PLRG
Programming Language
Research Group

JavaScript Static Analysis for Evolving Language Specifications

SIGPL Winter School 2022

Jihyeok Park

PLRG @ KAIST

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SAFE: Formal Specification and Implementation of a Scalable Analysis Framework for ECMAScript

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Abstract

The prevalent uses of JavaScript in web programming have revealed security vulnerability issues of JavaScript applications, which emphasizes the need for JavaScript analyzers to detect such issues. Recently, researchers have proposed several analyzers of JavaScript programs and some web service companies have developed various JavaScript engines. However, unfortunately, most of the tools are not documented well, thus it is very hard to understand and modify them. Or, such tools are often not open to the public.

In this paper, we present formal specification and implementation of SAFE, a scalable analysis framework for ECMAScript, developed for the JavaScript research community. This is the very first attempt to provide both formal specification and its open-source implementation for JavaScript, compared to the existing approaches focused on only one of them. To make it more amenable for other researchers to use our framework, we formally define three kinds of intermediate representations for JavaScript used in


```
1   function Wheel4() { this.wheel = 4 }
2   function Car() { this.maxspeed = 200 }
3   Car.prototype = new Wheel4;
4   var modernCar = new Car;
5
6   var beforeModern =
7       modernCar instanceof Car; // true
8
9   function Wheel6() { this.wheel = 6 }
10  Car.prototype = new Wheel6;
11  var afterModern =
12      modernCar instanceof Car; // false
13  var truck = new Car;
14  var aftertruck =
15      truck instanceof Car; // true
```

Figure 1. Unintuitive behavior of JavaScript prototypes

ECMA-262: ECMAScript Specification

TC 39

ecma INTERNATIONAL

Syntax

ArrayLiteral`[Yield, Await]` :

[*Elision*`opt`]

[*ElementList*`[?Yield, ?Await]`]

[*ElementList*`[?Yield, ?Await]` , *Elision*`opt`]

The production of *ArrayLiteral* in ES12

Semantics

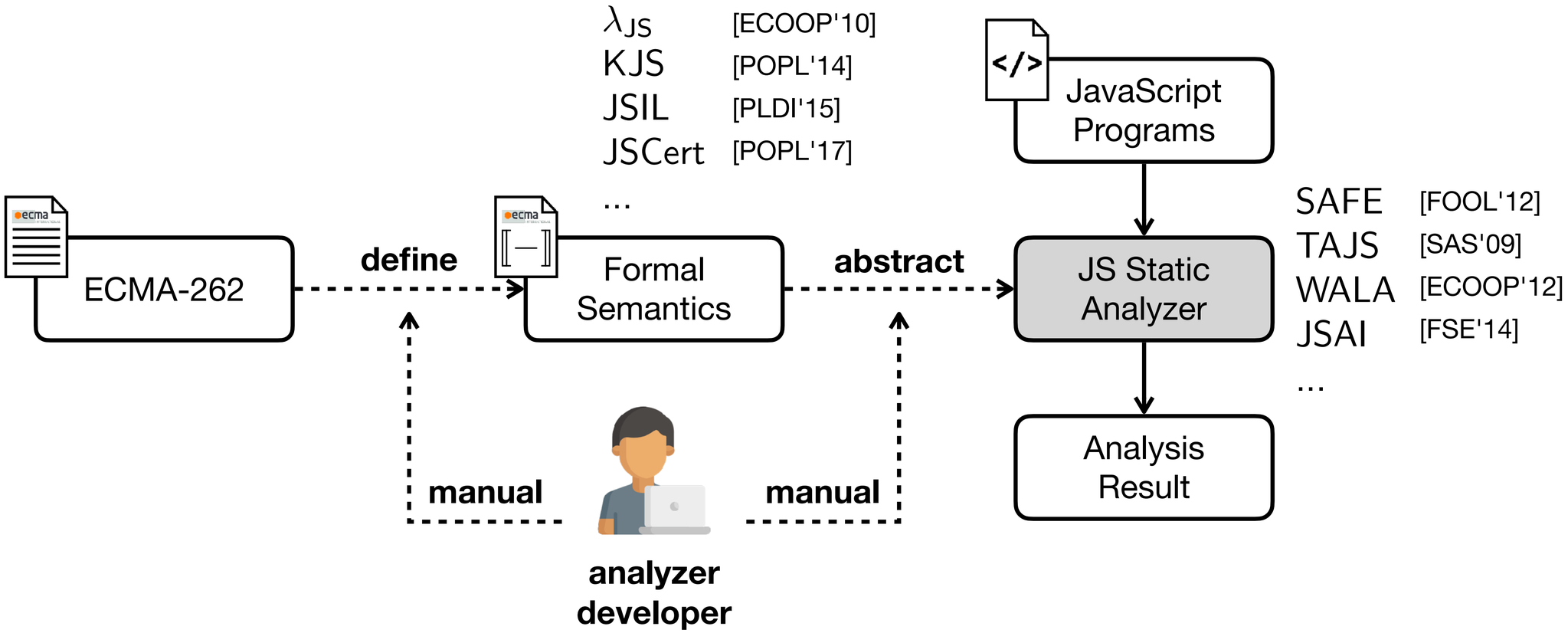
13.2.5.2 Runtime Semantics: Evaluation

ArrayLiteral : [*ElementList* , *Elision*`opt`]

