScript Spec.)



Conformance Tests

Conformance

Test262
(Official Test Suite)

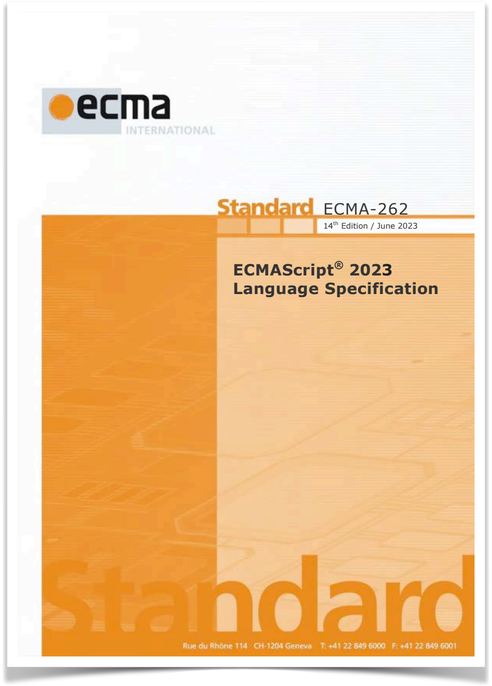
GraalVM™

QuickJS

moddable

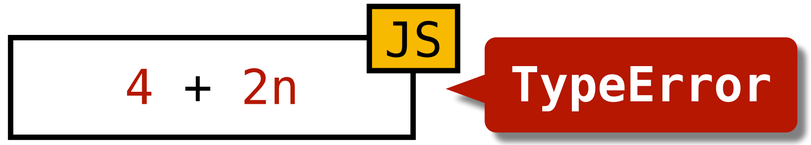
JavaScript Engines

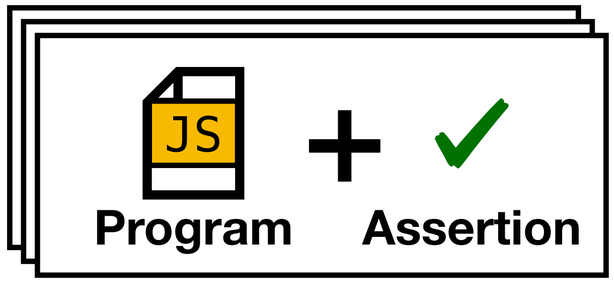
Conformance of JavaScript Engines



ECMA-262
(JavaScript Spec.)

Example:





Conformance Tests

Test262
(Official Test Suite)

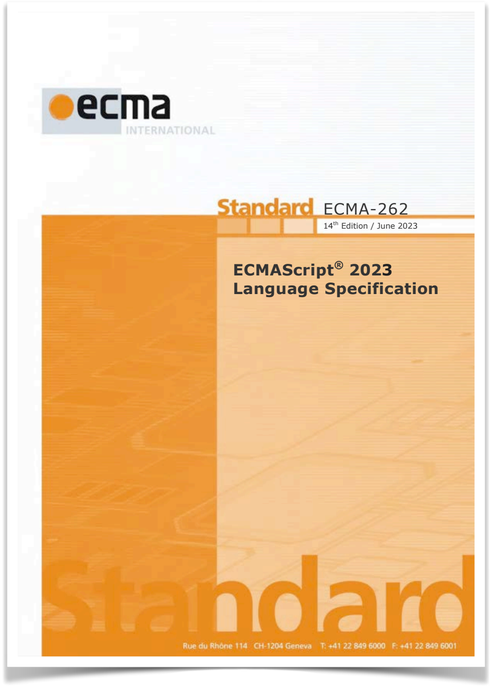
GraalVM™

QuickJS

moddable

JavaScript
Engines

Problem - Manual Approach



ECMA-262
(JavaScript Spec.)

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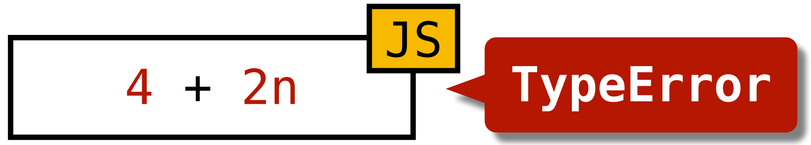
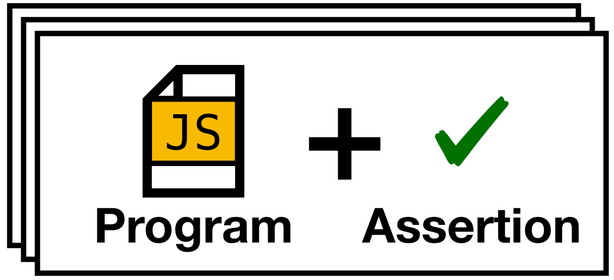




Conformance Tests

Conformance

Test262
(Official Test Suite)

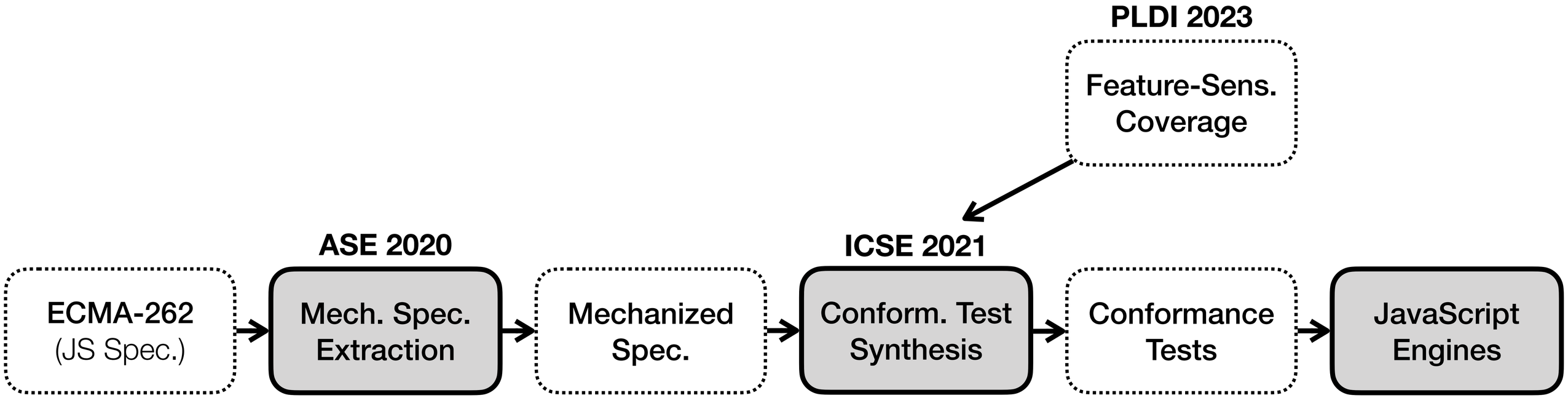
Manual

GraalVM™

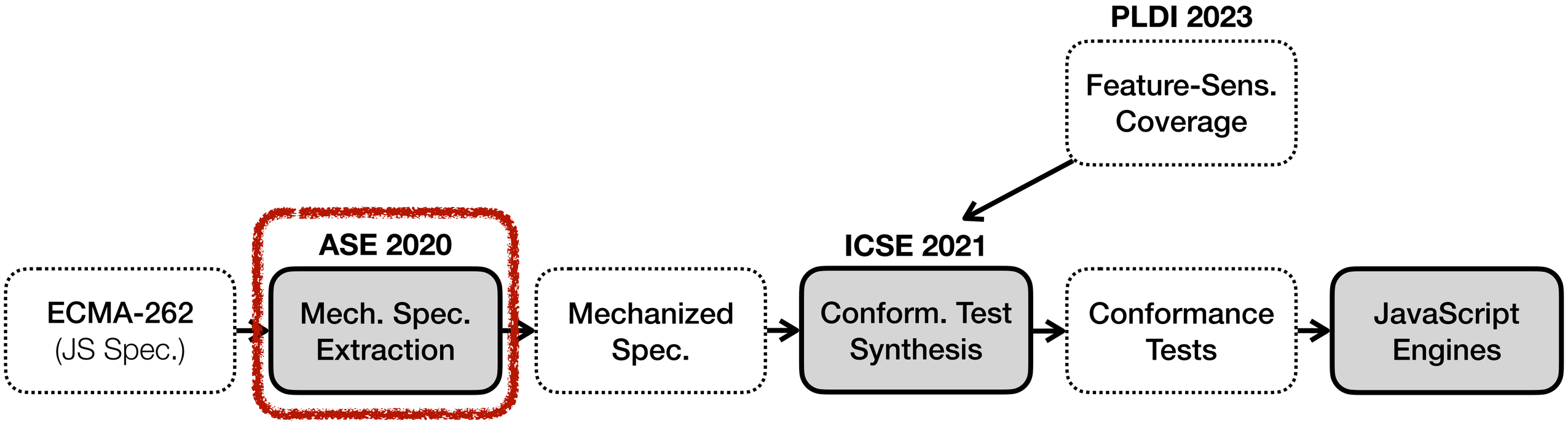
QuickJS

moddable

JavaScript Engines

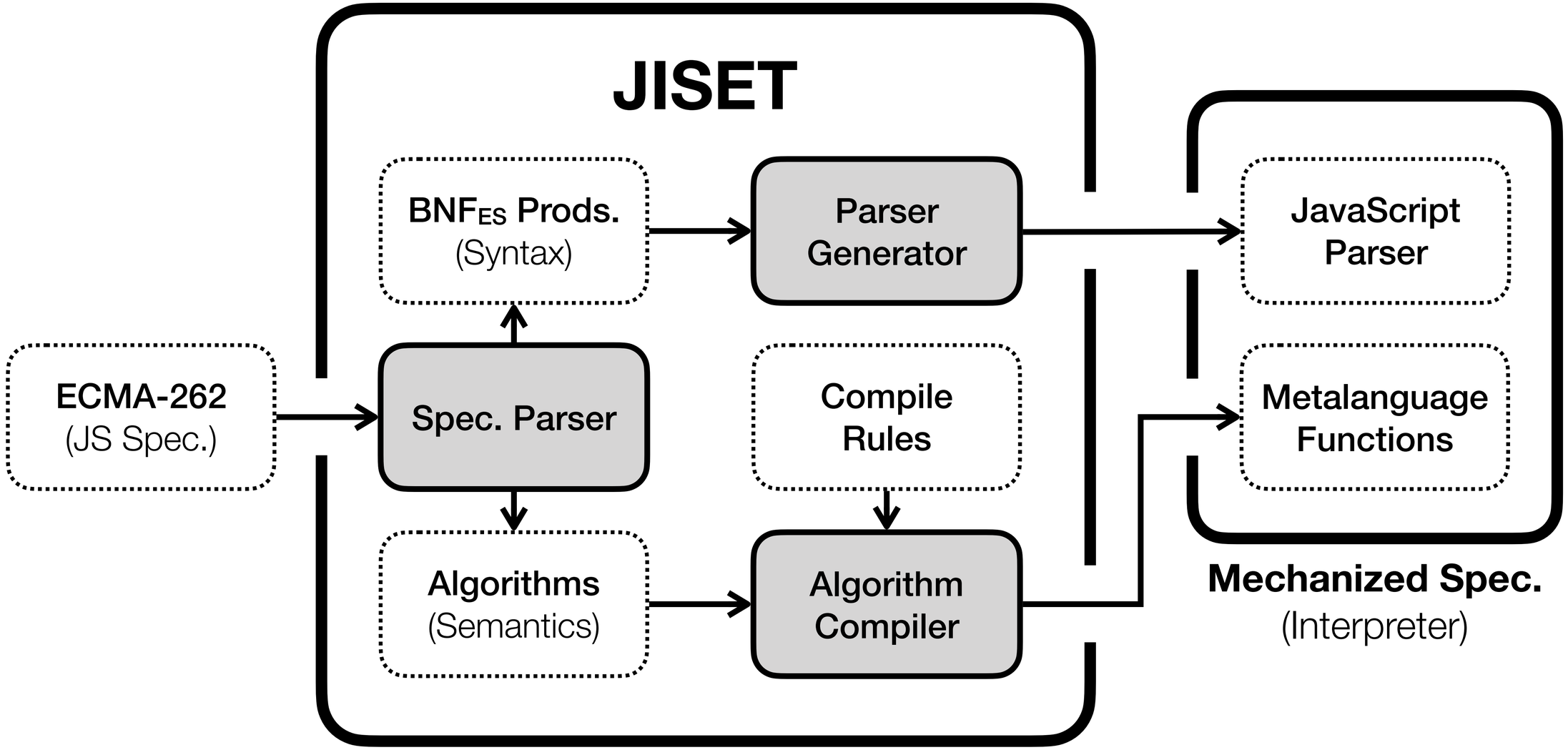


[ASE'20] J. Park, J. Park, S. An, and S. Ryu, **JISET: JavaScript IR-based Semantics Extraction Toolchain**

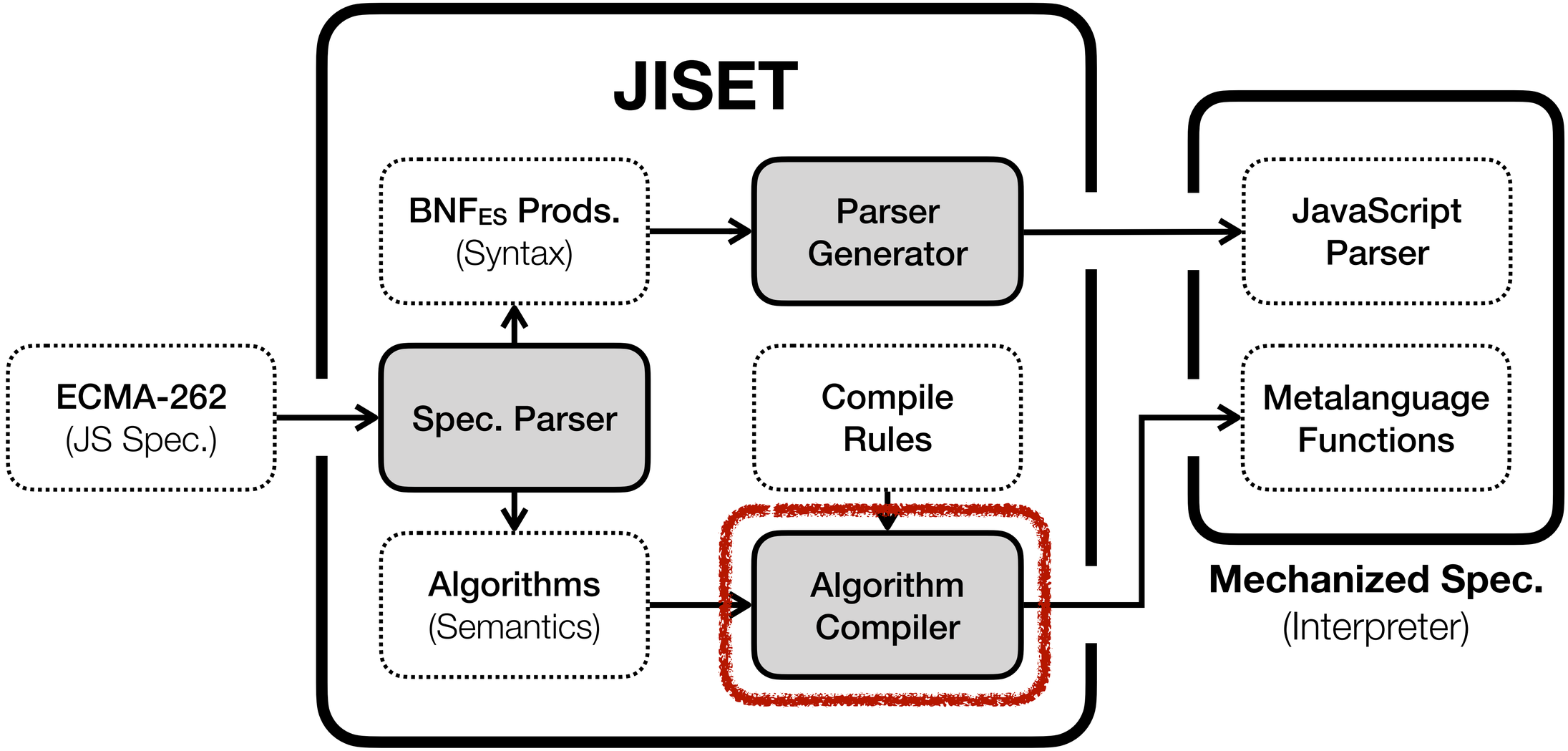


[ASE'20] J. Park, J. Park, S. An, and S. Ryu, **JISET: JavaScript IR-based Semantics Extraction Toolchain**

JISET (JavaScript IR-based Semantics Extraction Toolchain)



JISET (JavaScript IR-based Semantics Extraction Toolchain)



JISET - **Metalanguage** for **Spec.** (ECMA-262)

$$
\begin{array}{lll}
\text{Programs} & \mathfrak{P} \ni P & ::= f^* \\
\text{Functions} & \mathcal{F} \ni f & ::= \texttt{syntax}^? \ \texttt{def x(x}^*\texttt{) \{}[\ell : i]^*\texttt{\}} \\
\text{Variables} & \mathcal{X} \ni \texttt{x} & \\
\text{Labels} & \mathcal{L} \ni \ell & \\
\text{Instructions} & \mathcal{I} \ni i & ::= r := e \mid \texttt{x} := \texttt{\{\}} \mid \texttt{x} := e(e^*) \\
 & & \quad \mid \ \texttt{if}\ e\ \ell\ \ell \mid \texttt{return}\ e \\
\text{Expressions} & \mathcal{E} \ni e & ::= v^{\mathrm{p}} \mid \mathrm{op}(e^*) \mid r \\
\text{References} & \mathcal{R} \ni r & ::= \texttt{x} \mid e\texttt{[}e\texttt{]} \mid e\texttt{[}e\texttt{]}_{\mathrm{js}}
\end{array}
$$

• • •

$$
\begin{array}{lll}
\text{Values} & v \in \mathbb{V} & = \mathbb{A} \uplus \mathbb{V}^{\mathrm{p}} \uplus \mathbb{T} \uplus \mathcal{F} \\
\text{Primitive Values} & v^{\mathrm{p}} \in \mathbb{V}^{\mathrm{p}} & = \mathbb{V}_{\mathsf{bool}} \uplus \mathbb{V}_{\mathsf{int}} \uplus \mathbb{V}_{\mathsf{str}} \uplus \cdots \\
\text{JS ASTs} & t \in \mathbb{T} &
\end{array}
$$

• • •

JISET - **Metalanguage** for **Spec.** (ECMA-262)

Programs	$\mathfrak{P} \ni P ::= f^*$
Functions	$\mathcal{F} \ni f ::= \texttt{syntax}^? \texttt{ def x(x}^*\texttt{) \{}[l : i]^*\texttt{\}}$
Variables	$\mathcal{X} \ni \texttt{x}$
Labels	$\mathcal{L} \ni l$
Instructions	$\mathcal{I} \ni i ::= r := e \mid \texttt{x} := \texttt{\{\}} \mid \texttt{x} := e(e^*)$
	$\mid \texttt{ if } e\ l\ l \mid \texttt{return } e$
Expressions	$\mathcal{E} \ni e ::= v^{\text{p}} \mid \text{op}(e^*) \mid r$
References	$\mathcal{R} \ni r ::= \texttt{x} \mid e\texttt{[}e\texttt{]} \mid e\texttt{[}e\texttt{]}_{\text{js}}$

• • •

Values	$v \in \mathbb{V}$	$= \mathbb{A} \uplus \mathbb{V}^{\text{p}} \uplus \mathbb{T} \uplus \mathcal{F}$
Primitive Values	$v^{\text{p}} \in \mathbb{V}^{\text{p}}$	$= \mathbb{V}_{\text{bool}} \uplus \mathbb{V}_{\text{int}} \uplus \mathbb{V}_{\text{str}} \uplus \cdots$
JS ASTs	$t \in \mathbb{T}$	

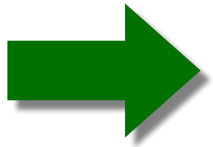
• • •

JISET - Algorithm Compiler

ApplyStringOrNumericBinaryOperator (*lval*, *opText*, *rval*)

1. If *opText* is **+**, then
    a. Let *lprim* be ? ToPrimitive(*lval*).
    b. Let *rprim* be ? ToPrimitive(*rval*).
    c. If *lprim* is a String or *rprim* is a String, then
        i. Let *lstr* be ? ToString(*lprim*).
        ii. Let *rstr* be ? ToString(*rprim*).
        iii. Return the string-concatenation of *lstr* and *rstr*.
    d. Set *lval* to *lprim*.
    e. Set *rval* to *rprim*.
2. NOTE: At this point, it must be a numeric operation.
3. Let *lnum* be ? ToNumeric(*lval*).
4. Let *rnum* be ? ToNumeric(*rval*).
5. If Type(*lnum*) is not Type(*rnum*), throw a **TypeError** exception.
...

118 Compile Rules



```
def ApplyStringOrNumericBinaryOperator(
  lval, opText, rval
) {
  if (= opText "+") {
    let lprim = [? ToPrimitive(lval)]
    let rprim = [? ToPrimitive(rval)]
    if (|| (= (typeof lprim) @String)
           (= (typeof rprim) @String)) {
      let lstr = [? ToString(lprim)]
      let rstr = [? ToString(rprim)]
      return (concat lstr rstr)
    }
    lval = lprim
    rval = rprim
  }
  let lnum = [? ToNumeric(lval)]
  let rnum = [? ToNumeric(rval)]
  if (! (= (typeof lnum) (typeof rnum))) {
    return comp[~throw~](new TypeError)
  }
  ...
}
```

JISET - Evaluation

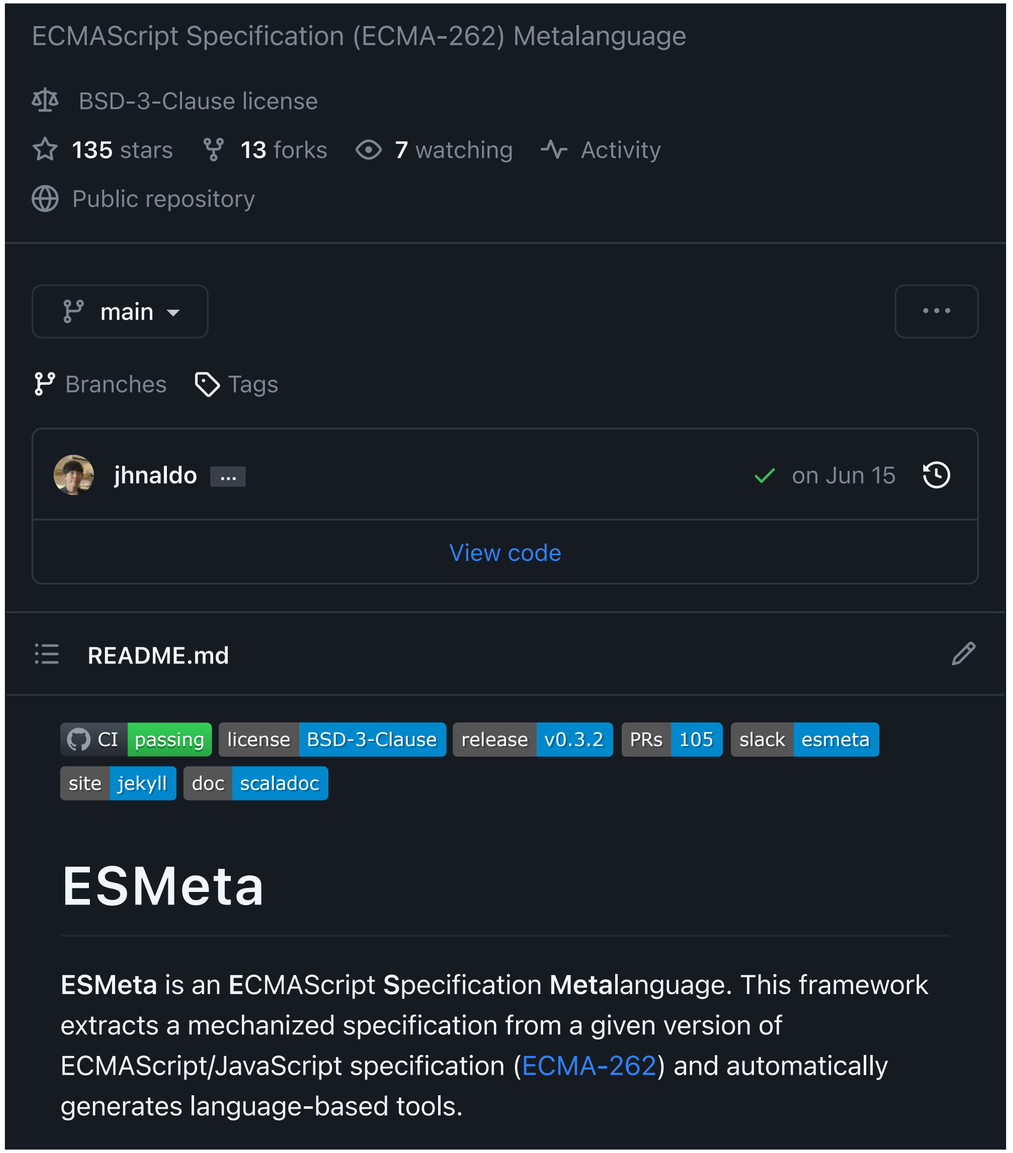
≈ 96% Compiled

auto manual

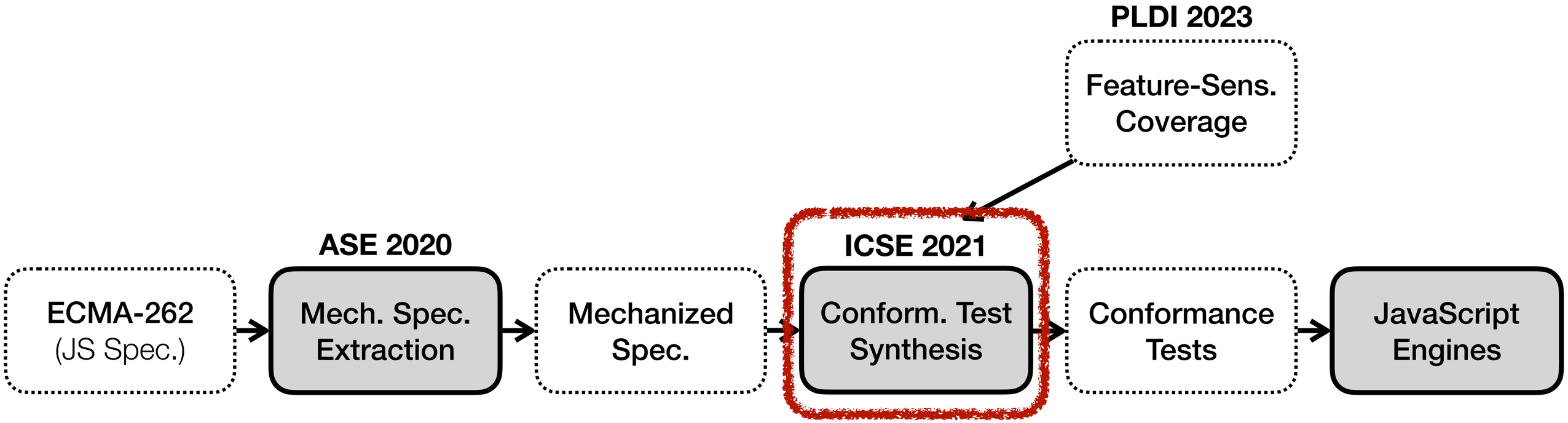
T: Total L: Core Language Semantics B: Bu

Version	# Algo.		
ES7	2,105	T	**10,471 / 10,982** (95.3
		L	**8,041 / 8,415** (95.56%)
		B	**2,430 / 2,567** (94.66%)
ES8	2,238	T	**11,181 / 11,732** (95.30%)
		L	**8,453 / 8,811** (95.94%)
		B	**2,728 / 2,921** (93.39%)
ES9	2,370	T	**11,849 / 12,393** (95.61%)
		L	**8,932 / 9,311** (95.93%)
		B	**2,917 / 3,082** (94.65%)
ES10	2,396	T	**12,022 / 12,569** (95.65%)
		L	**9,073 / 9,456** (94.95%)
		B	**2,949 / 3,113** (94.73%)
ES11	2,521	T	**12,505 / 13,047** (94.85%)
		L	**9,495 / 9,881** (96.09%)
		B	**3,010 / 3,166** (95.07%)
ES12	2,640	T	**12,975 / 13,544** (95.80%)
		L	**9,717 / 10,136** (95.87%)
		B	**3,258 / 3,408** (95.60%)
Average	2,378	T	**11,834 / 12,378** (95.61%)
		L	**8,952 / 9,335** (95.90%)
		B	**2,882 / 3,043** (94.71%)

ESMeta



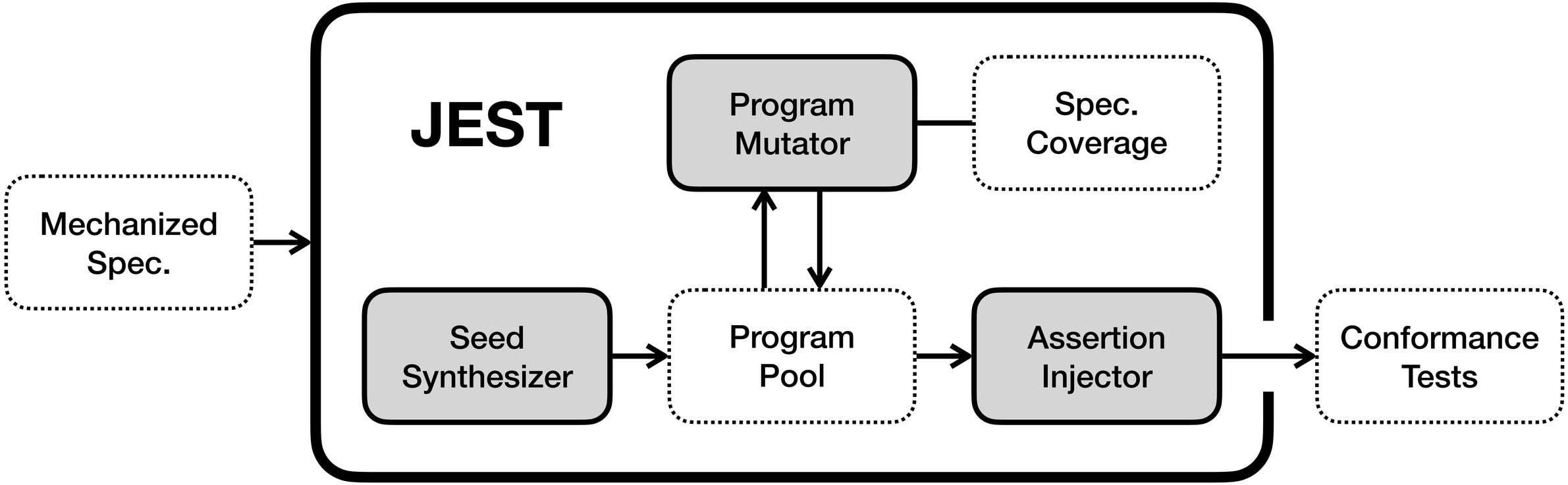
https://github.com/es-meta/esmeta



[ICSE'21] J. Park, S. An, D. Youn, G. Kim, and S. Ryu, **JEST: N+1-version Differential Testing of Both JavaScript Engines and Specification**

JEST (JavaScript Engines and Specification Tester)

- **Conformance Test Synthesis** using **Coverage-guided Fuzzing** in **Mechanized Spec.**



JEST - Coverage-guided Fuzzing (in Spec.)

ApplyStringOrNumericBinaryOperator (*lval*, *opText*, *rval*)

...

3. Let *lnum* be ? ToNumeric(*lval*).
4. Let *rnum* be ? ToNumeric(*rval*).
5. If Type(*lnum*) is not Type(*rnum*), throw a **TypeError** exception.
6. If *lnum* is a BigInt, then
   ...
7. Else,
   ...

JEST - Coverage-guided Fuzzing (in Spec.)

ApplyStringOrNumericBinaryOperator (*lval*, *opText*, *rval*)

...

3. Let *lnum* be ? ToNumeric(*lval*).
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6. If *lnum* is a BigInt, then
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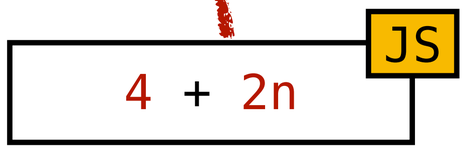
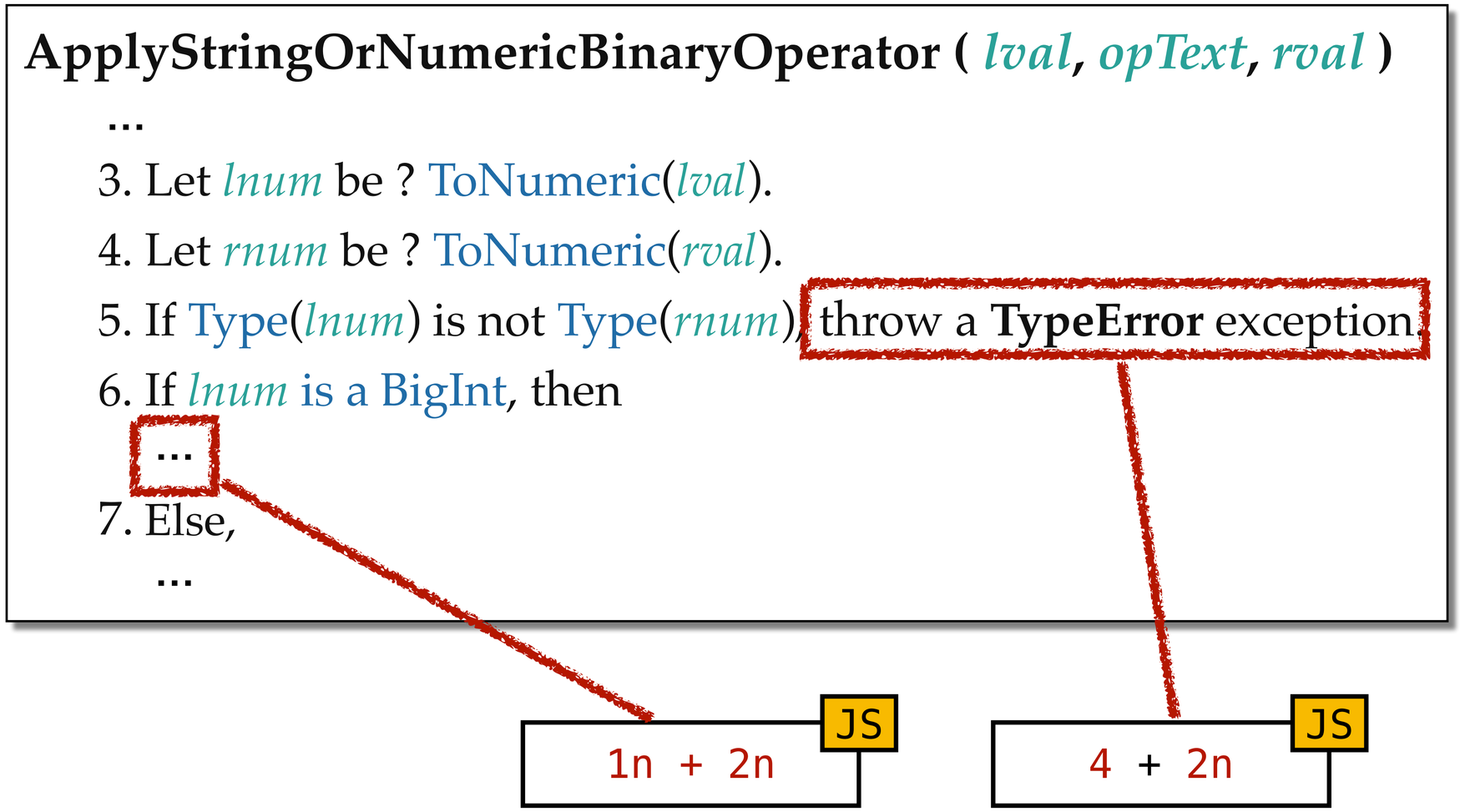
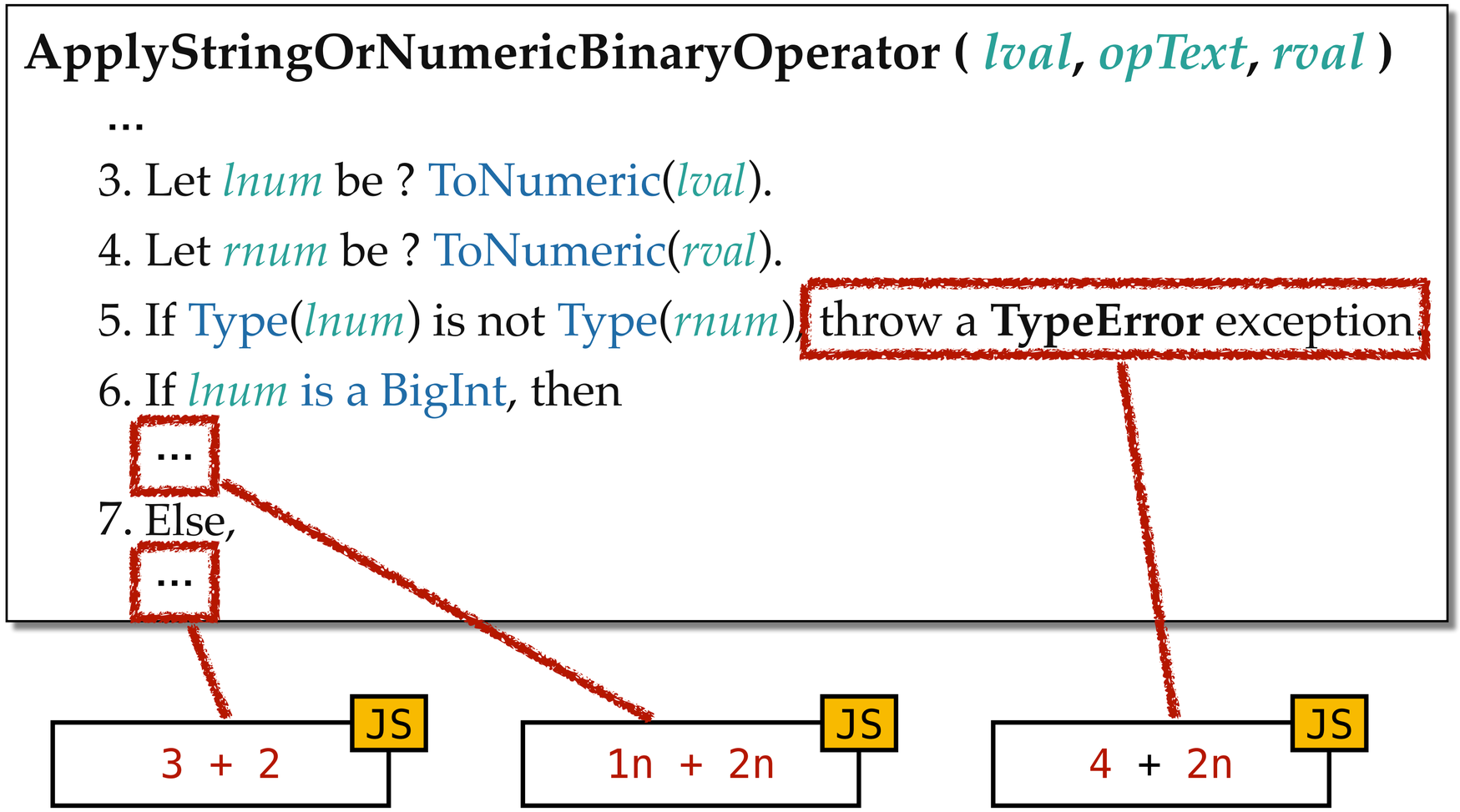
   ...



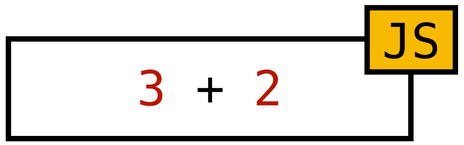
JEST - Coverage-guided Fuzzing (in Spec.)

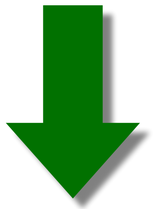


JEST - Coverage-guided Fuzzing (in Spec.)

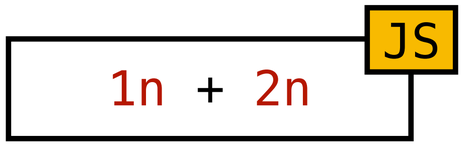


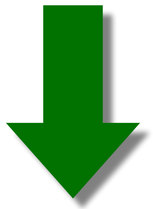
JEST - Assertion Injection



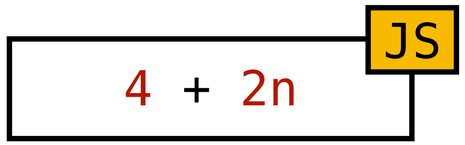


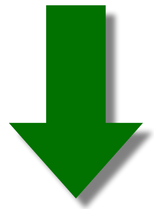
```
  var x = 3 + 2;
+ $assert.equal(x, 5);
```





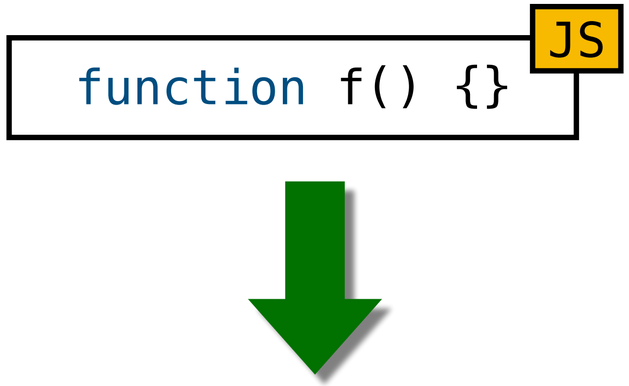
```
  var x = 1n + 2n;
+ $assert.equal(x, 3n);
```





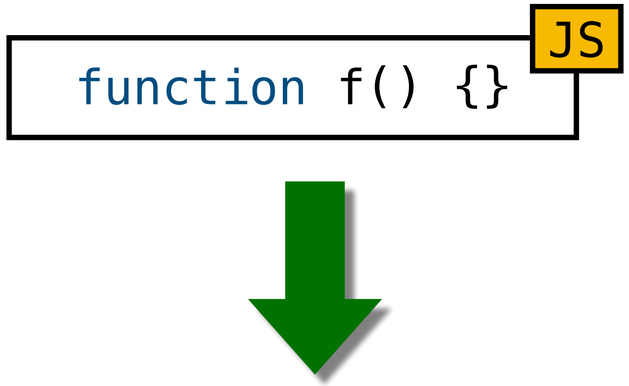
```
  var x = 4 + 2n;
+ // [THROW] TypeError
```

JEST - Assertion Injection




```
  function f() {}

+ $assert.equal(Object.getPrototypeOf(f), Function.prototype);

+ $assert.verifyProperty(f, "prototype", {
+   writable: true,
+   enumerable: false,
+   configurable: false,
+ });

+ $assert.compare(Reflect.ownKeys(f), ['length', 'name', 'prototype'], f);

+ ...
```

JEST - Assertion Injection



Prototype Chain

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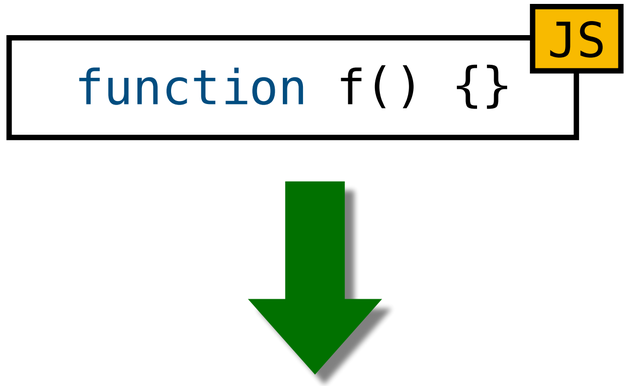
JEST - Assertion Injection

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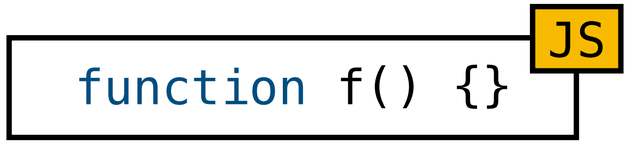
+ $assert.compare(Reflect.ownKeys(f), ['length', 'name', 'prototype'], f);

+ ...
```

Prototype Chain

Property Descriptor

JEST - Assertion Injection



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+ $assert.compare(Reflect.ownKeys(f), ['length', 'name', 'prototype'], f);

+ ...
```
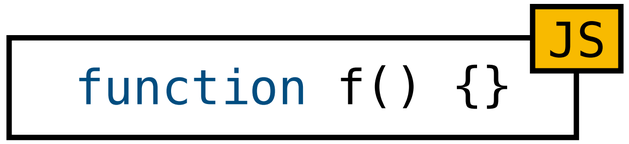

Prototype Chain

Property Descriptor

Property Order

JEST - Assertion Injection



```
  function f() {}

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+   writable: true,
+   enumerable: false,
+   configurable: false,
+ });

+ $assert.compare(Reflect.ownKeys(f), ['length', 'name', 'prototype'], f);

+ ...
```

Prototype Chain

Property Descriptor

Property Order

Etc.