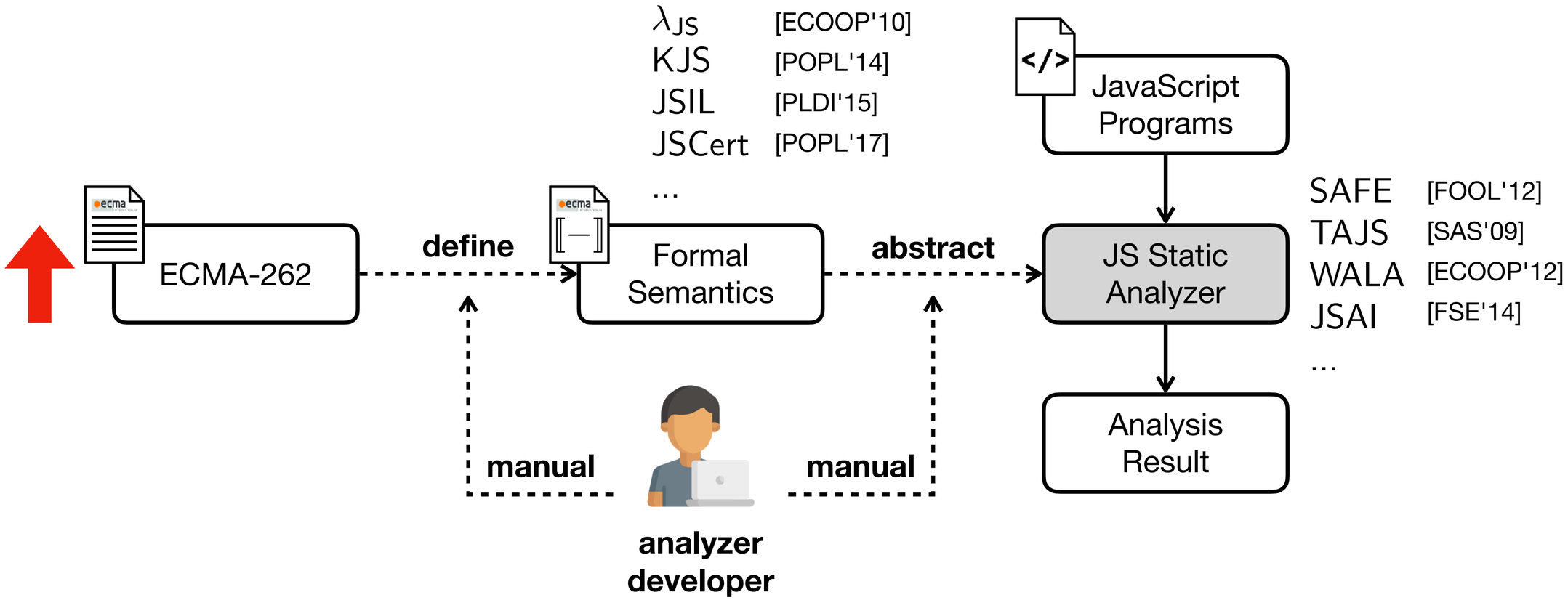
1. Let *array* be ! ArrayCreate(0).
2. Let *nextIndex* be the result of performing ArrayAccumulation for *ElementList* with arguments *array* and 0.
3. ReturnIfAbrupt(*nextIndex*).
4. If *Elision* is present, then
   a. Let *len* be the result of performing ArrayAccumulation for *Elision* with arguments *array* and *nextIndex*.
   b. ReturnIfAbrupt(*len*).
5. Return *array*.