JEST - Evaluation

- JEST synthesized 1,700 conformance tests from ES2020

44 Bugs Detected

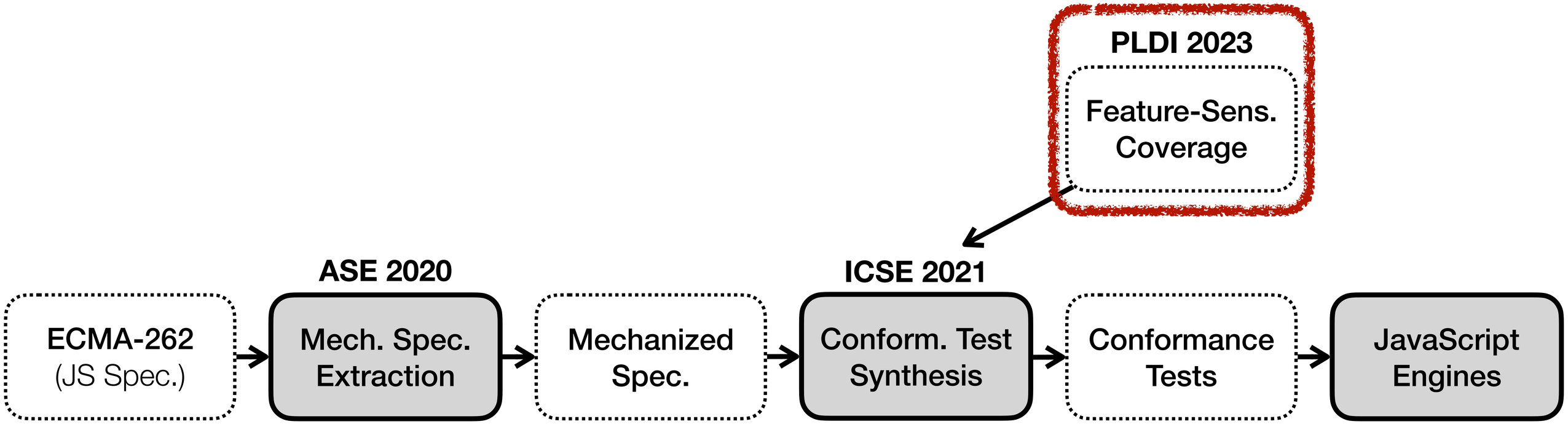
```
try { ++undefined; } catch (e) { }
```

TABLE II: The number of engine bugs detected by JEST

Engines	Exc	Abort	Var	Obj	Desc	Key	In	Total
V8	0	0	0	0	0	2	0	2
GraalVM	6	0	0	0	2	8	0	16
QuickJS	3	0	1	0	0	2	0	6
Moddable XS	12	0	0	0	3	5	0	20
Total	21	0	1	0	5	17	0	44

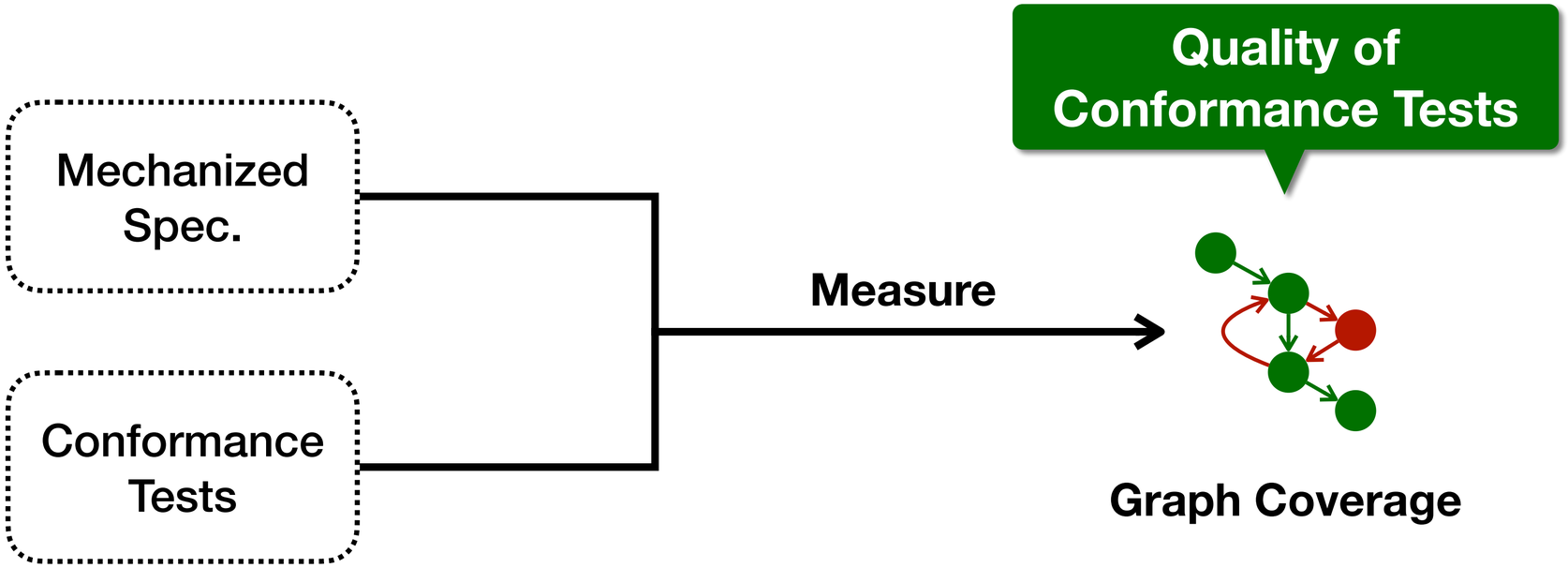
*"Right now, we are running Test262 and the V8 and Nashorn unit test suites in our CI for every change, it might make sense to **add your suite as well**."*

- A Developer of GraalVM

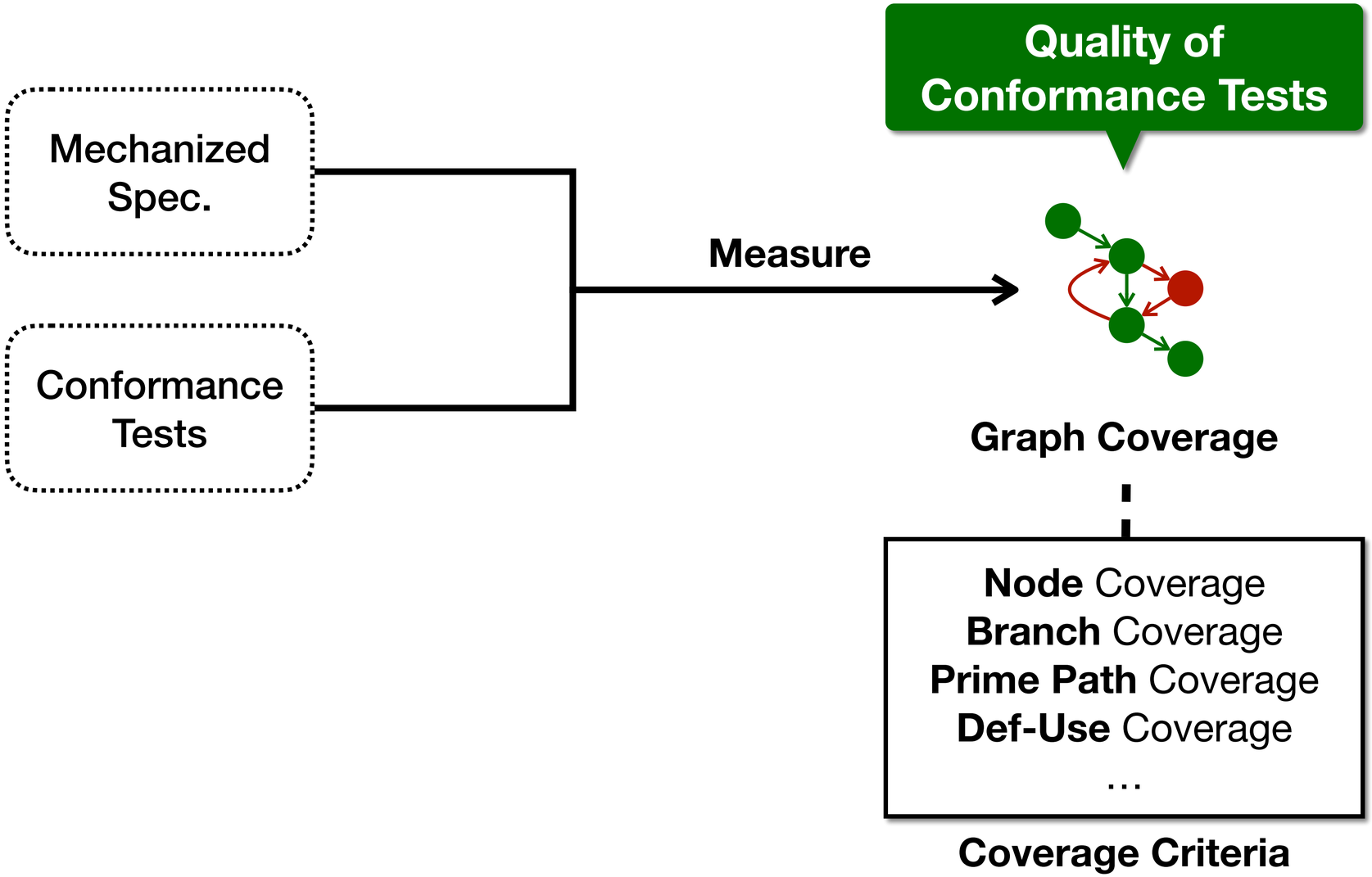


[PLDI'23] J. Park, D. Youn, K, Lee, and S. Ryu, **Feature-Sensitive Coverage for Conformance Testing of Programming Language Implementations**

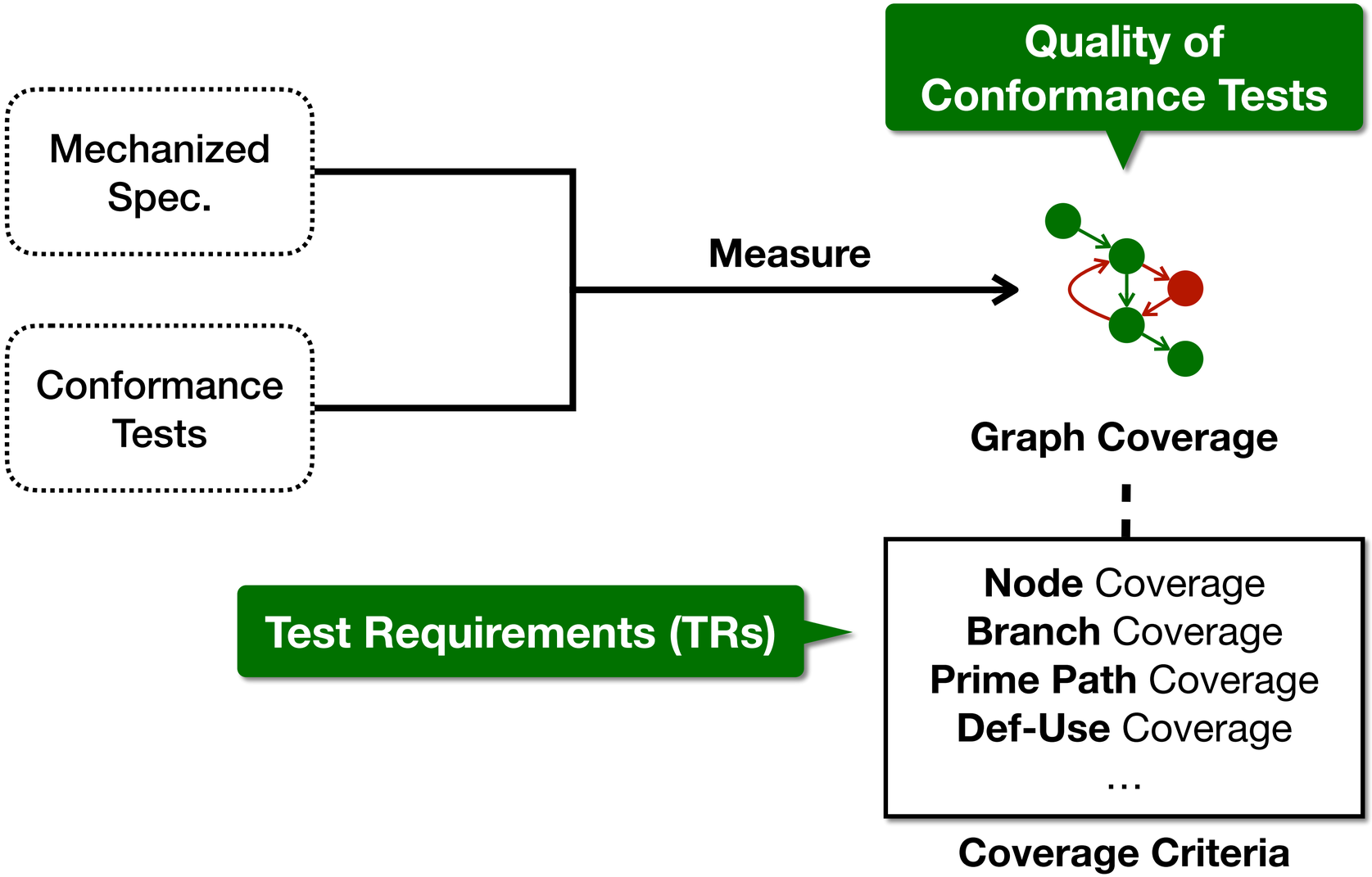
Graph Coverage for Language Specification



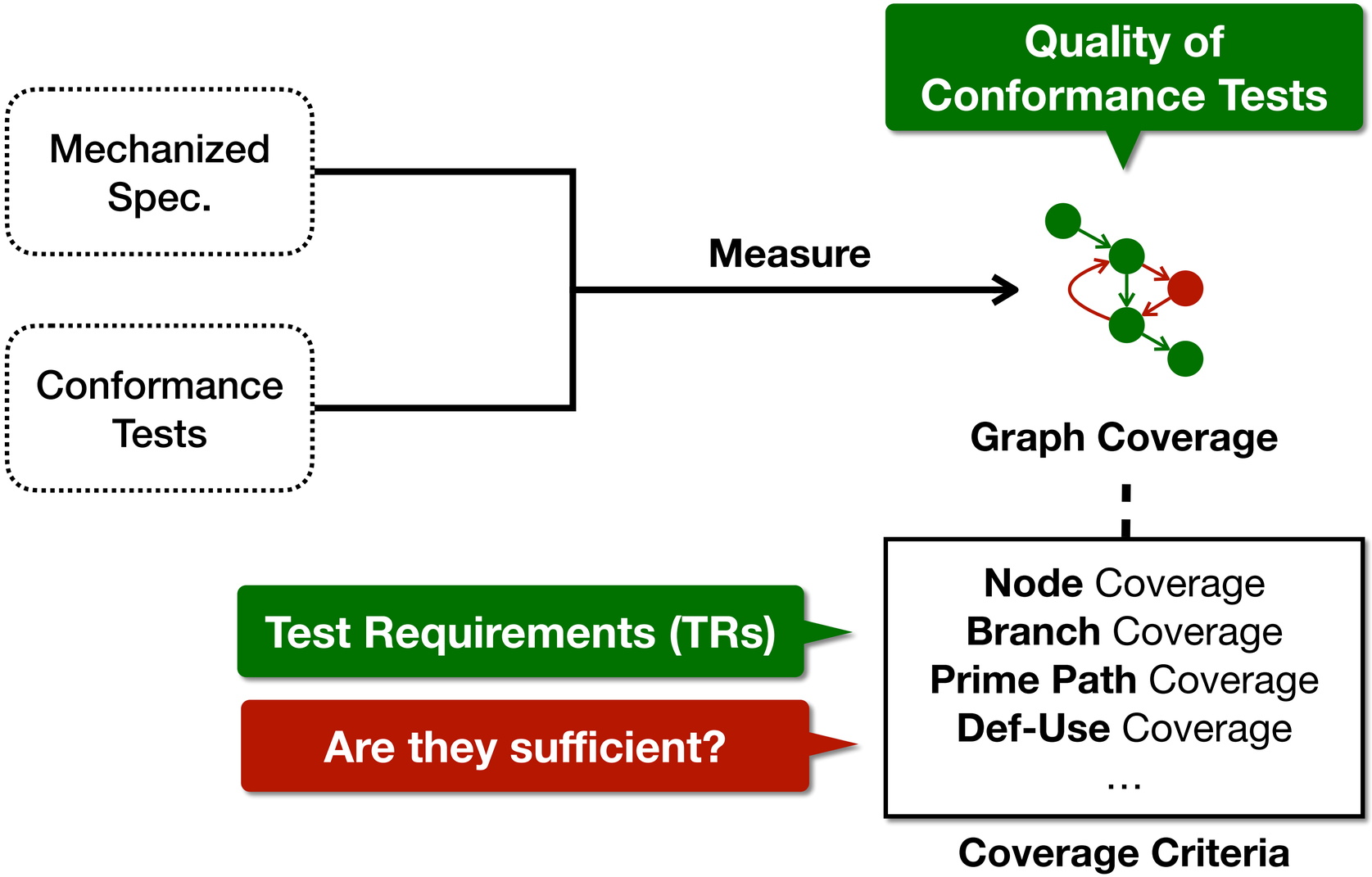
Graph Coverage for Language Specification



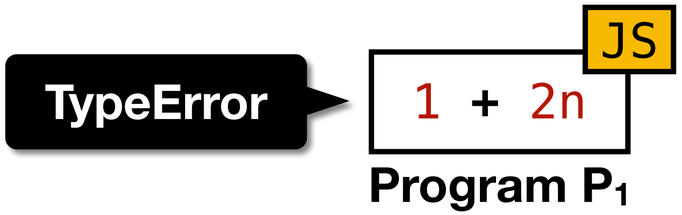
Graph Coverage for Language Specification



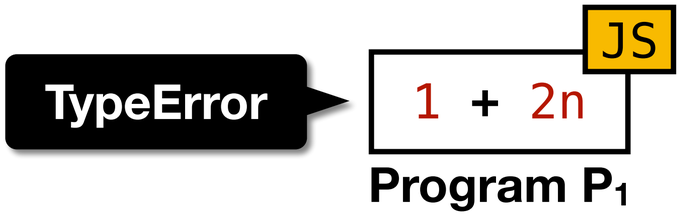
Graph Coverage for Language Specification



Motivating Example 1 with Node Coverage



Motivating Example 1 with Node Coverage



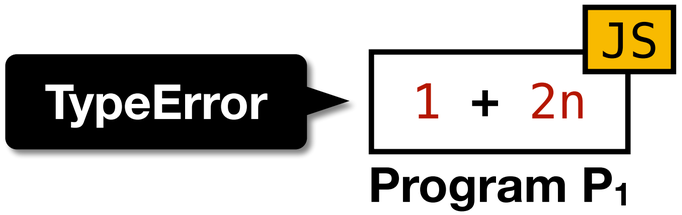
feat
ADD

Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*

1. Return ? **EvalStrOrNumBinExpr** (*AddExpr*, **+**, *MulExpr*).

Abstract Algorithms in **ECMA-262** (ES13, 2022), **JavaScript Language Specification**

Motivating Example 1 with Node Coverage



feat

ADD

Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*

1. Return ? **EvalStrOrNumBinExpr** (*AddExpr*, **+**, *MulExpr*).

EvalStrOrNumBinExpr (*lval*, *opText*, *rval*)

…

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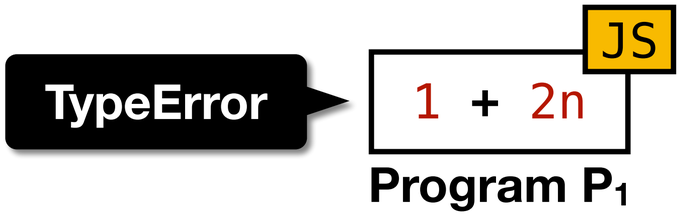
Abstract Algorithms in **ECMA-262** (ES13, 2022), **JavaScript Language Specification**

Motivating Example 1 with Node Coverage



feat **ADD**

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…

5. If **Type**(*lnum*) is different from **Type**(*rnum*), throw a **TypeError** exception.

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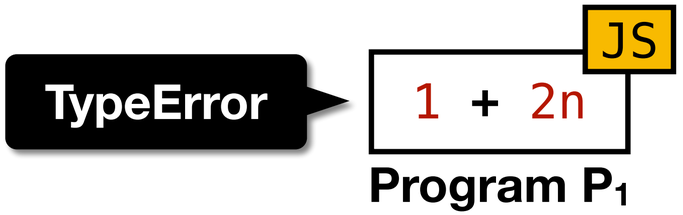

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Abstract Algorithms in **ECMA-262** (ES13, 2022), **JavaScript Language Specification**