The Evaluation algorithm for the third alternative of *ArrayLiteral* in ES12

Problem: Manual JavaScript Static Analyzer



Problem: Manual JavaScript Static Analyzer



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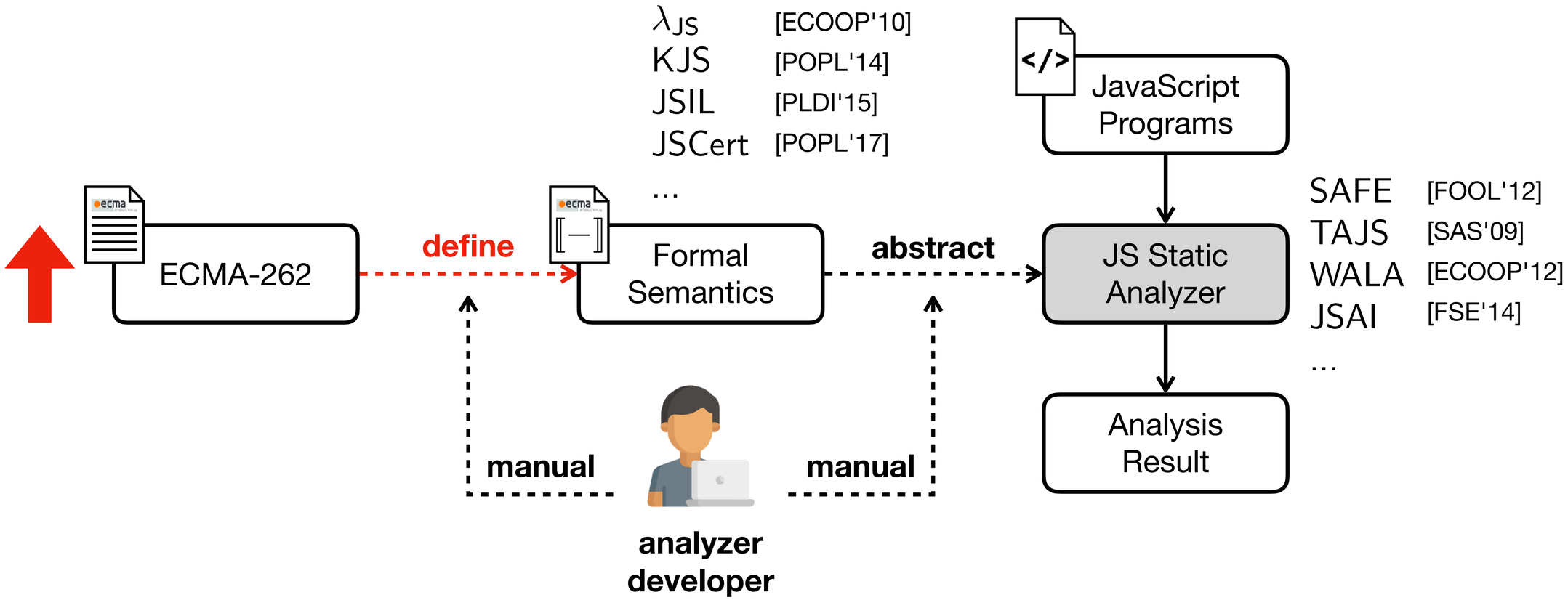
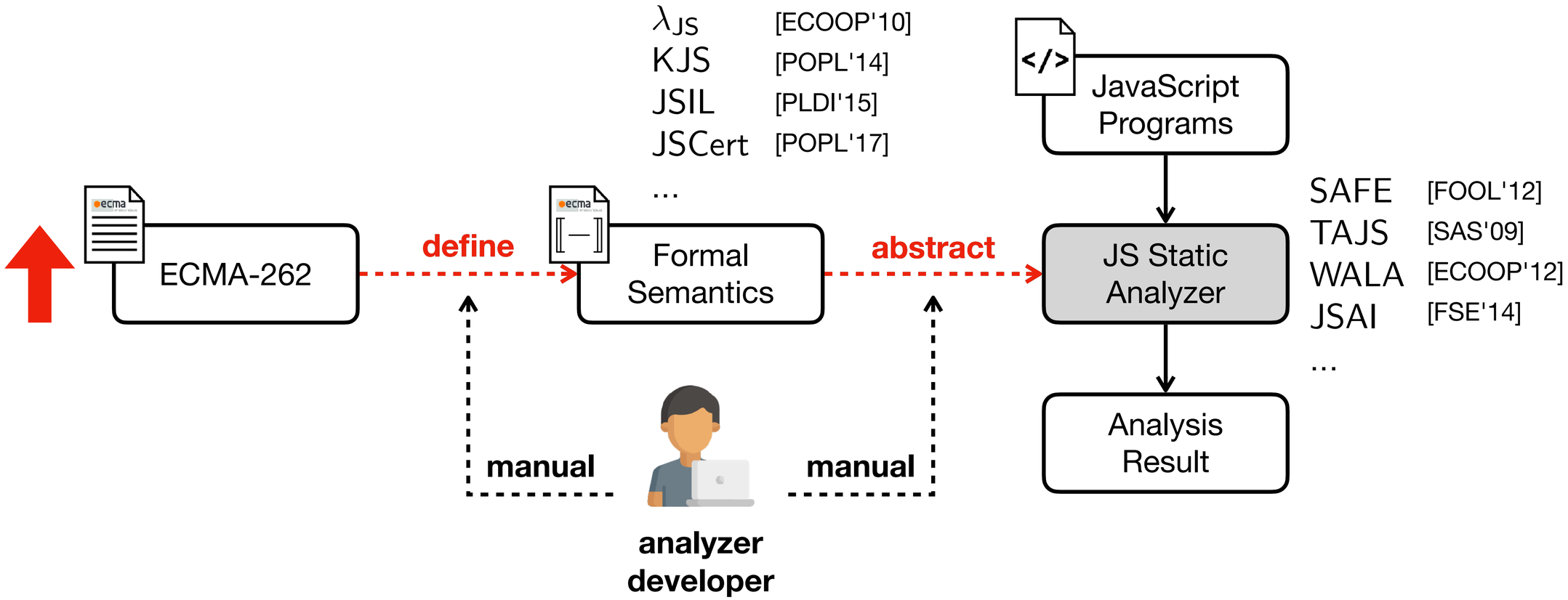
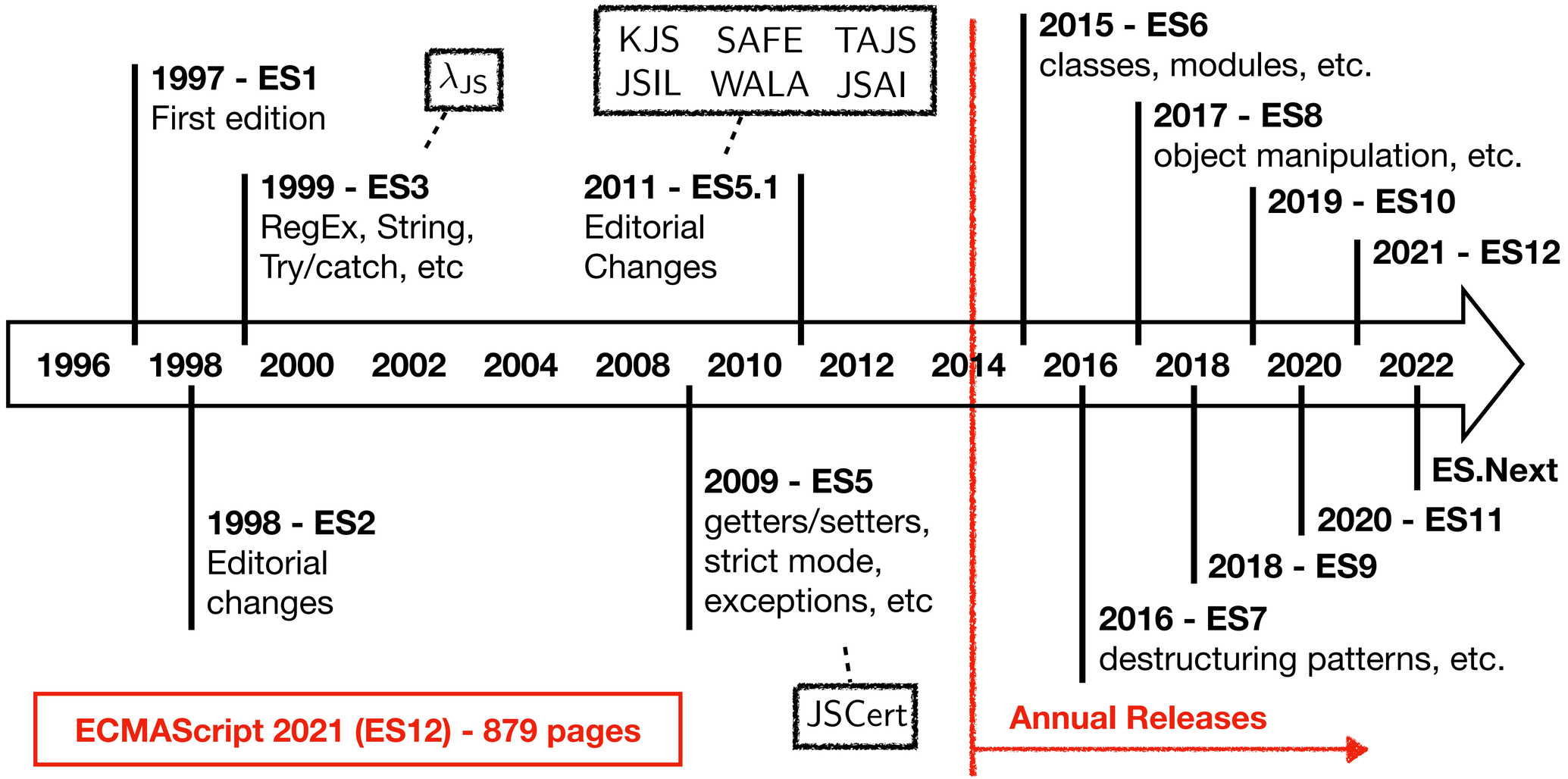