Motivating Example 1 with Node Coverage

Node Coverage

TR = Node

TypeError

JS

```
1 + 2n
```

Program P_1

feat

ADD

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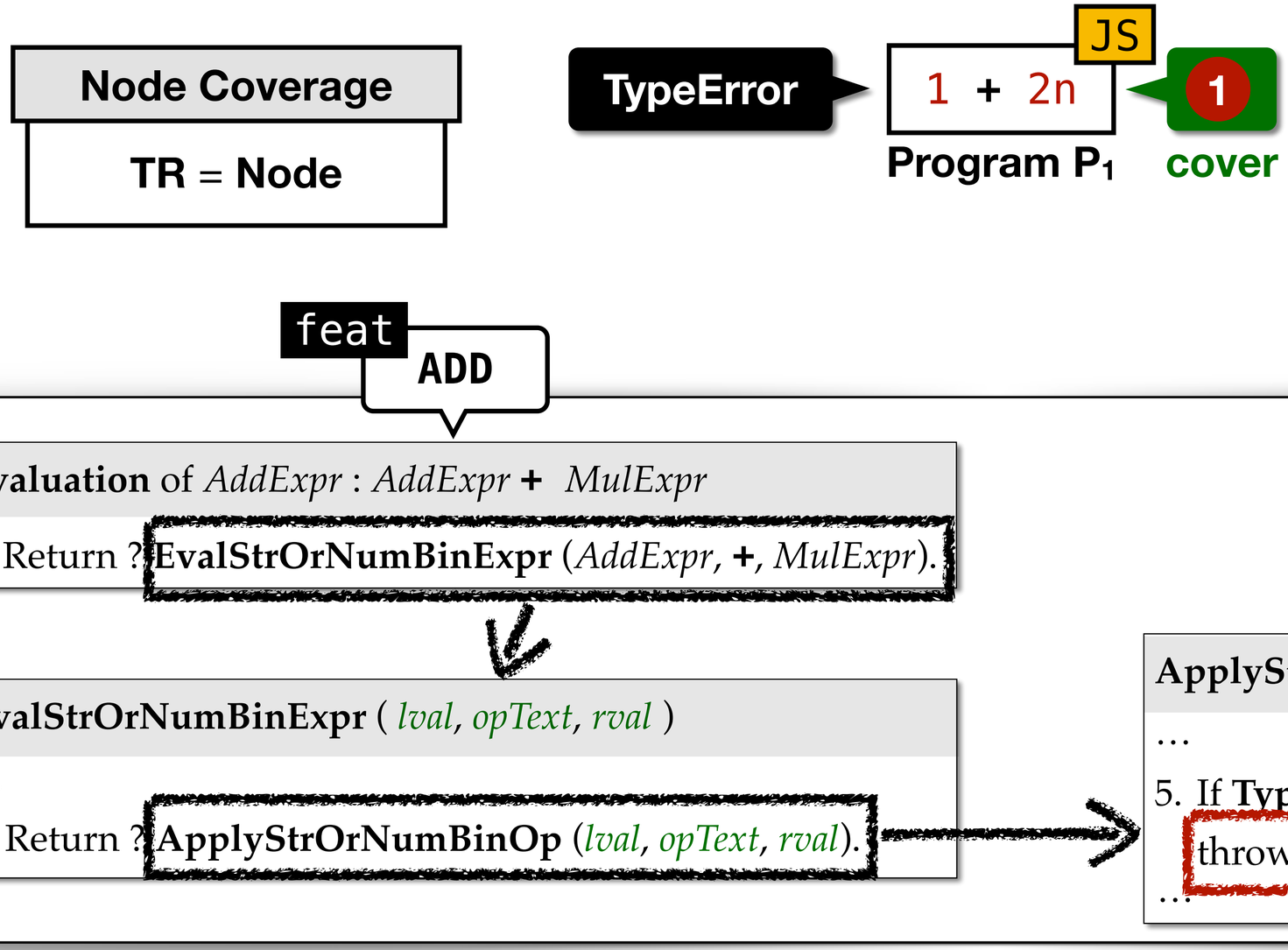

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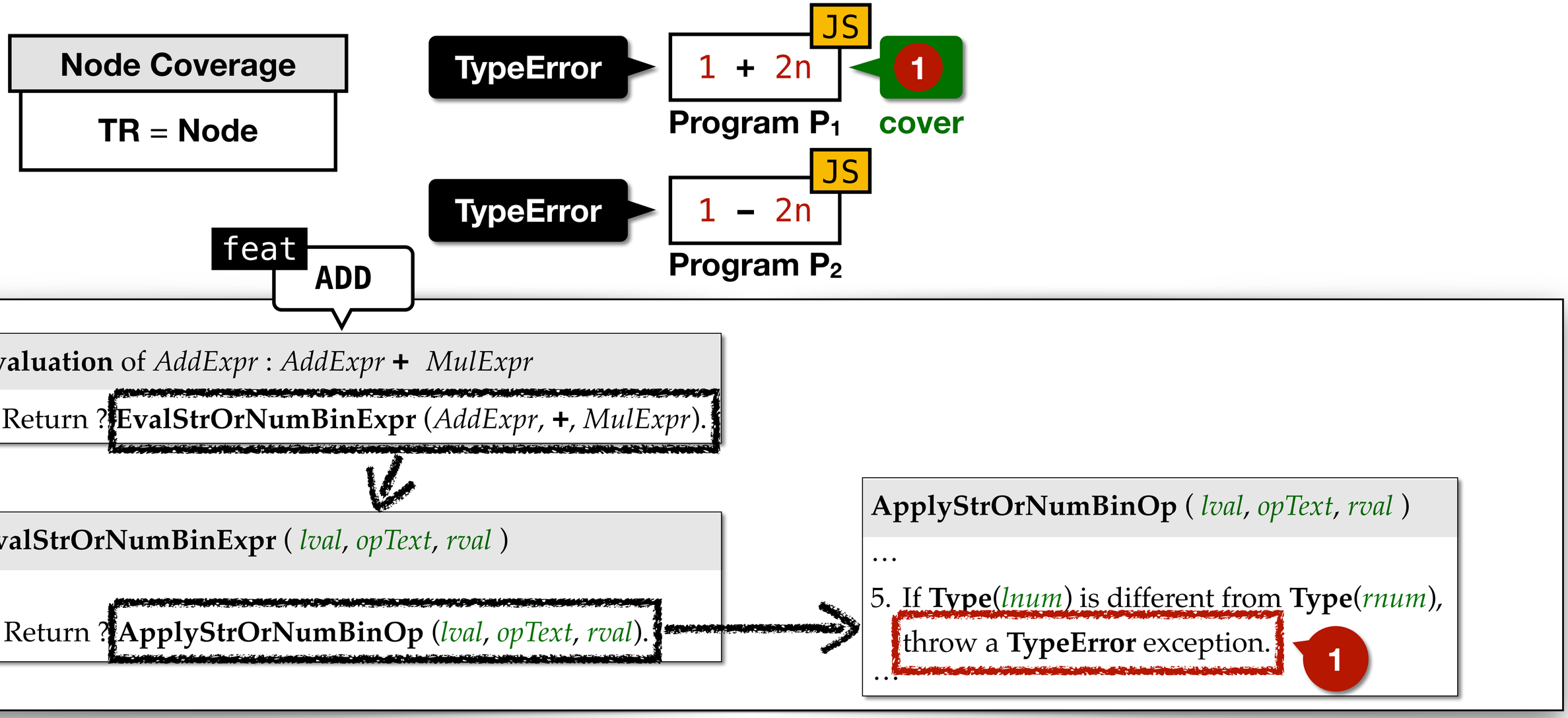

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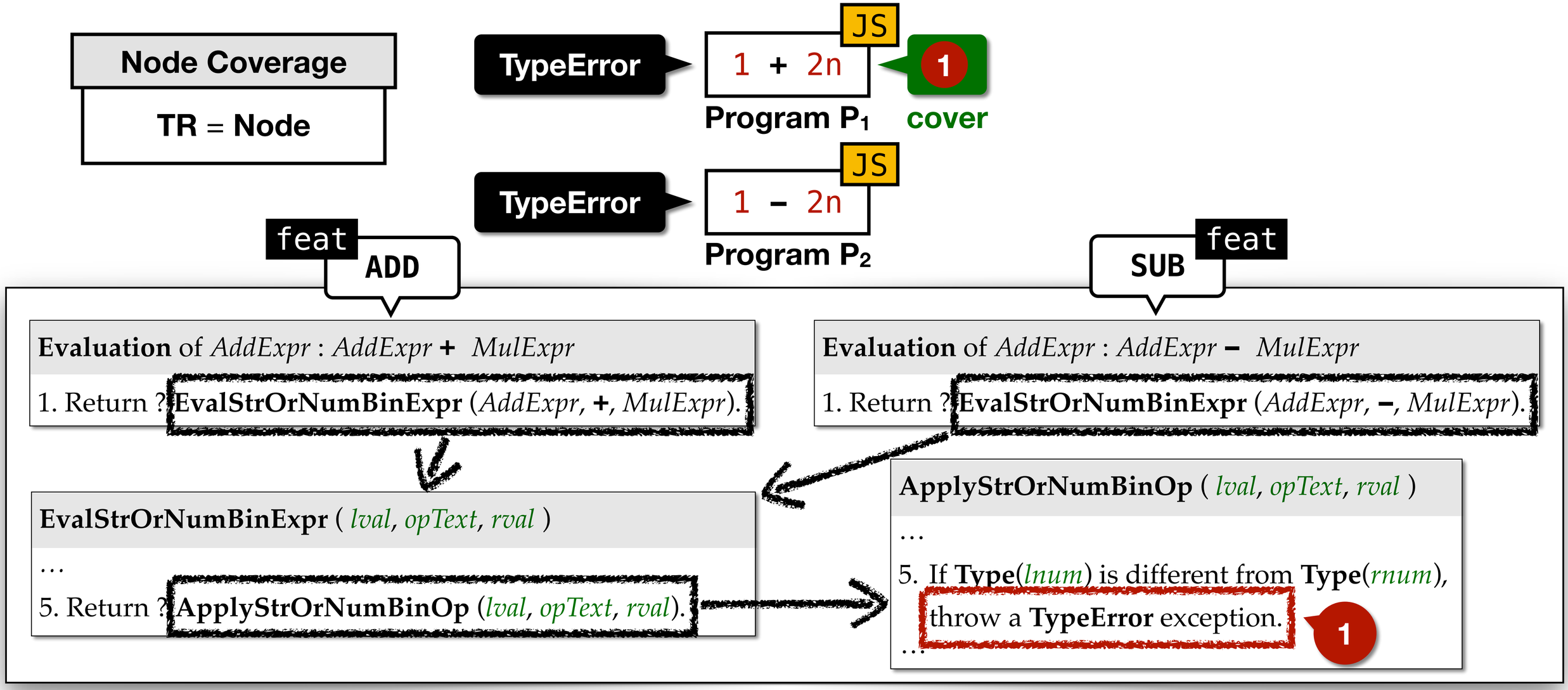

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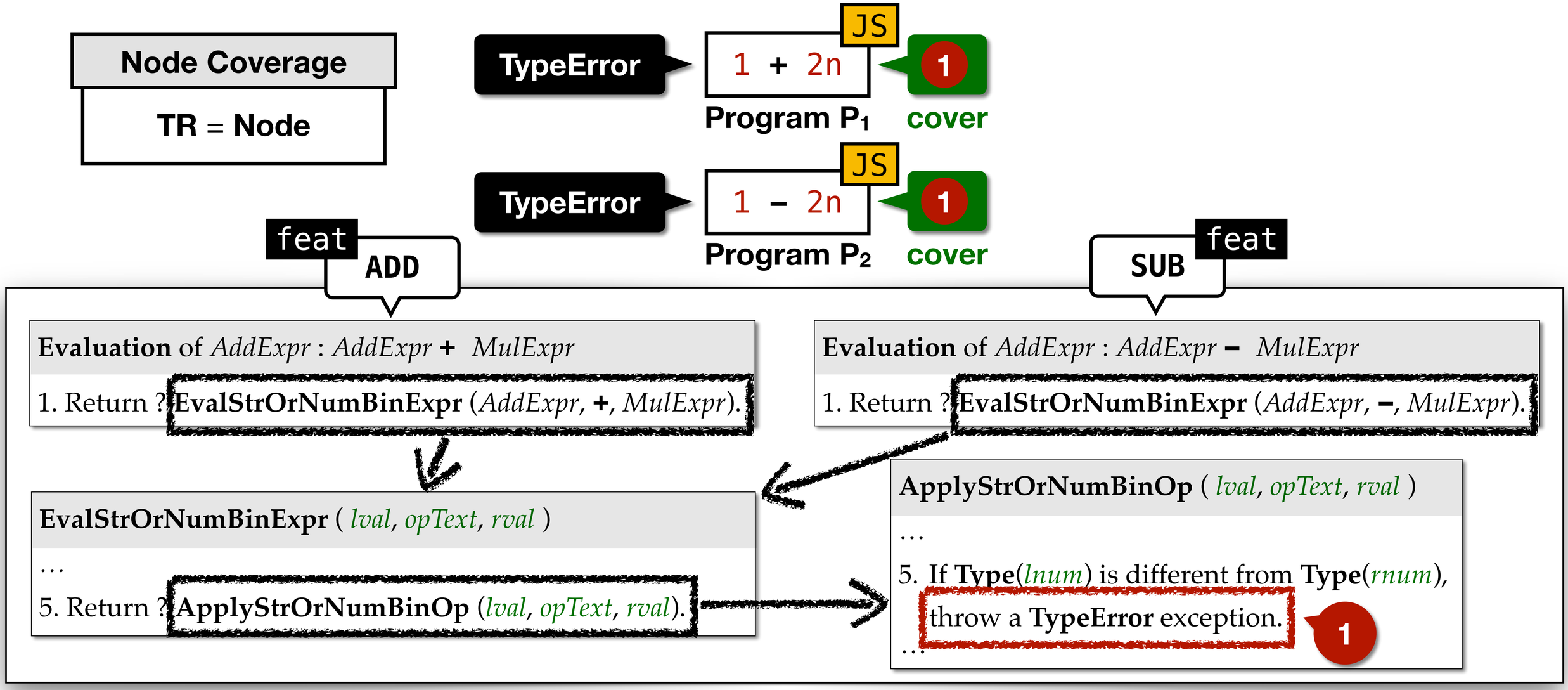

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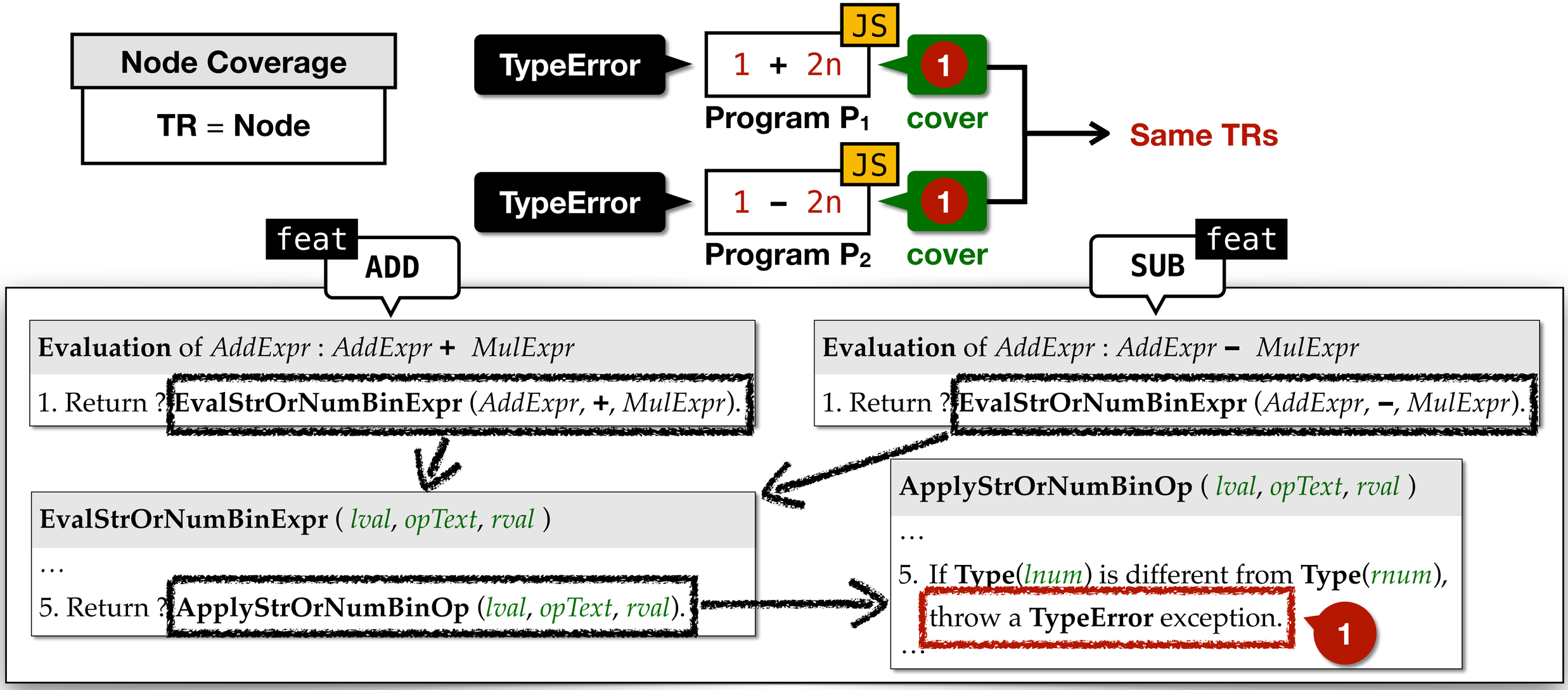

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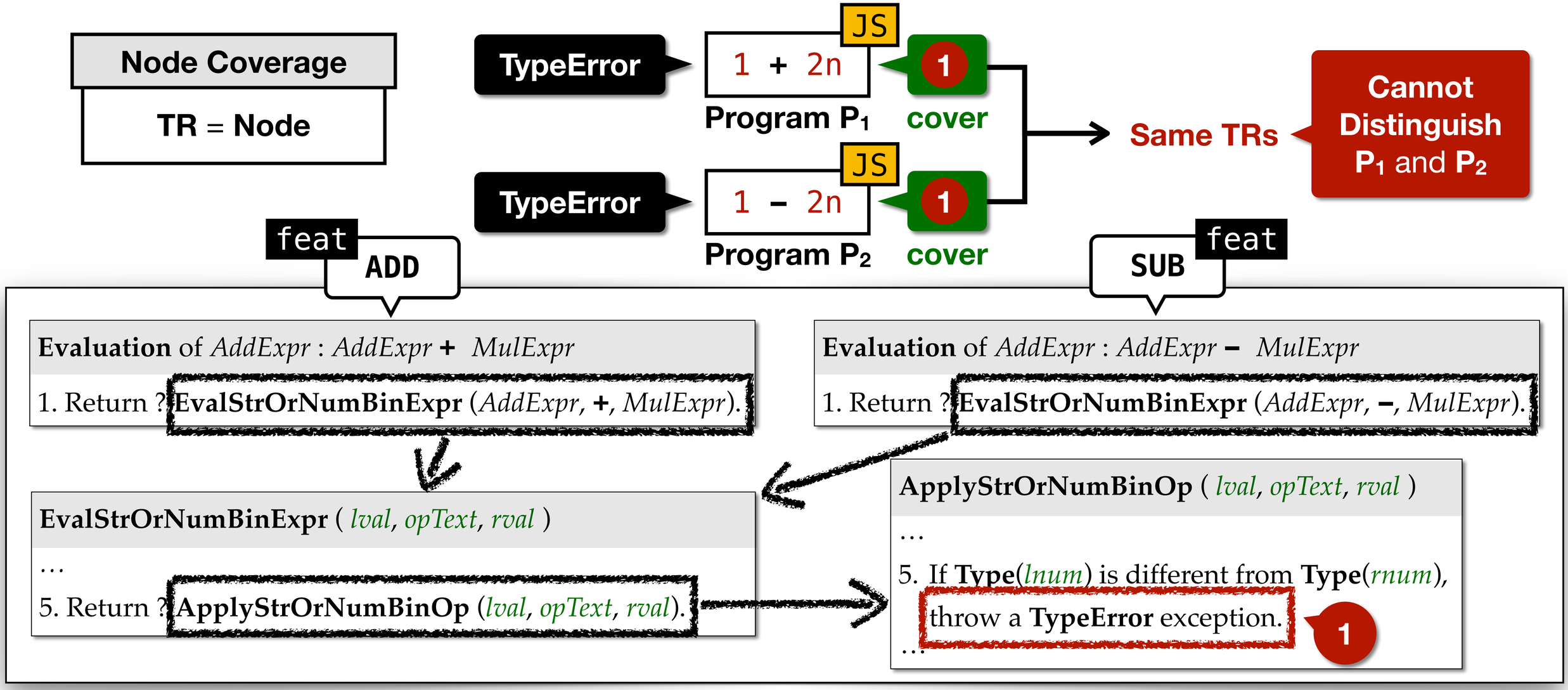
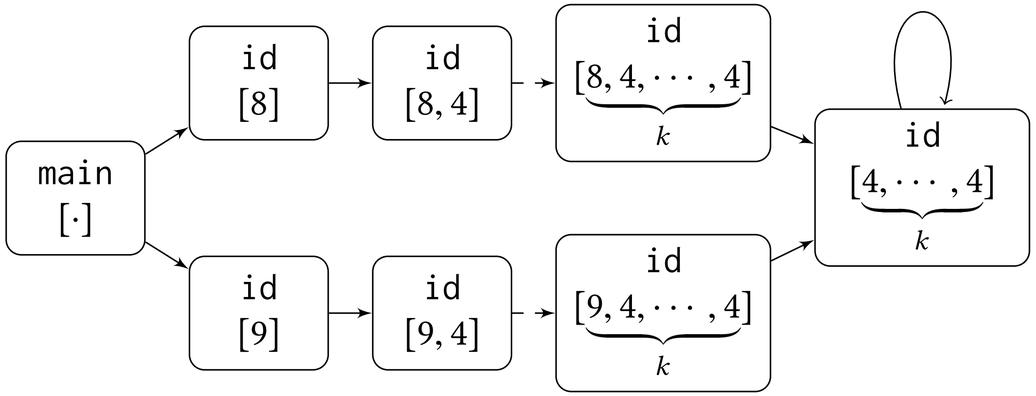


Abstract Algorithms in **ECMA-262** (ES13, 2022), **JavaScript Language Specification**

Insight from **Context Tunneling** [OOPSLA'18]

```
1  class A {} class B {}
2  class C {
3    static Object id (Object v, int i){
4        return i >= 0 ? id(v, i-1) : v;
5    }
6    public static void main (){
7      int i = input();
8      A a = (A) id(new A(), i); //Query 1
9      B b = (B) id(new B(), i); //Query 2
10   }
11 }
```



[OOPSLA'18] M. Jeon, S. Jeong, and H, Oh, **Precise and Scalable Points-to Analysis via Data-Driven Context Tunneling**

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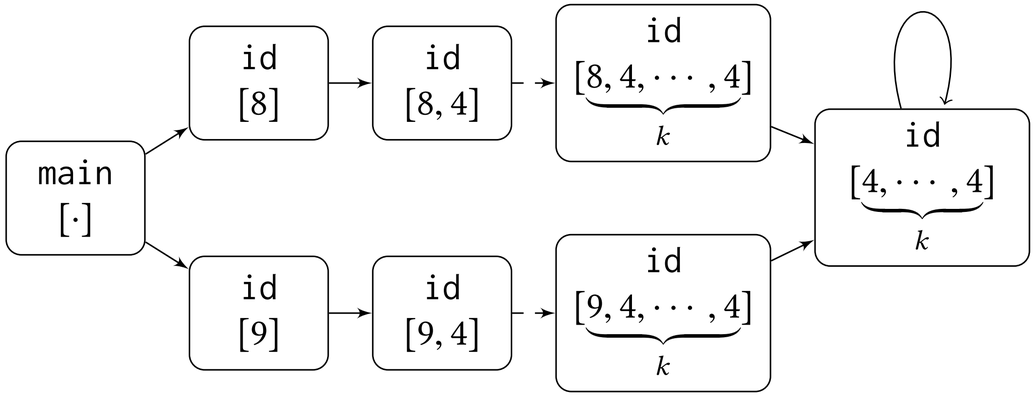

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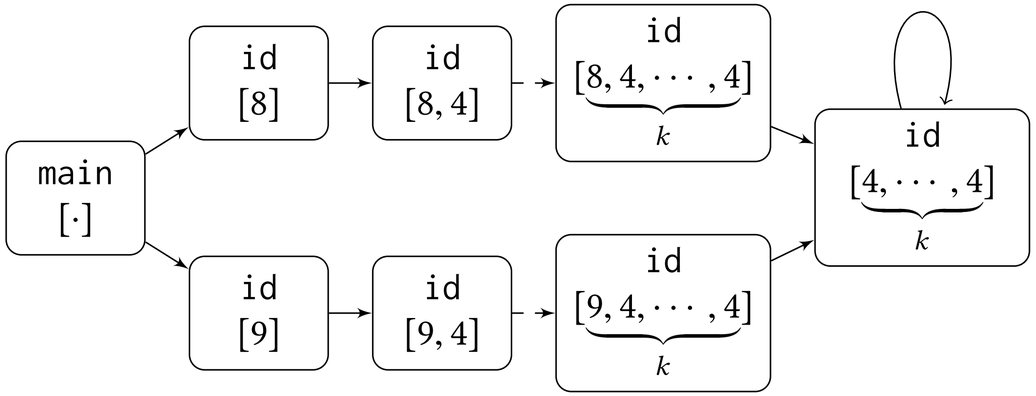

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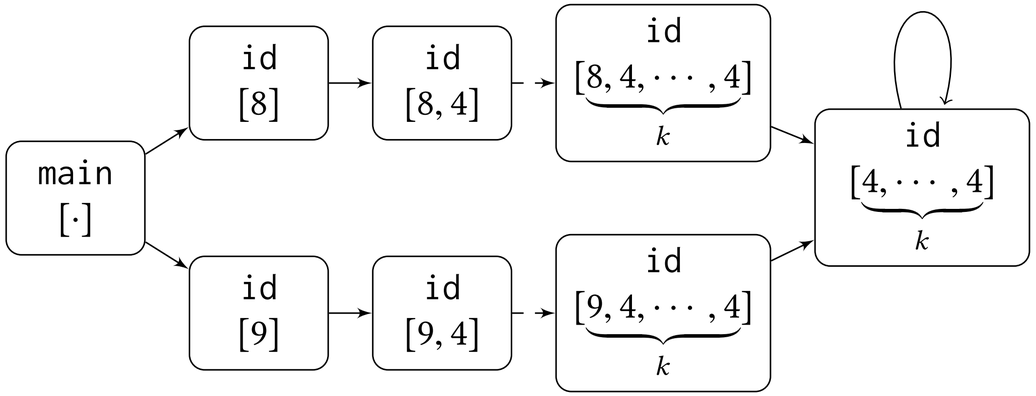

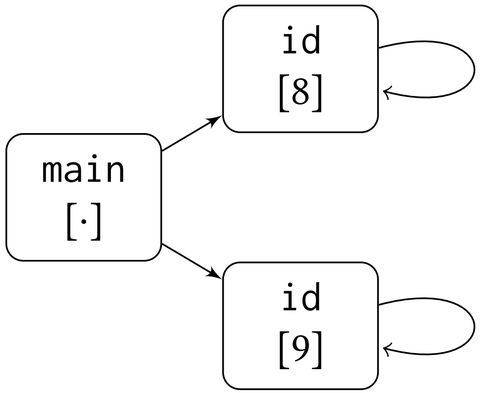

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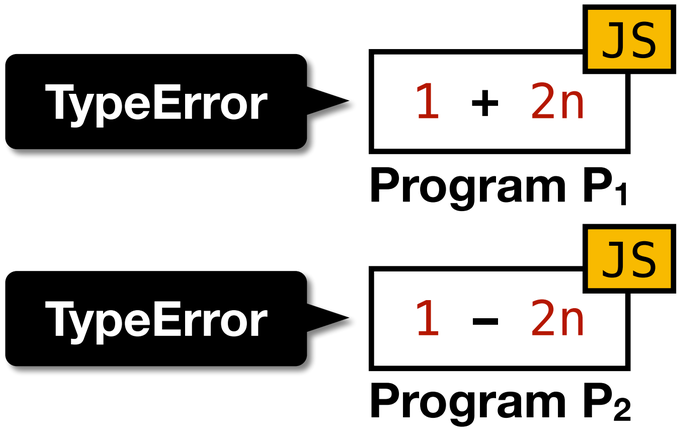
Feature-Sensitive (FS) Coverage



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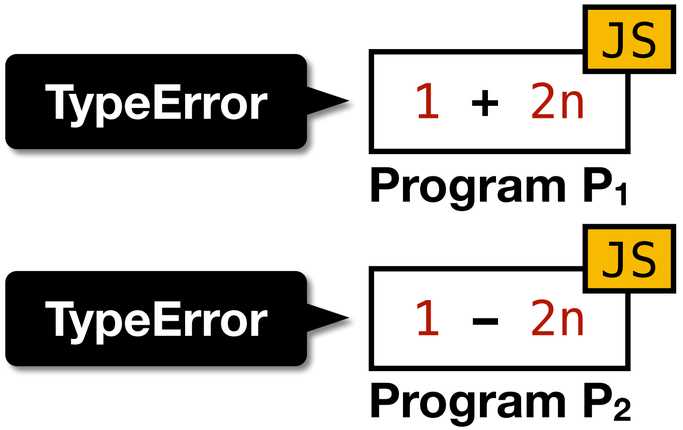

- Feature-Sensitive **(FS)** coverage criterion **divides**

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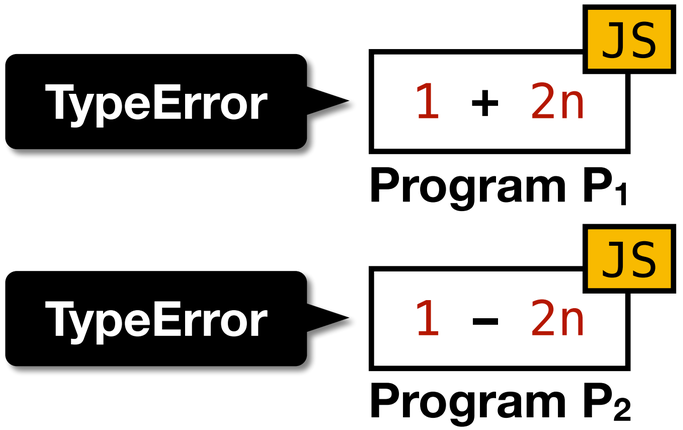
FS Coverage
TR = (Feature, given **TR)**

Feature-Sensitive (FS) Coverage



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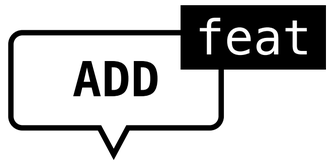

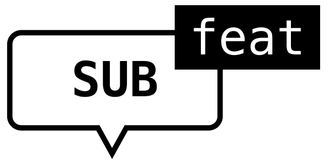

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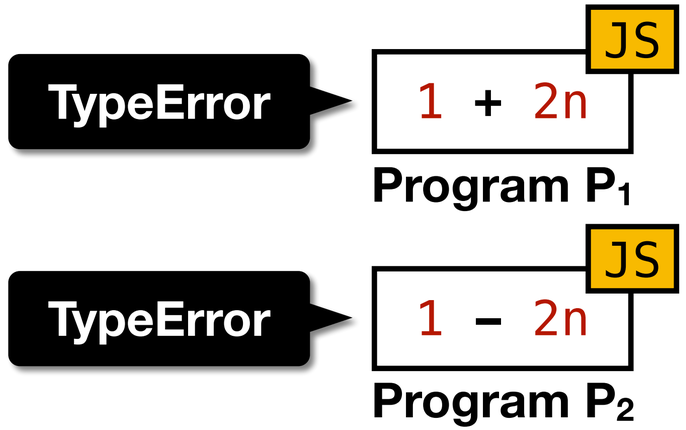
Feature-Sensitive (FS) Coverage

FS Node Coverage

TR = (Feature, Node)



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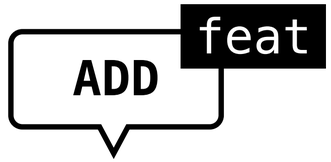
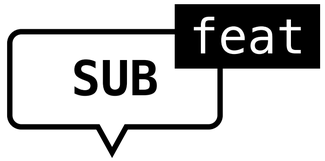
TR = (Feature, given **TR)**





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Feature-Sensitive (FS) Coverage

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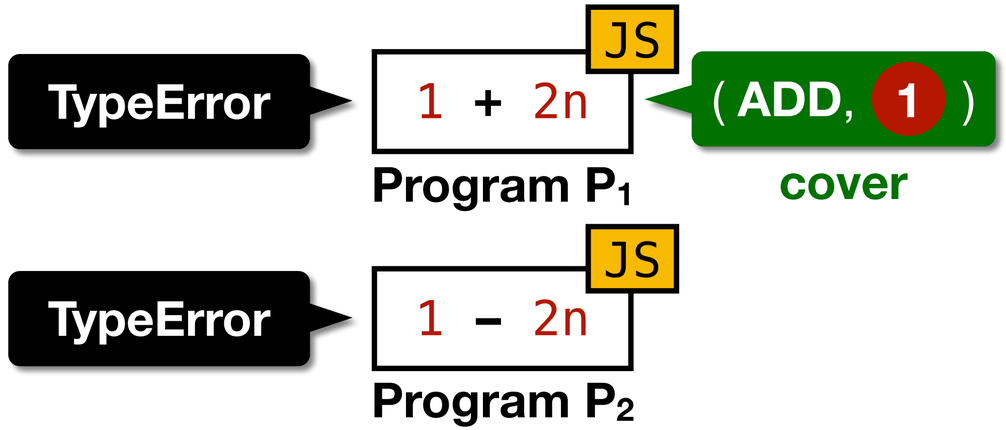

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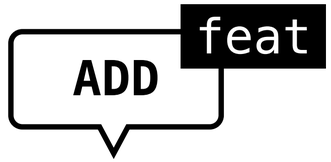

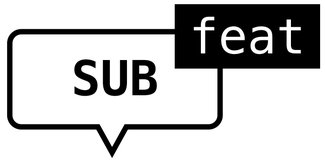

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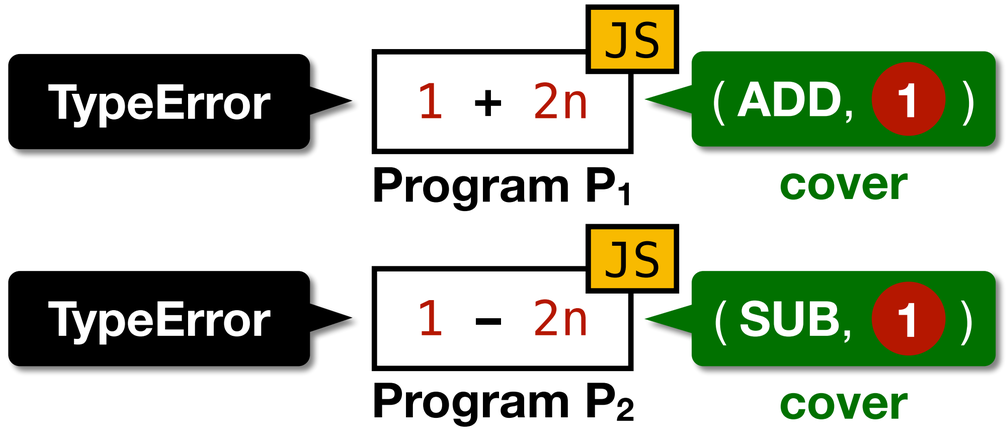

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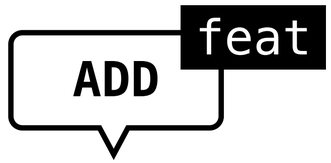

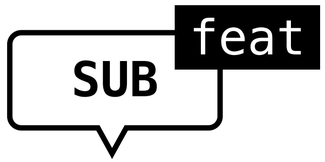

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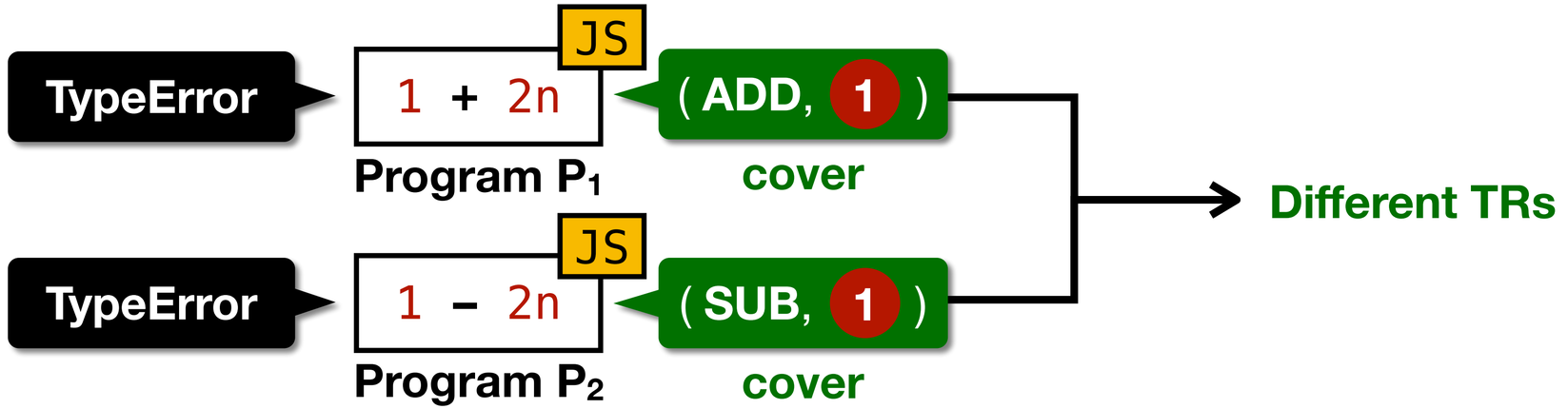

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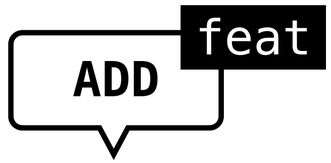

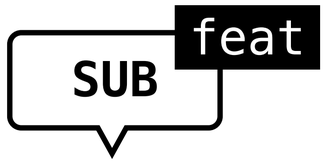

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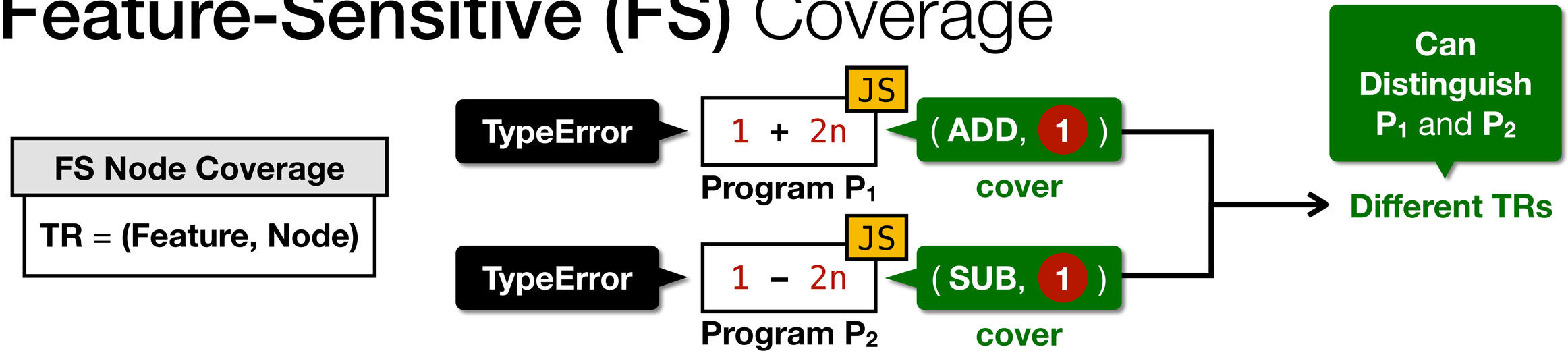

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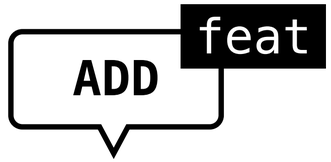

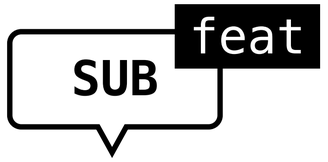

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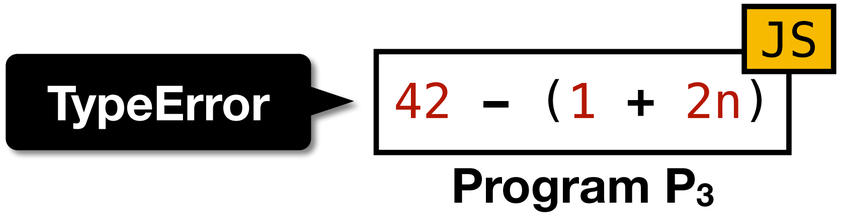
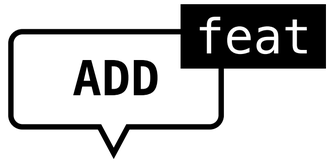
k-Feature-Sensitive (k-FS) Coverage



- k-**F**eature-**S**ensitive (**k-FS**) coverage criterion **divides** the given TRs with at most **k-innermost enclosing** language **features**

k-FS Coverage
TR = (Feature$^{\leq k}$, given **TR)**



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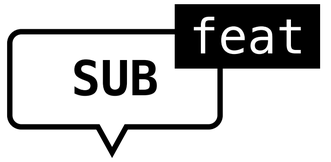


Evaluation of *AddExpr* : *AddExpr* **–** *MulExpr*
1. Return ? **EvalStrOrNumBinExpr** (*AddExpr*, **–**, *MulExpr*).

k-Feature-Sensitive (k-FS) Coverage

2-FS Node Coverage

TR = (Feature$^{\leq 2}$, Node)

TypeError

JS

```
42 - (1 + 2n)
```

Program P_3

- k-Feature-Sensitive (**k-FS**) coverage criterion **divides** the given TRs with at most **k-innermost enclosing** language **features**

k-FS Coverage

TR = (Feature$^{\leq k}$, given TR)

feat **ADD**

Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*
1. Return ? **EvalStrOrNumBinExpr** (*AddExpr*, **+**, *MulExpr*).

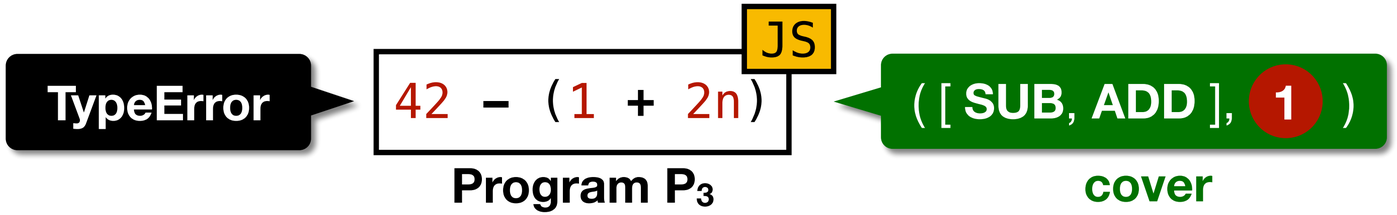
feat **SUB**

Evaluation of *AddExpr* : *AddExpr* **–** *MulExpr*
1. Return ? **EvalStrOrNumBinExpr** (*AddExpr*, **–**, *MulExpr*).

k-Feature-Sensitive (k-FS) Coverage

2-FS Node Coverage

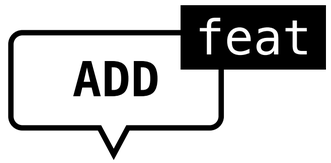
TR = (Feature$^{\leq 2}$, Node)

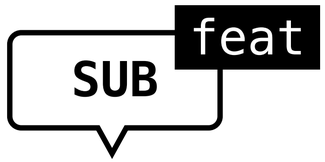


- k-**F**eature-**S**ensitive (**k-FS**) coverage criterion **divides** the given TRs with at most **k-innermost enclosing** language **features**

k-FS Coverage

TR = (Feature$^{\leq k}$, given **TR)**

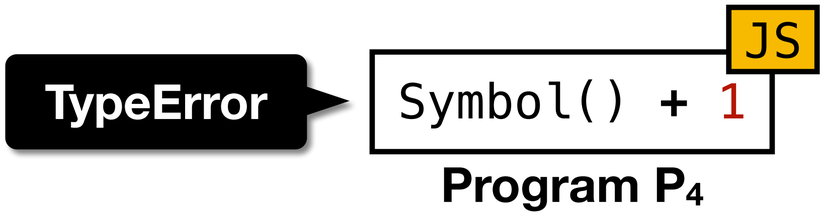




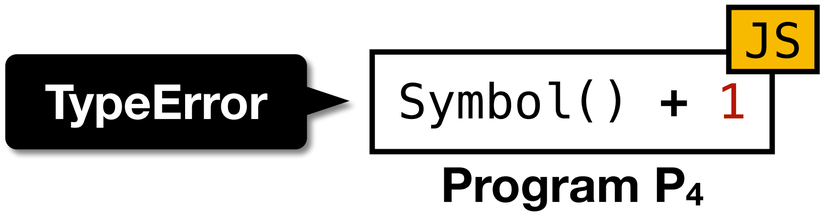
Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*
1. Return ? **EvalStrOrNumBinExpr** (*AddExpr*, **+**, *MulExpr*).

Evaluation of *AddExpr* : *AddExpr* **–** *MulExpr*
1. Return ? **EvalStrOrNumBinExpr** (*AddExpr*, **–**, *MulExpr*).