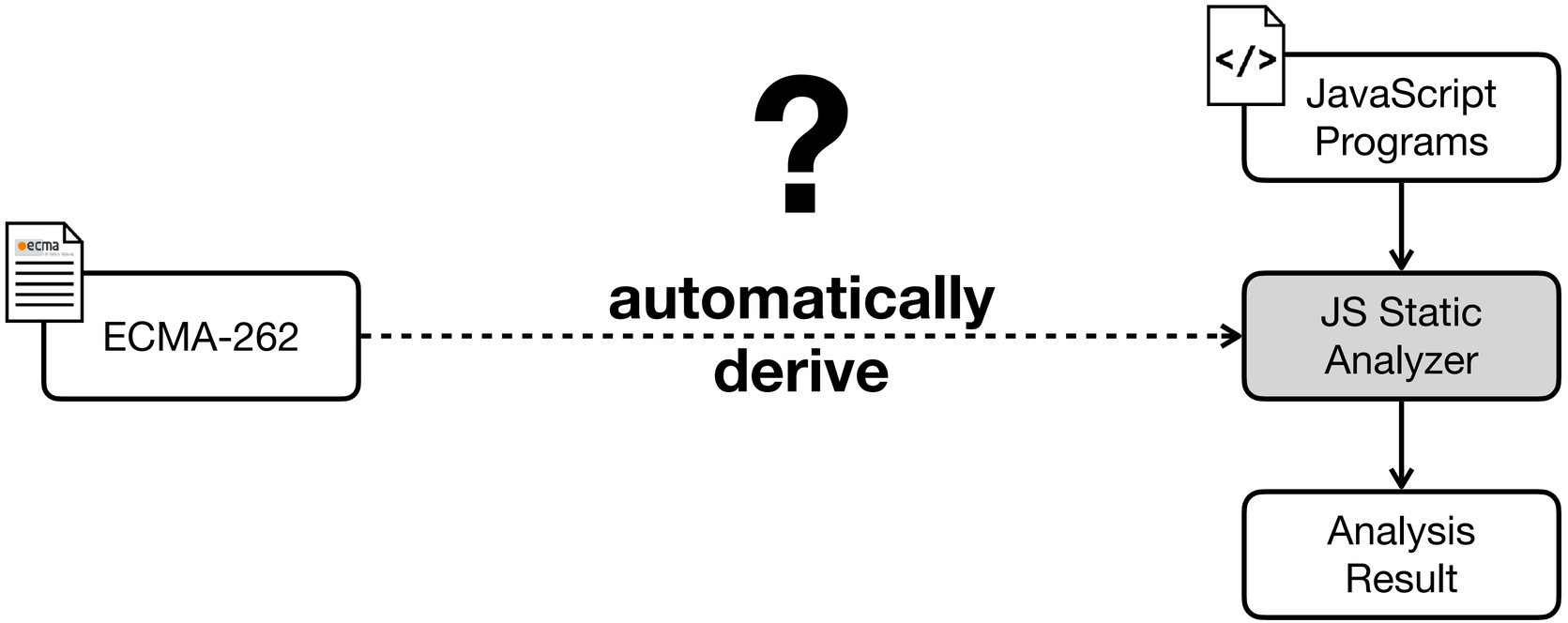
Problem: Manual JavaScript Static Analyzer