Motivating Example 2



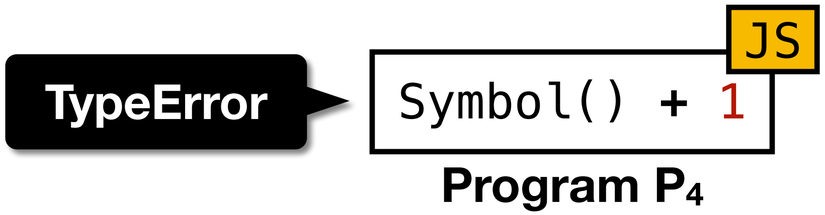
Motivating Example 2

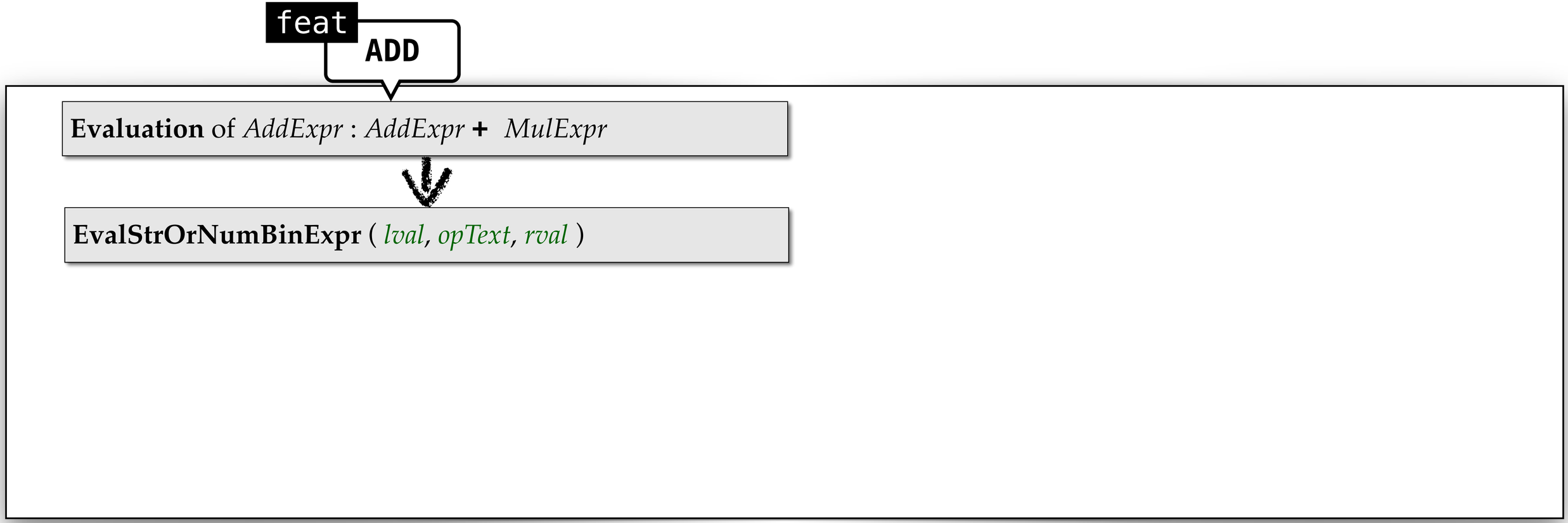


feat **ADD**

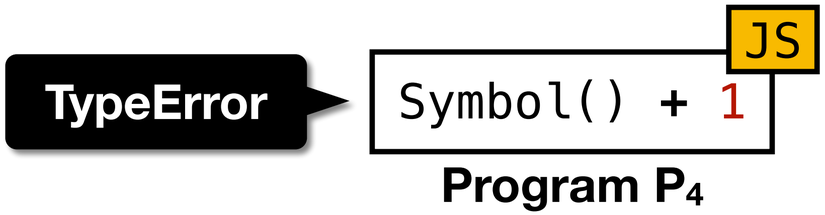
Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*

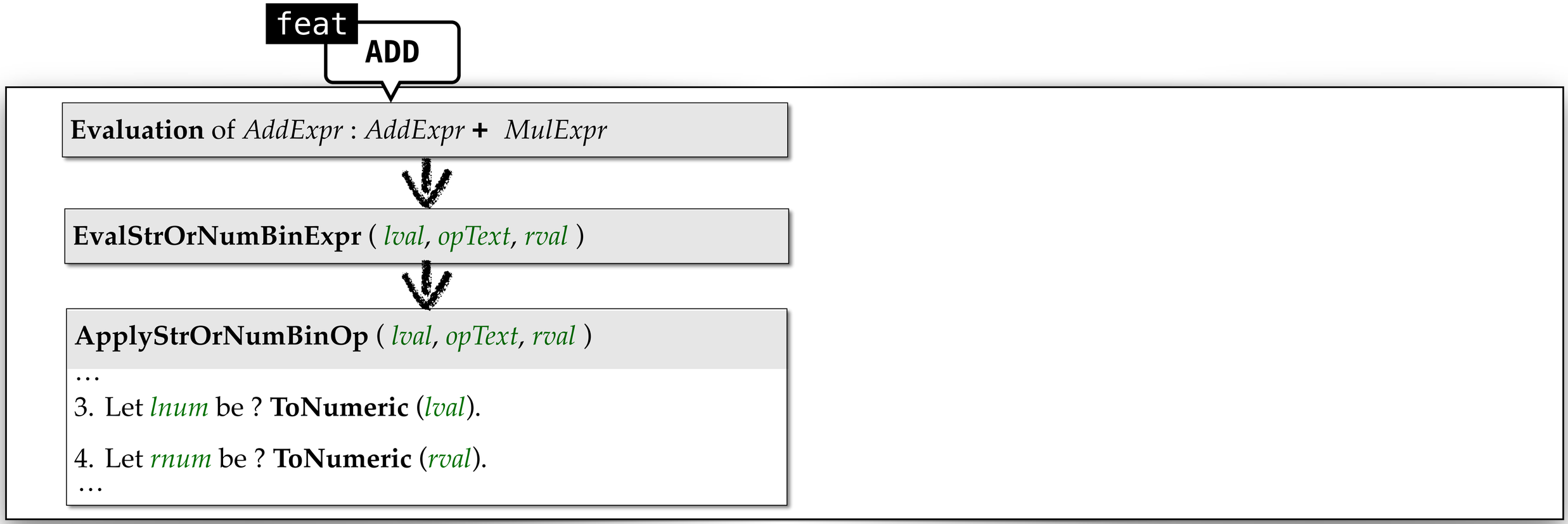
Motivating Example 2



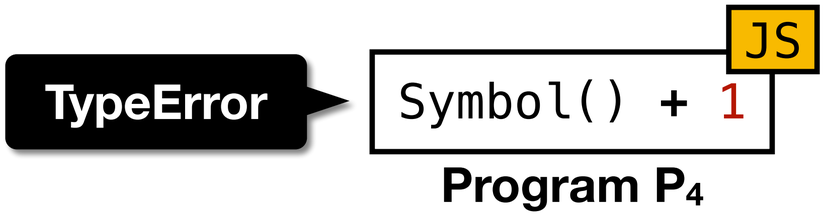


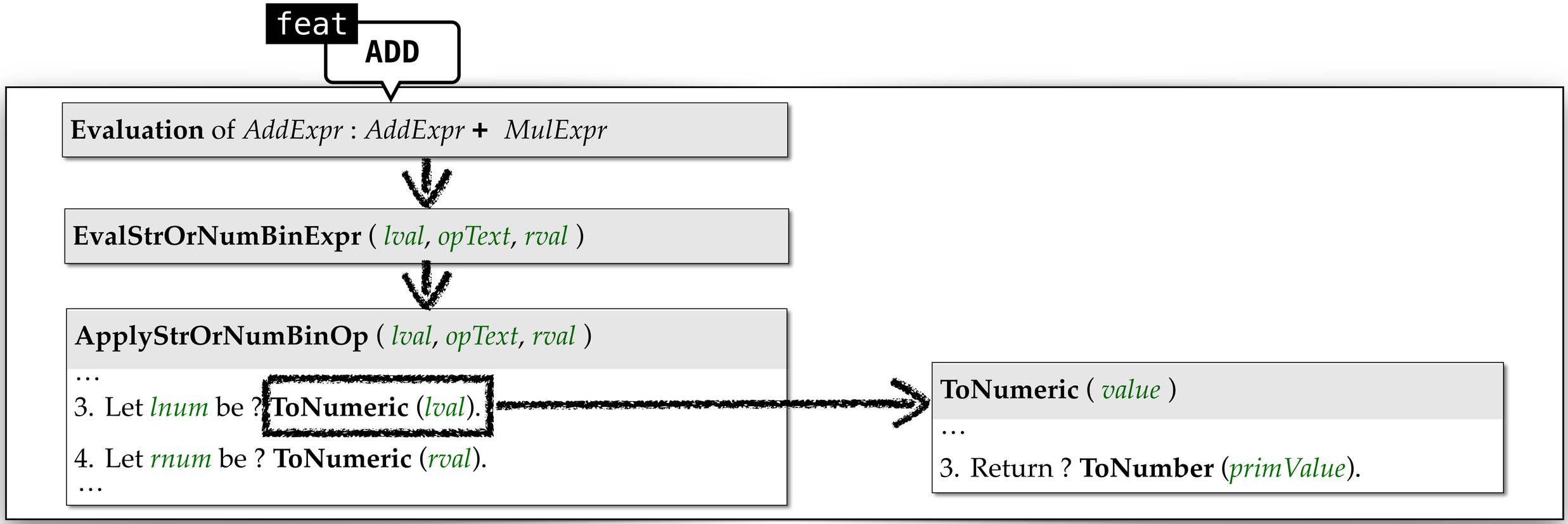
Motivating Example 2



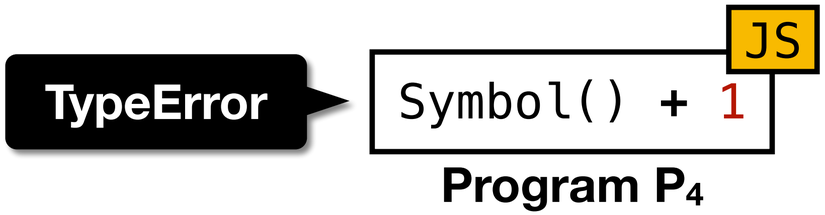


Motivating Example 2





Motivating Example 2



feat **ADD**

Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*

EvalStrOrNumBinExpr (*lval*, *opText*, *rval*)

ApplyStrOrNumBinOp (*lval*, *opText*, *rval*)

…

3. Let *lnum* be ? **ToNumeric** (*lval*).

4. Let *rnum* be ? **ToNumeric** (*rval*).

…

ToNumeric (*value*)

…

3. Return ? **ToNumber** (*primValue*).

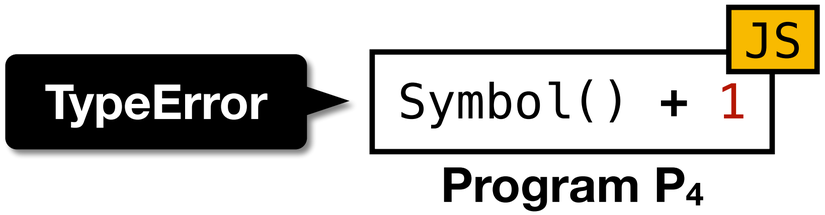
ToNumber (*argument*)

…

6. If **Type** (*argument*) is Symbol,
   throw a **TypeError** exception.

…

Motivating Example 2



feat **ADD**

Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*

EvalStrOrNumBinExpr (*lval*, *opText*, *rval*)

ApplyStrOrNumBinOp (*lval*, *opText*, *rval*)

…

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4. Let *rnum* be ? **ToNumeric** (*rval*).

…

ToNumeric (*value*)

…

3. Return ? **ToNumber** (*primValue*).

ToNumber (*argument*)

…

6. If **Type** (*argument*) is Symbol,
   throw a **TypeError** exception.

…

2

Motivating Example 2

1-FS Node Coverage

TR = (Feature, Node)

TypeError

JS

```
Symbol() + 1
```

Program P_4

feat **ADD**

Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*

EvalStrOrNumBinExpr (*lval*, *opText*, *rval*)

ApplyStrOrNumBinOp (*lval*, *opText*, *rval*)

…

3. Let *lnum* be ? **ToNumeric** (*lval*).

4. Let *rnum* be ? **ToNumeric** (*rval*).

…

ToNumeric (*value*)

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ToNumber (*argument*)

…

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…

2

Motivating Example 2

1-FS Node Coverage

TR = (Feature, Node)

TypeError

JS

```
Symbol() + 1
```

Program P_4

(ADD, 2)

cover

`feat` **ADD**

Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*

EvalStrOrNumBinExpr (*lval*, *opText*, *rval*)

ApplyStrOrNumBinOp (*lval*, *opText*, *rval*)

…

3. Let *lnum* be ? **ToNumeric** (*lval*).

4. Let *rnum* be ? **ToNumeric** (*rval*).

…

ToNumeric (*value*)

…

3. Return ? **ToNumber** (*primValue*).

ToNumber (*argument*)

…

6. If **Type** (*argument*) is Symbol,
   throw a **TypeError** exception.

…

2

Motivating Example 2

1-FS Node Coverage

TR = (Feature, Node)

TypeError `Symbol() + 1` JS

Program P_4

(**ADD**, **2**) **cover**

TypeError `1 + Symbol()` JS

Program P_5

`feat` **ADD**

Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*

EvalStrOrNumBinExpr (*lval*, *opText*, *rval*)

ApplyStrOrNumBinOp (*lval*, *opText*, *rval*)

…

3. Let *lnum* be ? **ToNumeric** (*lval*).

4. Let *rnum* be ? **ToNumeric** (*rval*).

…

ToNumeric (*value*)

…

3. Return ? **ToNumber** (*primValue*).

ToNumber (*argument*)

…

6. If **Type** (*argument*) is Symbol, throw a **TypeError** exception.

…

2

Motivating Example 2

1-FS Node Coverage

TR = (Feature, Node)

TypeError `Symbol() + 1` JS

Program P_4

(**ADD**, **2**) **cover**

TypeError `1 + Symbol()` JS

Program P_5

`feat` **ADD**

Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*

EvalStrOrNumBinExpr (*lval*, *opText*, *rval*)

ApplyStrOrNumBinOp (*lval*, *opText*, *rval*)

…

3. Let *lnum* be ? **ToNumeric** (*lval*).

4. Let *rnum* be ? **ToNumeric** (*rval*).

…

ToNumeric (*value*)

…

3. Return ? **ToNumber** (*primValue*).

ToNumber (*argument*)

…

6. If **Type** (*argument*) is Symbol,

throw a **TypeError** exception. **2**

…

Motivating Example 2

1-FS Node Coverage

TR = (Feature, Node)

TypeError `Symbol() + 1` (JS) — **Program P_4** — (**ADD**, **2**) **cover**

TypeError `1 + Symbol()` (JS) — **Program P_5** — (**ADD**, **2**) **cover**

`feat` **ADD**

Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*

EvalStrOrNumBinExpr (*lval*, *opText*, *rval*)

ApplyStrOrNumBinOp (*lval*, *opText*, *rval*)

…

3. Let *lnum* be ? **ToNumeric** (*lval*).

4. Let *rnum* be ? **ToNumeric** (*rval*).

…

ToNumeric (*value*)

…

3. Return ? **ToNumber** (*primValue*).

ToNumber (*argument*)

…

6. If **Type** (*argument*) is Symbol,

throw a **TypeError** exception. **2**

…

Motivating Example 2

1-FS Node Coverage

TR = (Feature, Node)

TypeError `Symbol() + 1` (JS) — **Program P_4** — **(ADD, 2)** **cover**

TypeError `1 + Symbol()` (JS) — **Program P_5** — **(ADD, 2)** **cover**

→ **Same TRs**

`feat` **ADD**

Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*

↓

EvalStrOrNumBinExpr (*lval*, *opText*, *rval*)

↓

ApplyStrOrNumBinOp (*lval*, *opText*, *rval*)

…

3. Let *lnum* be ? **ToNumeric** (*lval*).

4. Let *rnum* be ? **ToNumeric** (*rval*).

…

→ **ToNumeric** (*value*)

…

3. Return ? **ToNumber** (*primValue*).

↑

ToNumber (*argument*)

…

6. If **Type** (*argument*) is Symbol,
   throw a **TypeError** exception. **2**

…

Motivating Example 2

1-FS Node Coverage

TR = (Feature, Node)

TypeError `Symbol() + 1` (JS) — **Program P_4** — (**ADD**, **2**) **cover**

TypeError `1 + Symbol()` (JS) — **Program P_5** — (**ADD**, **2**) **cover**

Cannot Distinguish P_4 and P_5

Same TRs

`feat` **ADD**

Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*

EvalStrOrNumBinExpr (*lval*, *opText*, *rval*)

ApplyStrOrNumBinOp (*lval*, *opText*, *rval*)

…

3. Let *lnum* be ? **ToNumeric** (*lval*).

4. Let *rnum* be ? **ToNumeric** (*rval*).

…

ToNumeric (*value*)

…

3. Return ? **ToNumber** (*primValue*).

ToNumber (*argument*)

…

6. If **Type** (*argument*) is Symbol, throw a **TypeError** exception. **2**

…

Motivating Example 2

1-FS Node Coverage

TR = (Feature, Node)

TypeError `Symbol() + 1` (JS) — **Program P_4** — (ADD, 2) — cover

TypeError `1 + Symbol()` (JS) — **Program P_5** — (ADD, 2) — cover

Cannot Distinguish P_4 and P_5

Same TRs

`feat` **ADD**

Evaluation of *AddExpr* : *AddExpr* **+** *MulExpr*

3 call

EvalStrOrNumBinExpr (*lval*, *opText*, *rval*)

4 call

ApplyStrOrNumBinOp (*lval*, *opText*, *rval*)

…

3. Let *lnum* be ? **ToNumeric** (*lval*). — 5 call

4. Let *rnum* be ? **ToNumeric** (*rval*). — 6 call

…

ToNumeric (*value*) — 7 call

…

3. Return ? **ToNumber** (*primValue*).

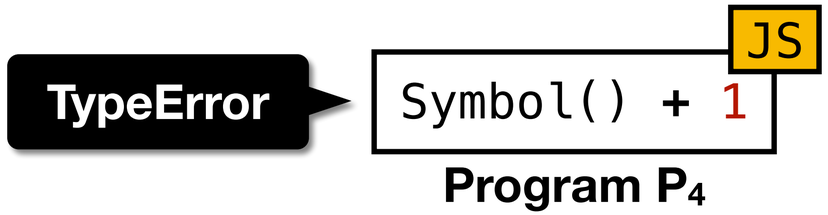
ToNumber (*argument*)

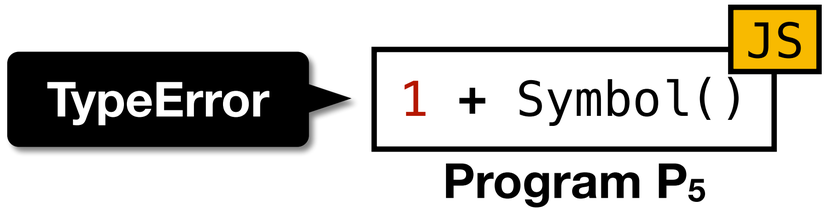
…

6. If **Type** (*argument*) is Symbol, throw a **TypeError** exception. — 2

…

k-Feature-Call-Path-Sensitive (k-FCPS) Coverage



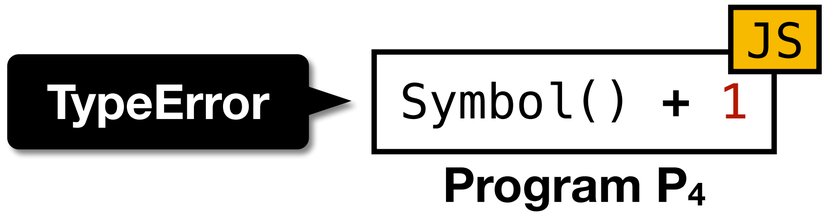


- k-**F**eature-**C**all-**P**ath-**S**ensitive (k-**FCPS**) coverage criterion divides the k-FS TRs with the **call-paths from** the innermost enclosing language feature

k-FCPS Coverage

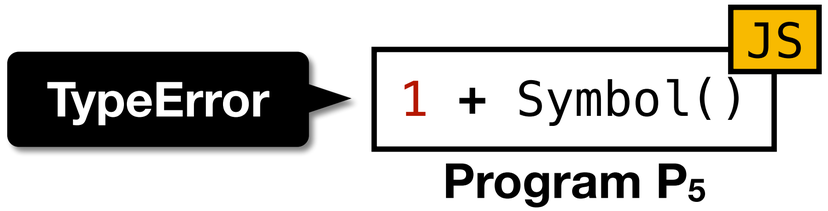
TR = (Feature$^{\leq k}$, Call-Path, given **TR)**

k-Feature-Call-Path-Sensitive (k-FCPS) Coverage



1-FCPS Node Coverage

TR = (Feature, Call-Path, Node)



- k-**F**eature-**C**all-**P**ath-**S**ensitive (k-**FCPS**) coverage criterion divides the k-FS TRs with the **call-paths from** the innermost enclosing language feature

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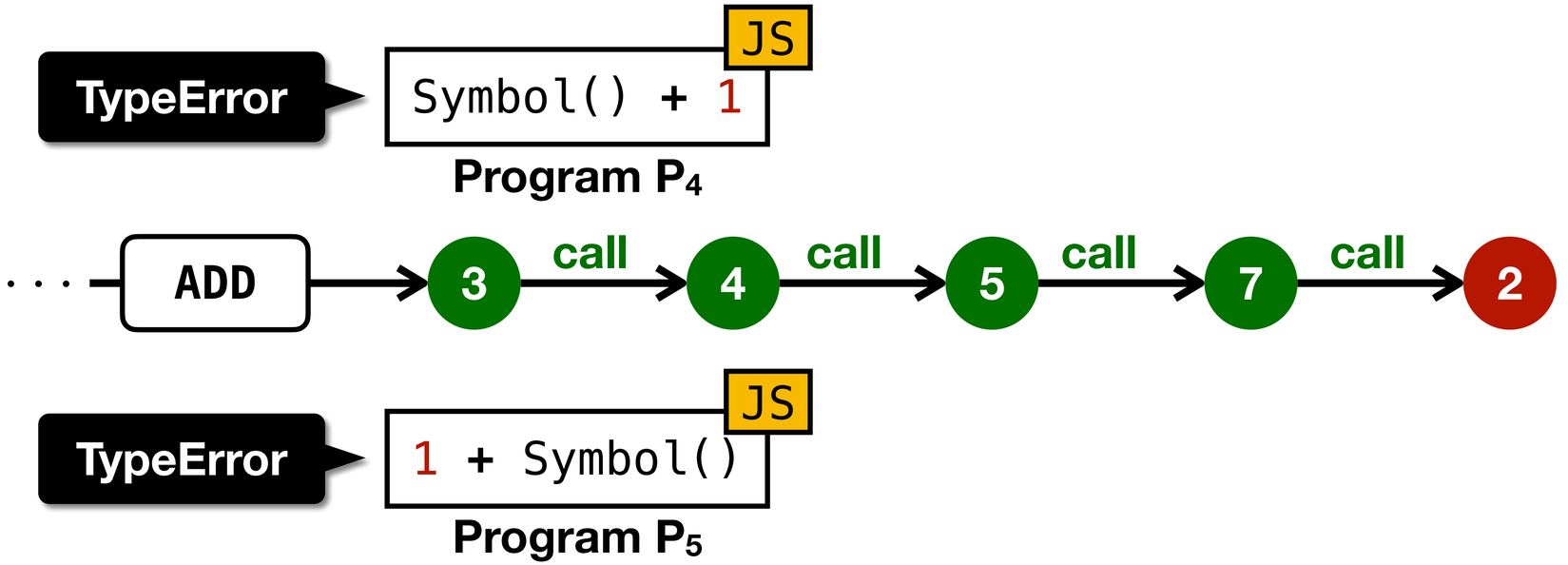
k-Feature-Call-Path-Sensitive (k-FCPS) Coverage



1-FCPS Node Coverage

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k-FCPS Coverage

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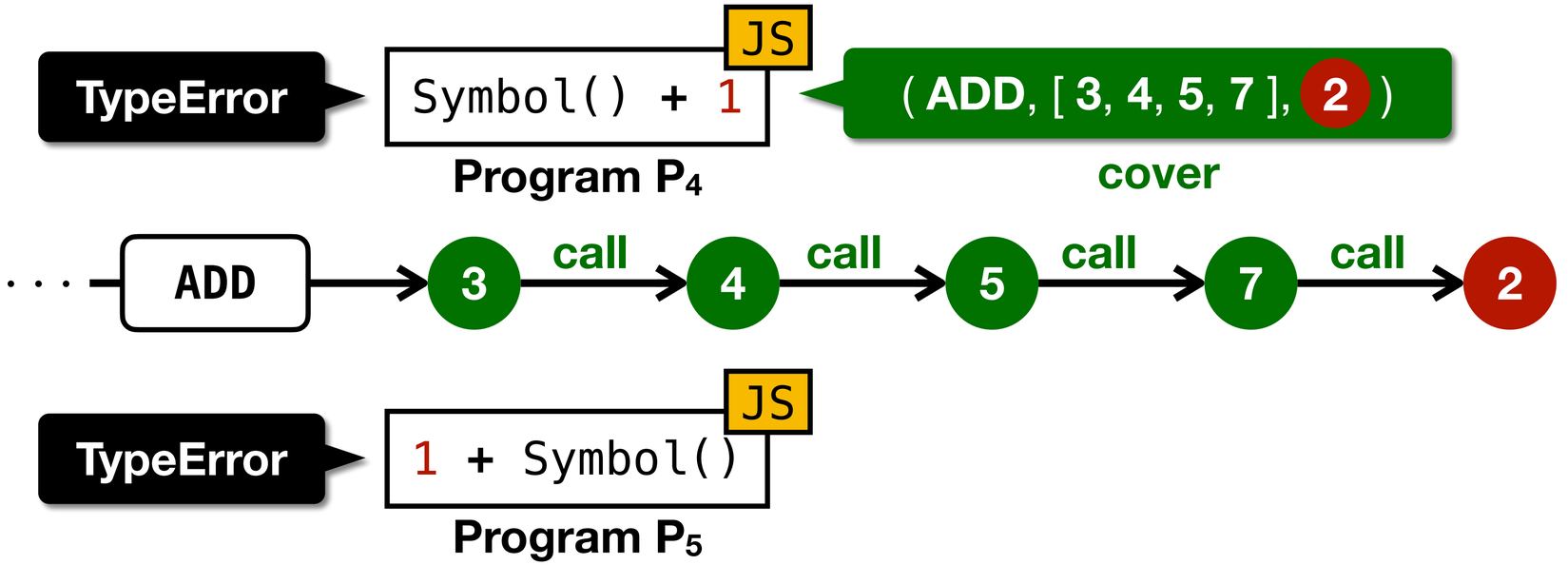
k-Feature-Call-Path-Sensitive (k-FCPS) Coverage



1-FCPS Node Coverage

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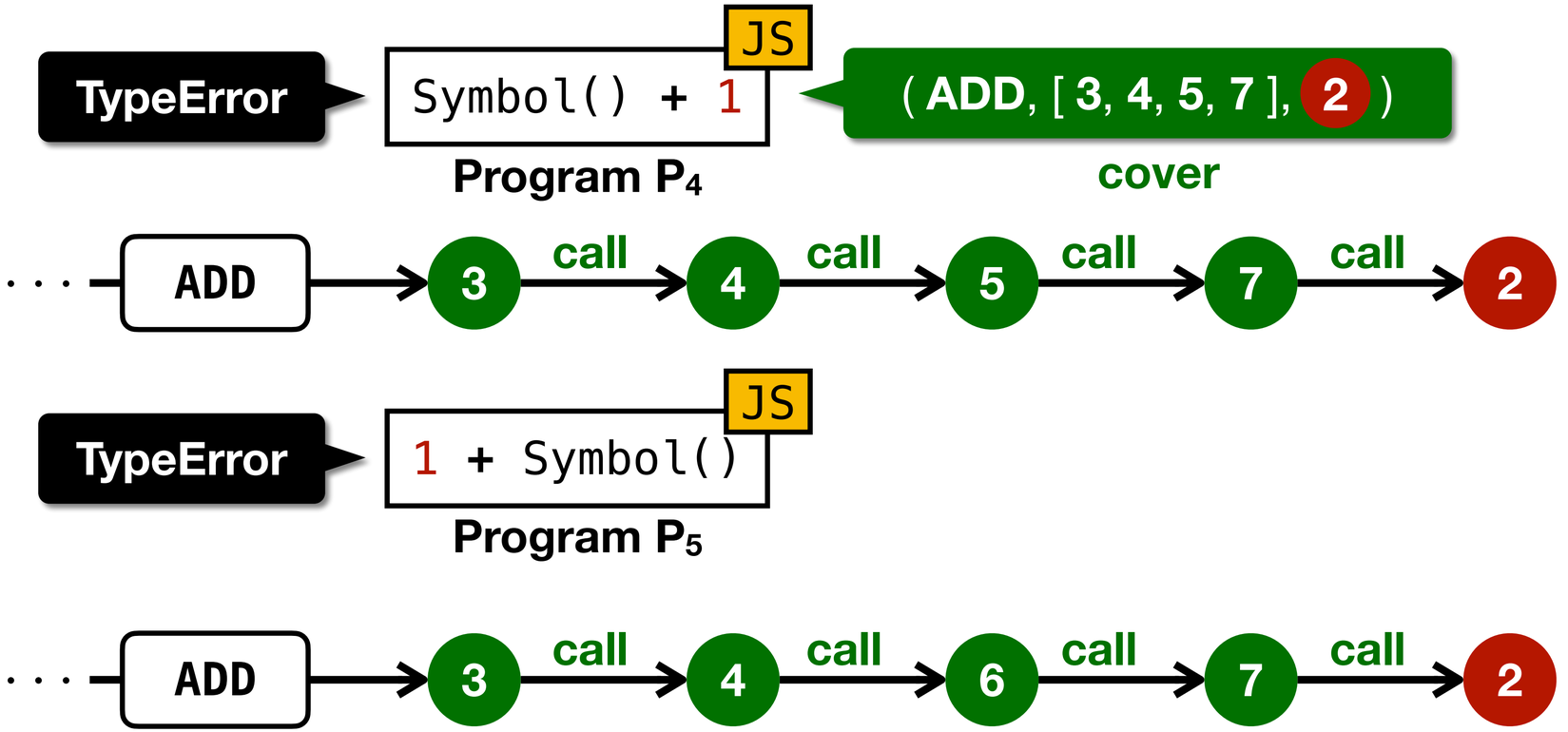
k-Feature-Call-Path-Sensitive (k-FCPS) Coverage



1-FCPS Node Coverage

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k-FCPS Coverage

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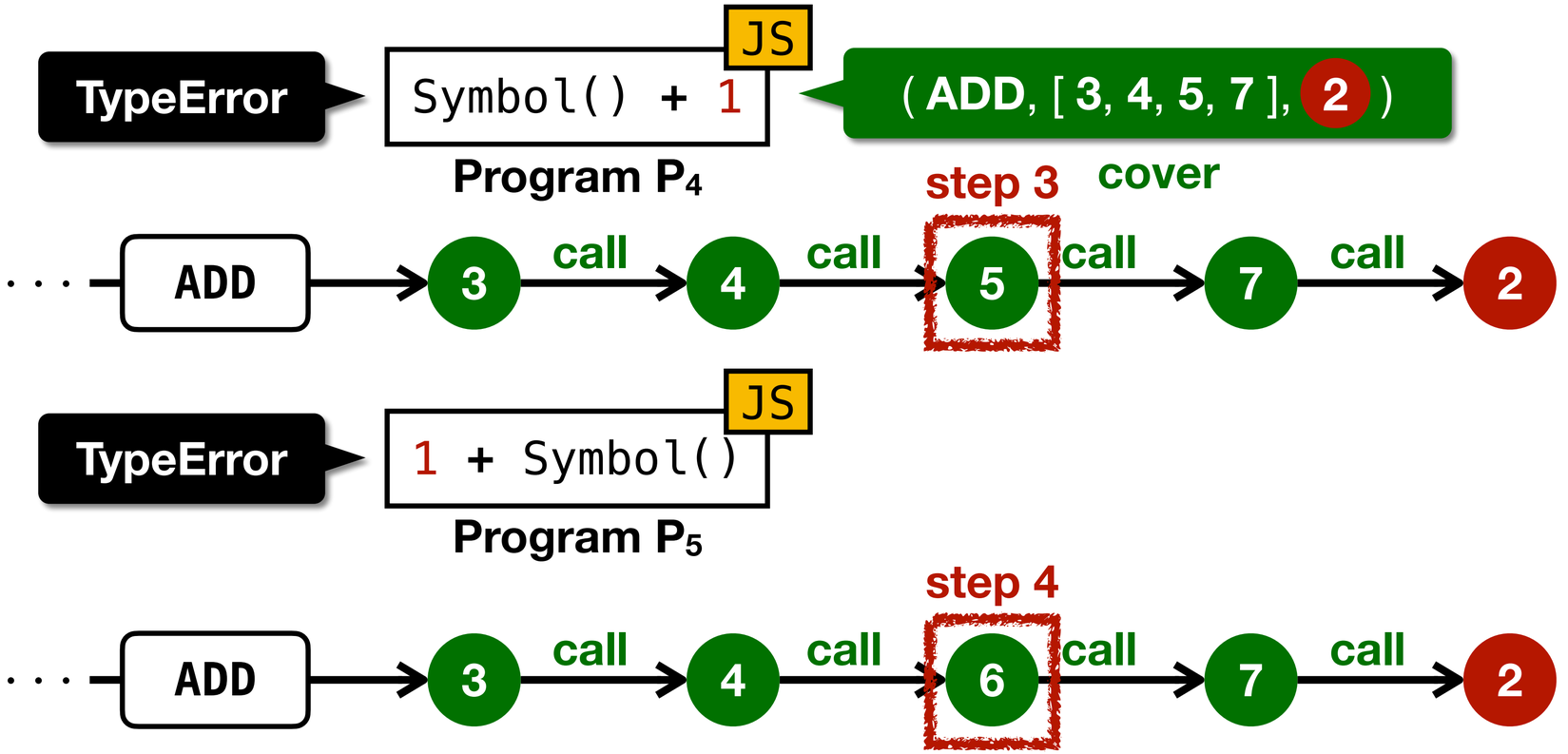
k-Feature-Call-Path-Sensitive (k-FCPS) Coverage



1-FCPS Node Coverage

TR = (Feature, Call-Path, Node)

- k-**F**eature-**C**all-**P**ath-**S**ensitive (k-**FCPS**) coverage criterion divides the k-FS TRs with the **call-paths from** the innermost enclosing language feature

k-FCPS Coverage

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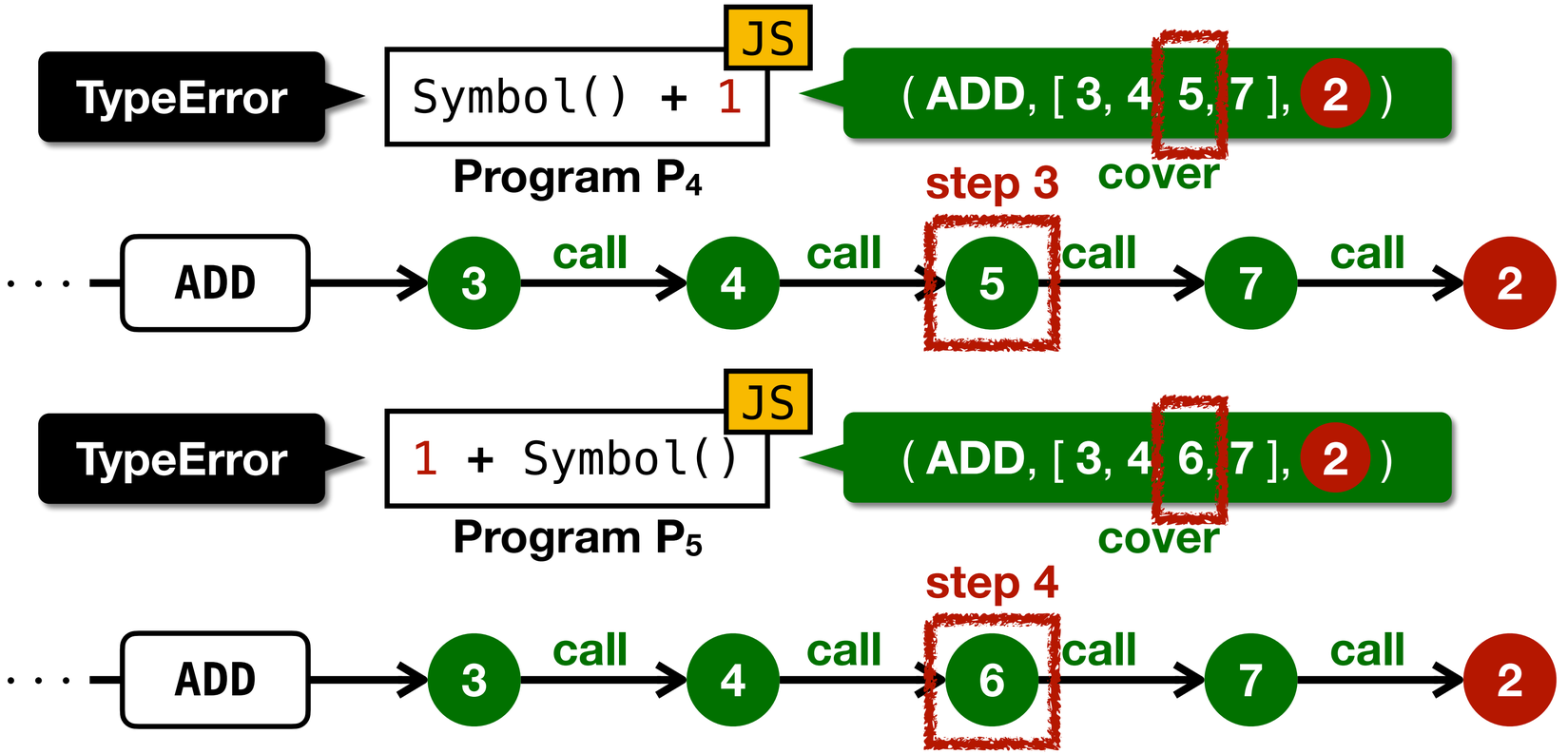
k-Feature-Call-Path-Sensitive (k-FCPS) Coverage



1-FCPS Node Coverage

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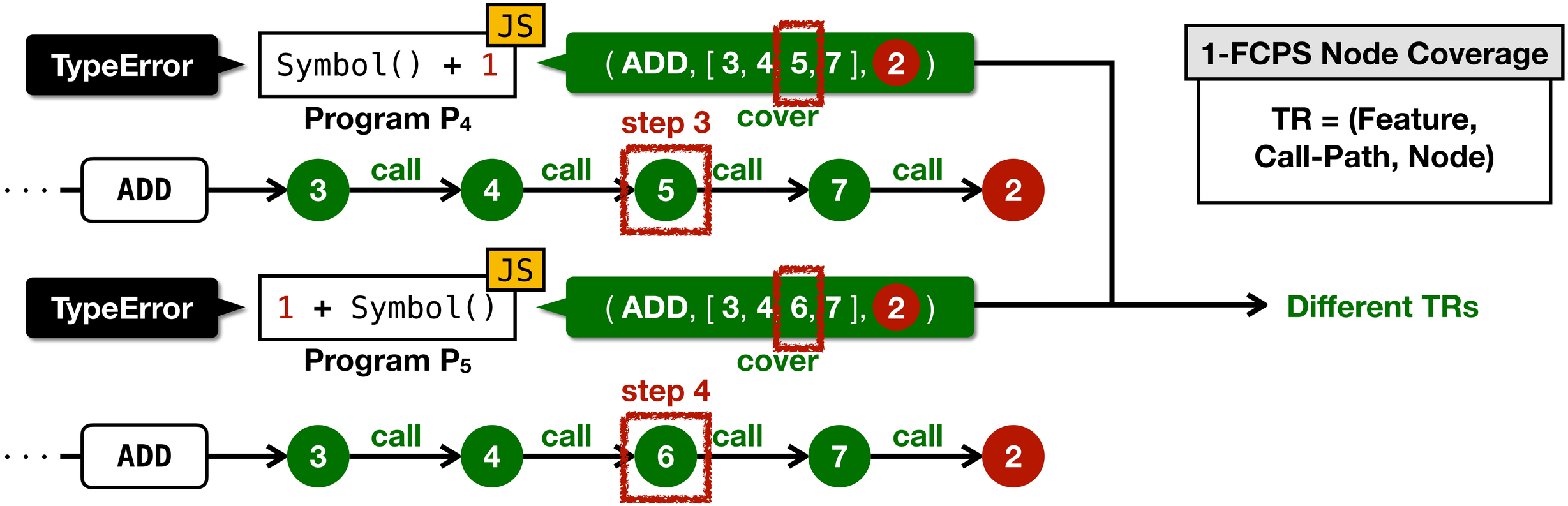
k-Feature-Call-Path-Sensitive (k-FCPS) Coverage



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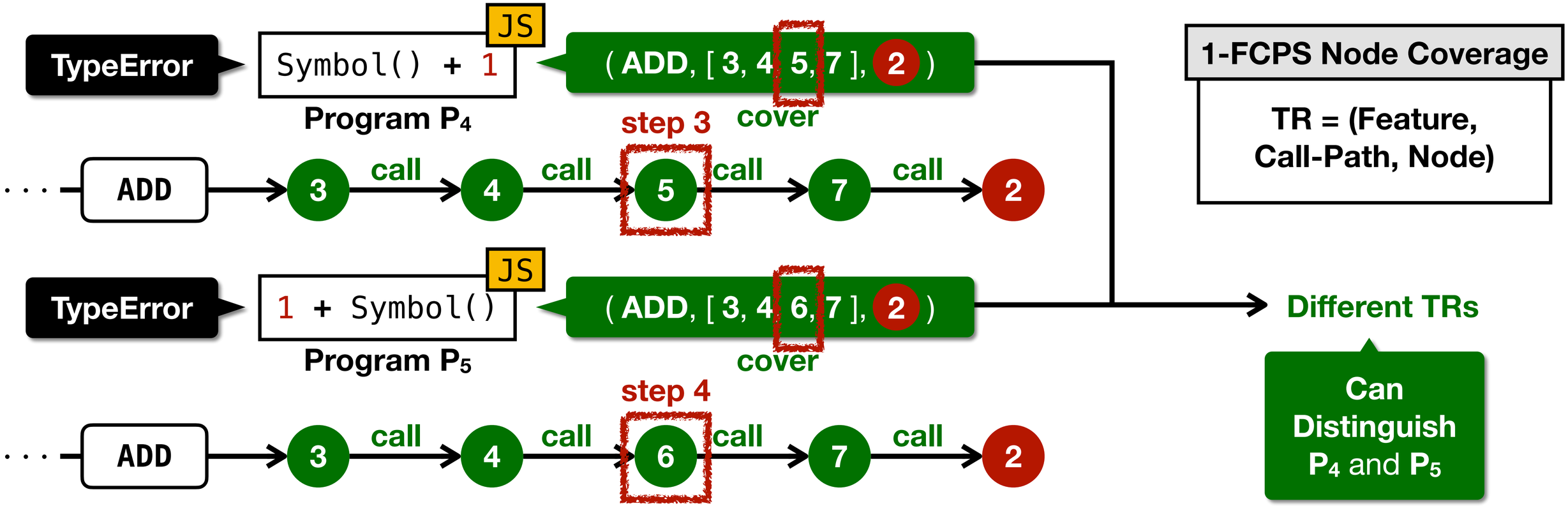
k-Feature-Call-Path-Sensitive (k-FCPS) Coverage



- k-**F**eature-**C**all-**P**ath-**S**ensitive (k-**FCPS**) coverage criterion divides the k-FS TRs with the **call-paths from** the innermost enclosing language feature

k-FCPS Coverage

TR = (Feature$^{\leq k}$, Call-Path, given **TR)**

Evaluation

5 different k-FS and k-FCPS coverage criteria

- **Conformance Test Synthesis** in 50 hours with **0-FS** / **1-FS** / **2-FS** / **1-FCPS** / **2-FCPS**
- **JavaScript Specification** — ECMA-262 for **ES13 (2022)**
- **JavaScript Implementations** — **4 Engines** and **4 Transpilers**

Kind	Name	Version	Release
Engine	**V8**	v10.8.121	2022.10.06
	JSC	v615.1.10	2022.10.26
	GraalJS	v22.2.0	2022.07.26
	SpiderMonkey	v107.0b4	2022.10.24
Transpiler	**Babel**	v7.19.1	2022.09.15
	SWC	v1.3.10	2022.10.21
	Terser	v5.15.1	2022.10.05
	Obfuscator	v4.0.0	2022.02.15

RQ1) Conformance Bug Detection

Kind	Name	Version	Release	# Detected Unique Bugs		
				# New	# Confirmed	# Reported
Engine	V8	v10.8.121	2022.10.06	0	0	4
	JSC	v615.1.10	2022.10.26	15	15	24
	GraalJS	v22.2.0	2022.07.26	9	9	10
	SpiderMonkey	v107.0b4	2022.10.24	1	3	4
	Total			**25**	**27**	**42**
Transpiler	Babel	v7.19.1	2022.09.15	30	30	35
	SWC	v1.3.10	2022.10.21	27	27	41
	Terser	v5.15.1	2022.10.05	1	1	18
	Obfuscator	v4.0.0	2022.02.15	0	0	7
	Total			**58**	**58**	**101**
Total				**83**	**85**	**143**

RQ1) Conformance Bug Detection

Kind	Name	Version	Release	# Detected Unique Bugs		
				# New	# Confirmed	# Reported
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RQ2) Effectiveness of k-FS Coverage Criteria

Coverage Criteria $C_{\mathbb{G}}$	# Covered k-F(CP)S-TR (k)			# Syn. Test	# Bug
	# Node	# Branch	# Total		
0-FS node-or-branch (0-fs)	10.0	5.6	15.6	2,111	55
1-FS node-or-branch (1-fs)	79.3	45.7	125.0	6,766	83
1-FCPS node-or-branch (1-fcps)	179.7	97.6	277.3	9,092	87
2-FS node-or-branch (2-fs)	1,199.8	696.3	1,896.1	97,423	102
2-FCPS node-or-branch (2-fcps)	2,323.1	1,297.6	3,620.7	122,589	111

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+28

Spec.