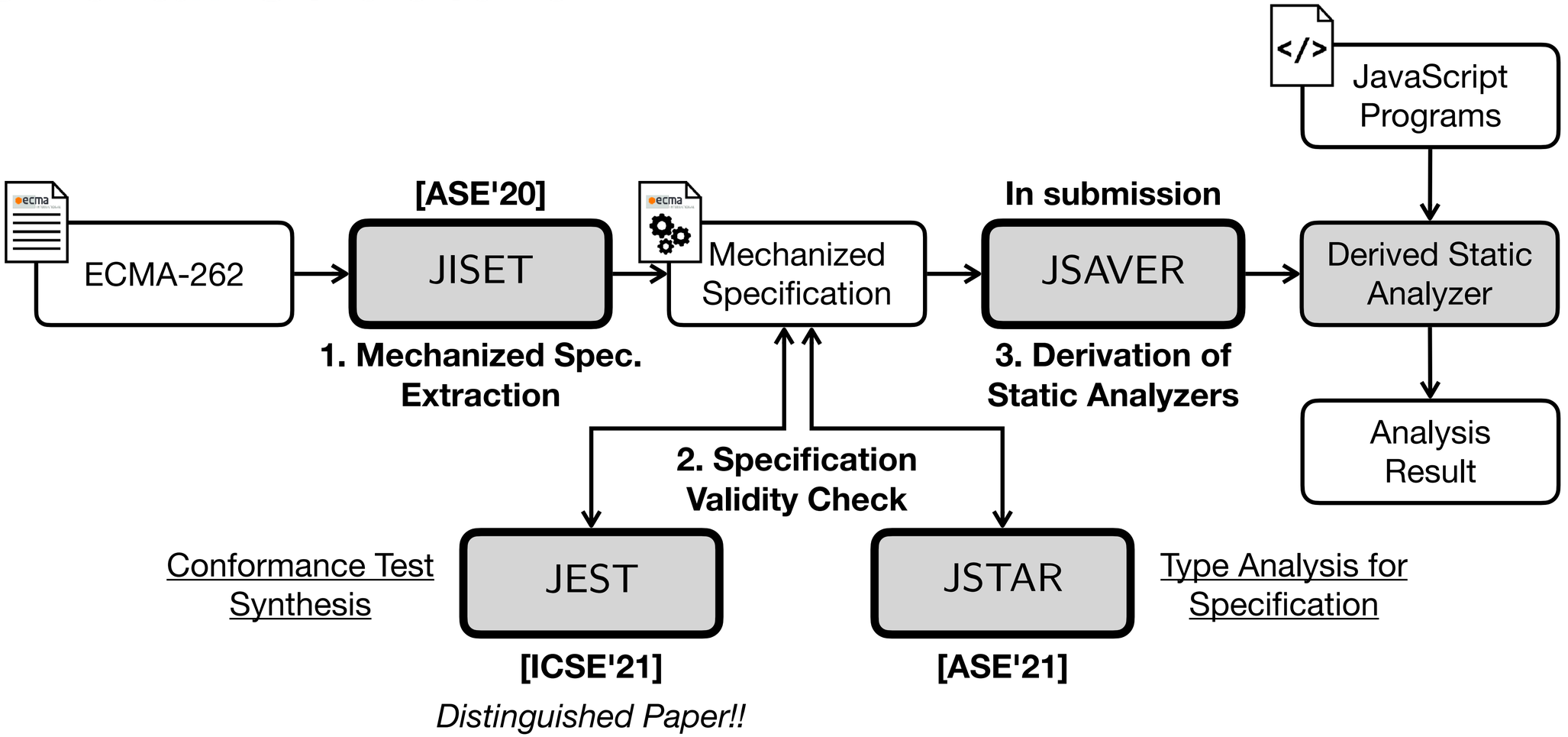
Problem: Fast Evolving JavaScript



Main Idea: Deriving Static Analyzer from Spec.



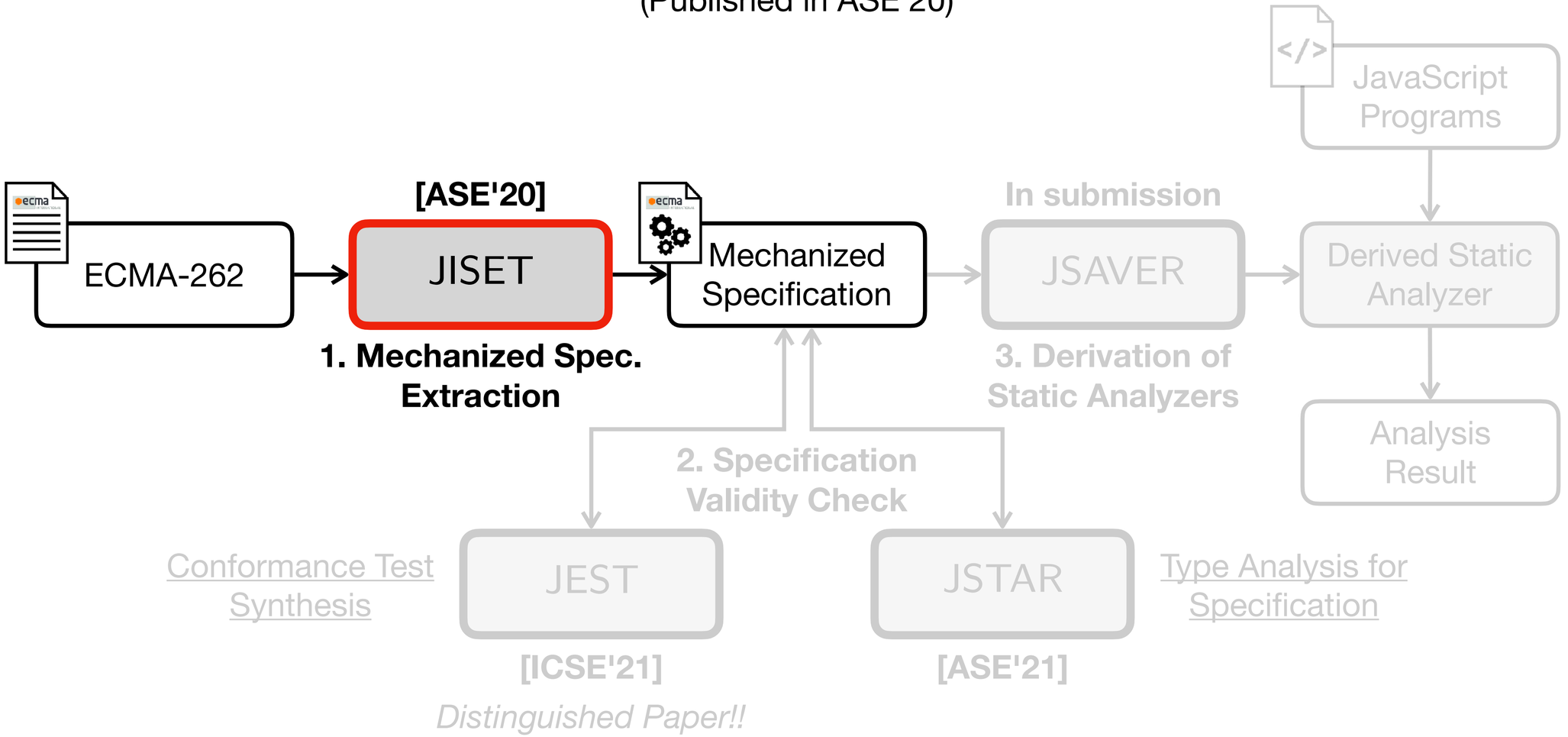
Overall Structure



JISET: JavaScript IR-based Semantics Extraction Toolchain

Jihyeok Park, Jihee Park, Seungmin An, and Sukyoung Ryu

(Published in ASE'20)



Motivation: Patterns in Writing Style of ECMA-262

13.2.5.2 Runtime Semantics: Evaluation

ArrayLiteral : [*ElementList* , *Elision*$_{opt}$]

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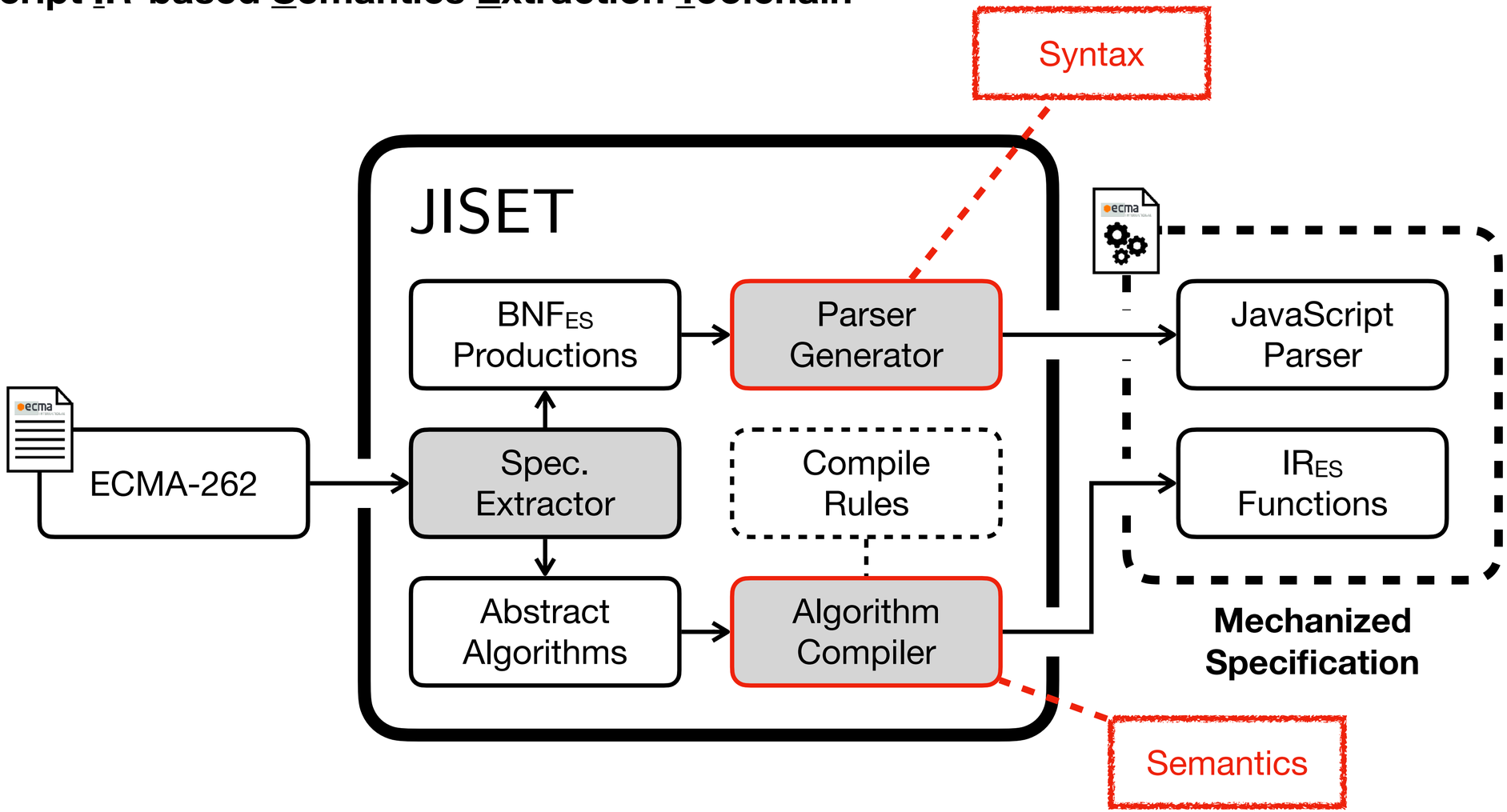
The Evaluation **algorithm for the third alternative of** *ArrayLiteral* **in ES12**