Expected

Terminated

```
for (let {} = 0; 0; ) ;
```

Wrong Result

Crash

Babel

Synthesized with **1-FS** but not with **0-FS**

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+28

+19

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2-FCPS node-or-branch (2-fcps)	2,323.1	1,297.6	3,620.7	122,589	111

+28

+19

Spec.

Expected

`Terminated`

```
for (let {} = 0; 0; ) ;
```

Wrong Result

`Crash`

Babel

Synthesized with **1-FS** but not with **0-FS**

Spec.

Expected

`"f"`

```
class C { async ["f"](){} }
C.prototype.f.name
```

Wrong Result

`"async"`

JSC

Synthesized with **2-FS** but not with **1-FS**

RQ3) Effectiveness of k-FCPS Coverage Criteria

Coverage Criteria $C_{\mathbb{G}}$	# Covered k-F(CP)S-TR (k)			# Syn. Test	# Bug
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+4

RQ3) Effectiveness of k-FCPS Coverage Criteria

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+4

+9

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+4

+9

Spec.

Expected

RangeError

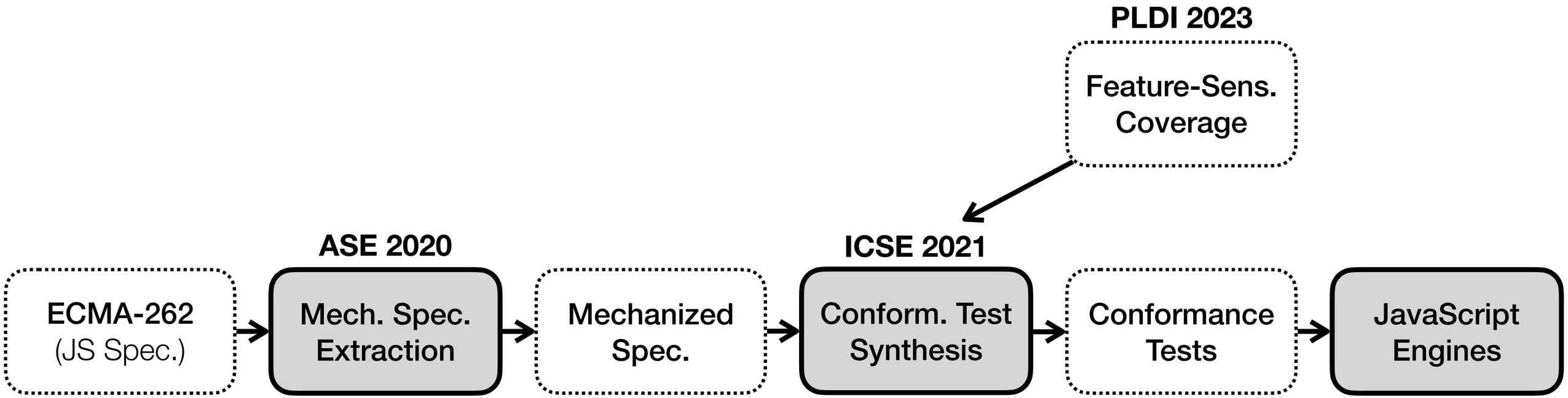
```
String.prototype
      .normalize
      .call(0, "");
```

Wrong Result

Terminated

GraalJS

Synthesized with **1-FCPS** or **2-FCPS** but not with **1-FS** or **2-FS**


PLDI 2023
Feature-Sens. Coverage
ASE 2020
ICSE 2021
ECMA-262 (JS Spec.)
Mech. Spec. Extraction
Mechanized Spec.
Conform. Test Synthesis
Conformance Tests
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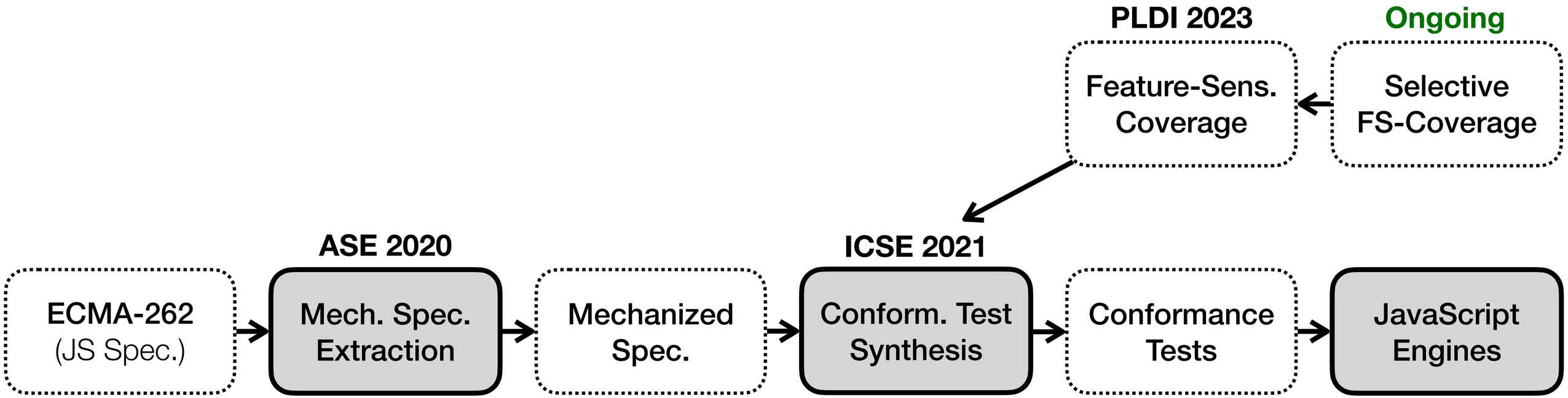
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Ongoing
Feature-Sens. Coverage
Selective FS-Coverage
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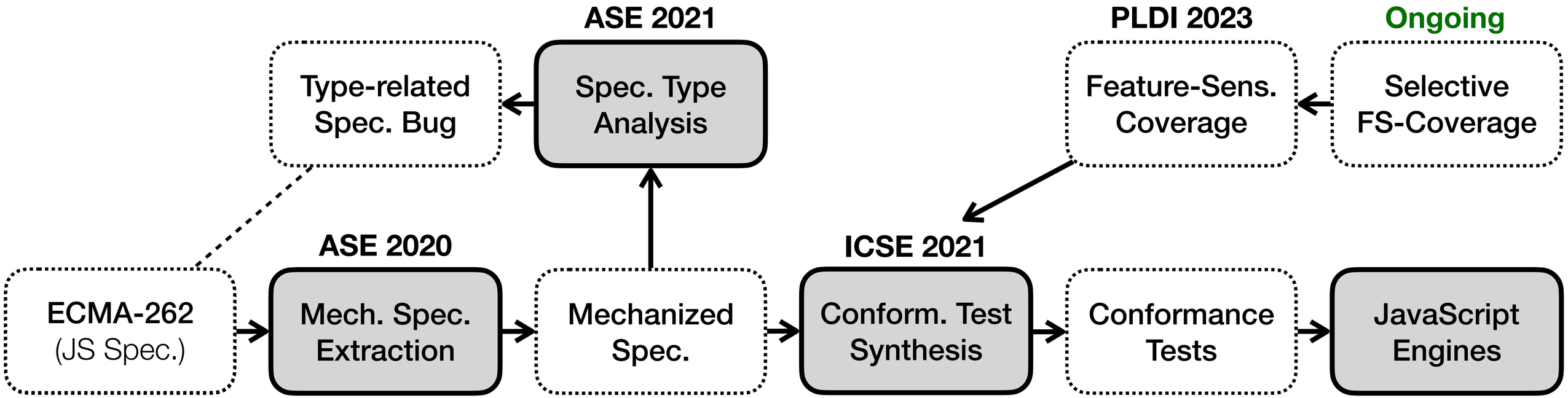
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Spec. Type Analysis
Feature-Sens. Coverage
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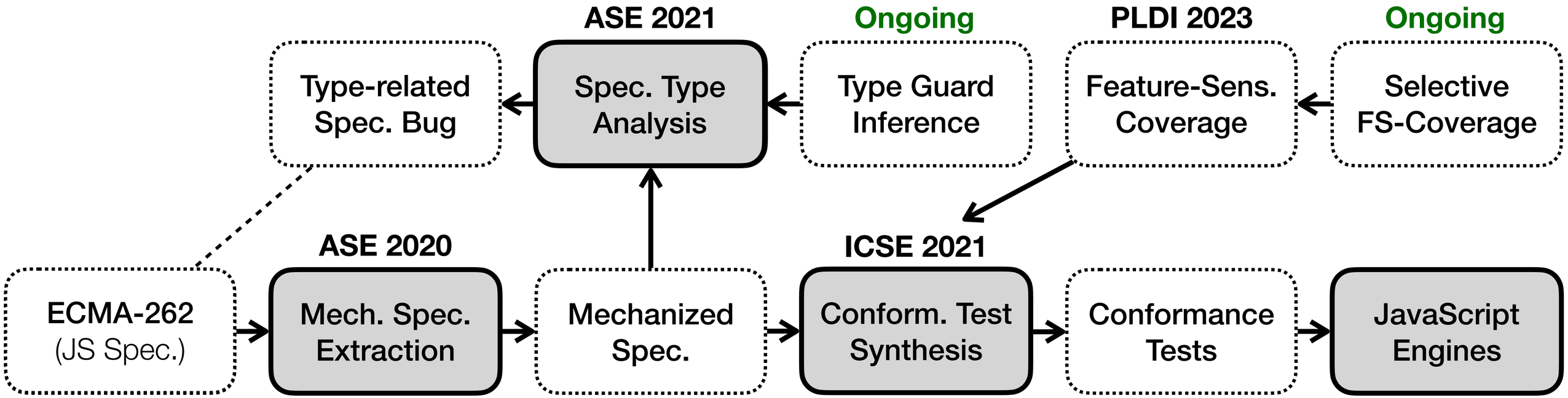
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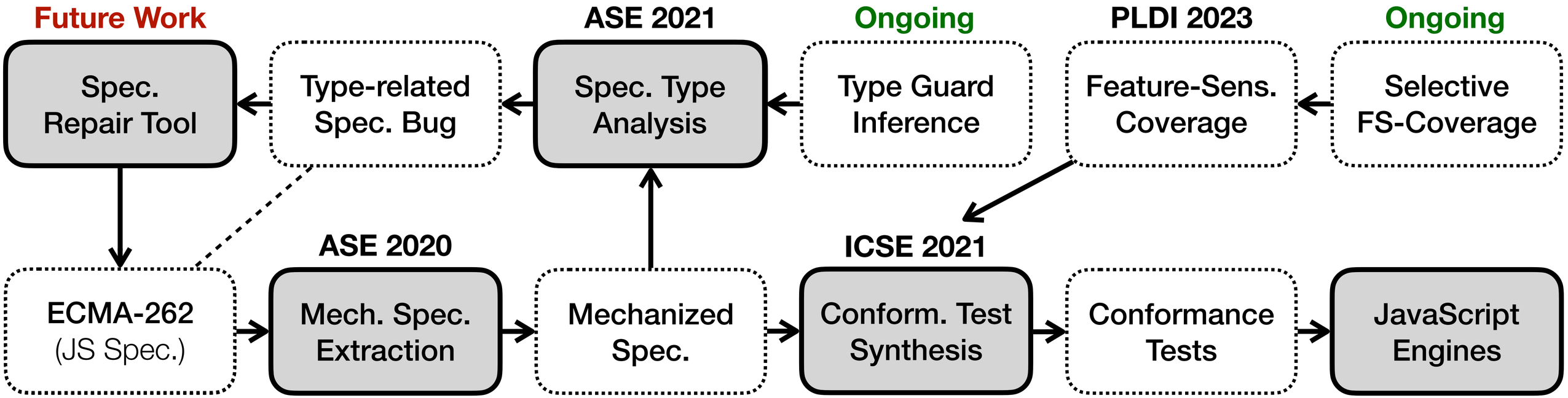
Future Work
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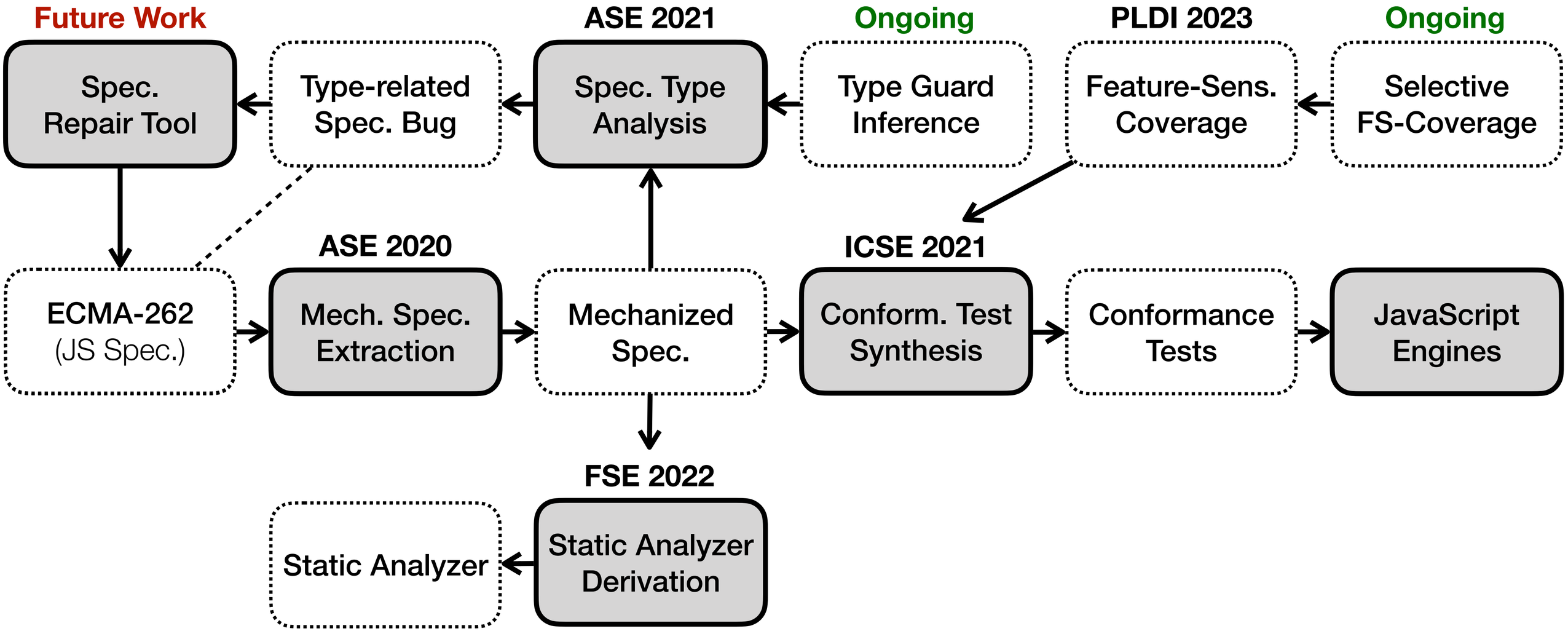
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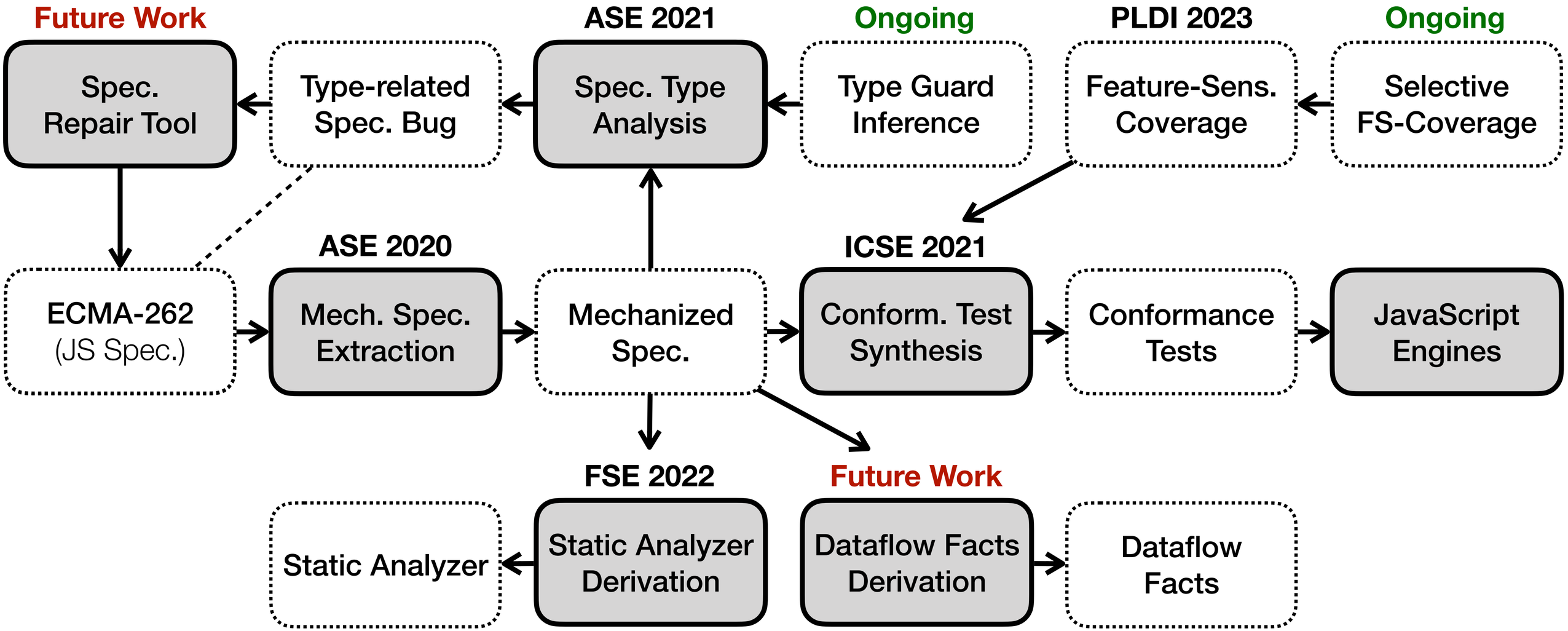
FSE 2022
Static Analyzer
Static Analyzer Derivation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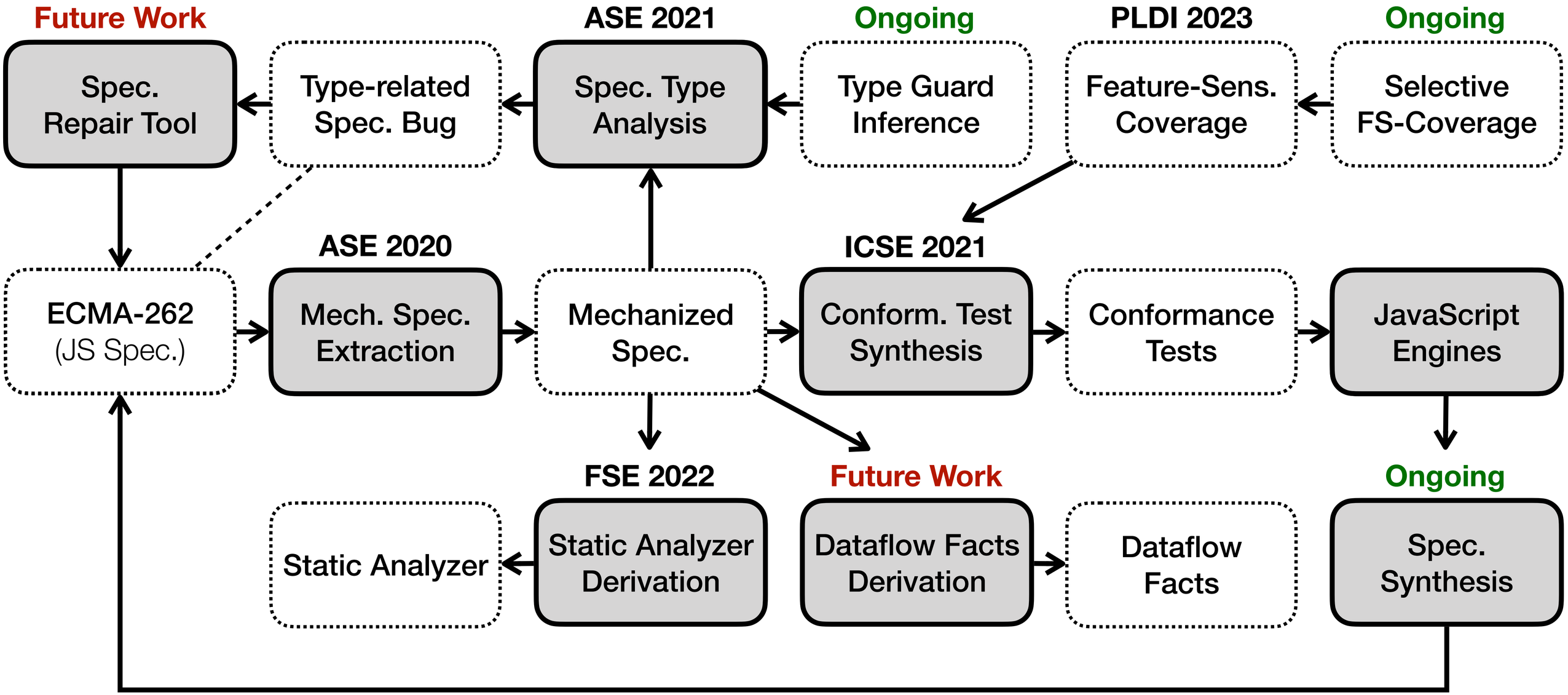
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