JISET [ASE'20]

JavaScript IR-based Semantics Extraction Toolchain



JISET - Parser Generator (Syntax)

JavaScript Parser in Scala

ArrayLiteral[Yield, Await] :

[*Elision*opt]

[*ElementList*[?Yield, ?Await]]

[*ElementList*[?Yield, ?Await] , *Elision*opt]

Parsing Expression Grammar
(+ Lookahead Parsing)

```
val ArrayLiteral: List[Boolean] => LAParser[T] = memo {
  case List(Yield, Await) =>
  "[" ~ opt(Elision) ~ "]"                ^^ ArrayLiteral0 |
  "[" ~ ElementList(Yield,Await) ~ "]" ^^ ArrayLiteral1 |
  "[" ~ ElementList(Yield,Await) ~ ","
      ~ opt(Elision)~ "]"                 ^^ ArrayLiteral2
}
```

(POPL'04) Bryan Ford, "Parsing Expression Grammars: A Recognition-based Syntactic Foundation"

JISET - Algorithm Compiler (Semantics)

13.2.5.2 Runtime Semantics: Evaluation

ArrayLiteral : [*ElementList* , *Elision*$_{opt}$]

1. Let *array* be ! ArrayCreate(0).
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IR$_{ES}$ Functions

118 Compile Rules for Steps in Abstract Algorithms

```
syntax def ArrayLiteral[2].Evaluation(
  this, ElementList, Elision
) {
  let array = [! (ArrayCreate 0)]
  let nextIndex = (ElementList.ArrayAccumulation array 0)
  [? nextIndex]
  if (! (= Elision absent)) {
    let len = (Elision.ArrayAccumulation array nextIndex)
    [? len]
  }
  return array
}
```

JISET - Evaluation

≈ 95% Compiled

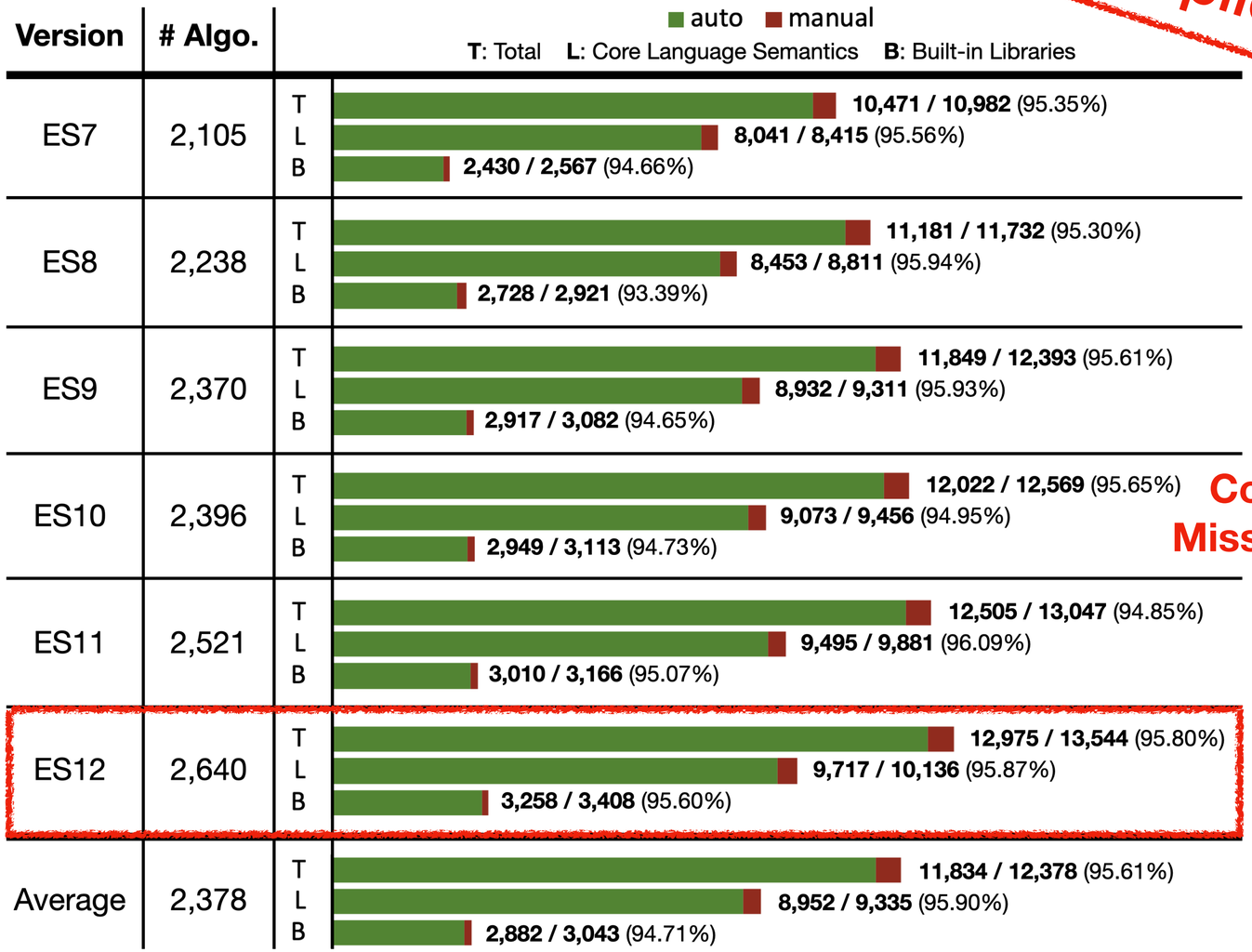
auto manual

T: Total **L**: Core Language Semantics **B**: Built-in Libraries

Version	# Algo.		
ES7	2,105	T	**10,471 / 10,982** (95.35%)
		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%)

JISET - Evaluation

≈ 95% Compiled



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Complete Missing Parts

JISET - Evaluation

≈ 95% Compiled

Passed All Tests

auto manual

T: Total **L**: Core Language Semantics **B**: Built-in Libraries

Version	# Algo.		
ES7	2,105	T	**10,471 / 10,982** (95.35%)
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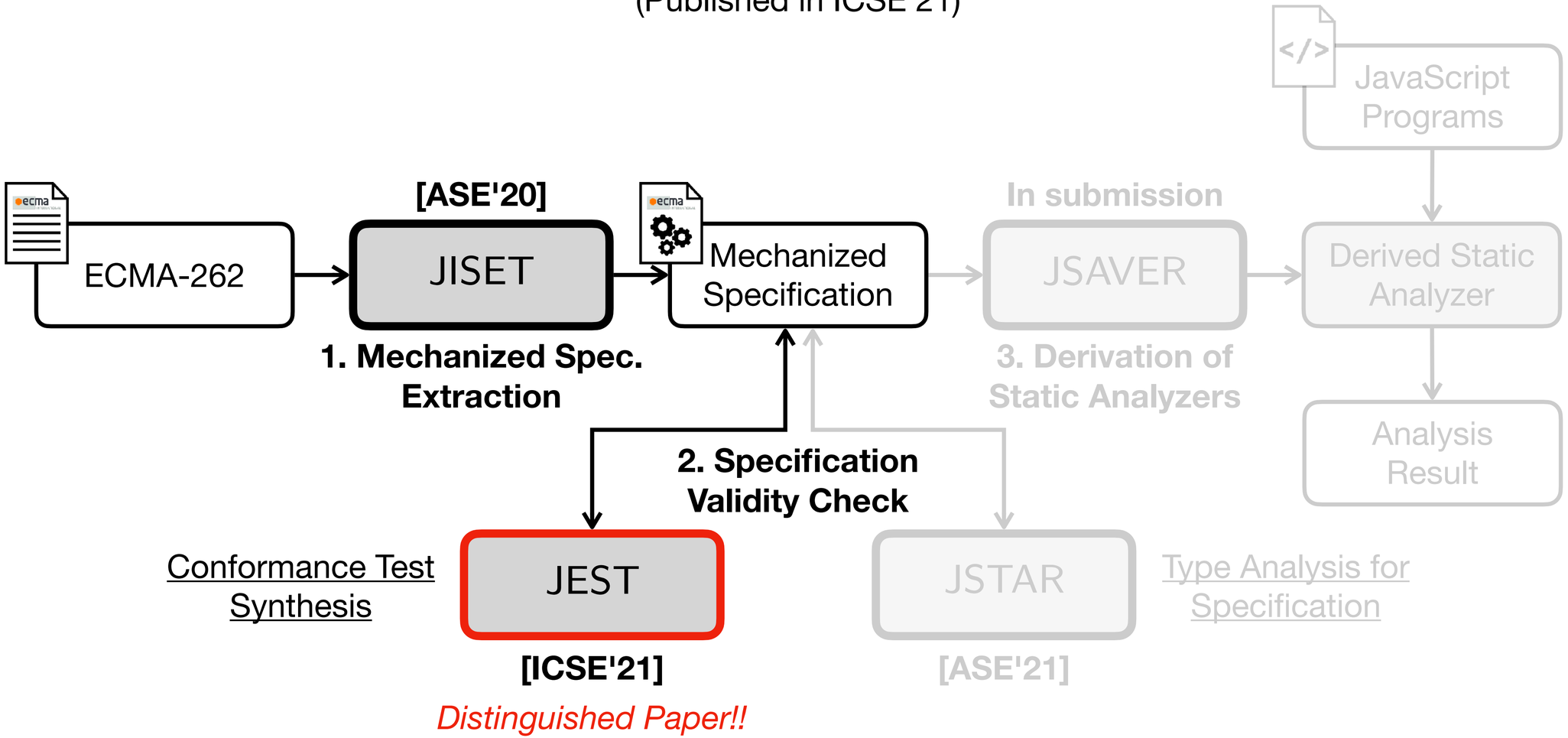
Complete Missing Parts

- **Test262**
  (Official Conformance Tests)
  - 18,556 applicable tests
- **Parsing tests**
  - Passed all 18,556 tests
- **Evaluation Tests**
  - Passed all 18,556 tests

JEST: N+1-version Differential Testing of Both JavaScript Engines

Jihyeok Park, Seungmin An, Dongjun Youn, Gyeongwon Kim, and Sukyoung Ryu

(Published in ICSE'21)



JEST - Conformance with Engines

ECMA-262

GraalVM

QuickJS

moddable

JavaScript Engines

JEST - N+1-version Differential Testing

ECMA-262

Synthesize

Test

test

test

test

test

GraalVM

QuickJS

moddable

JavaScript
Engines

JEST - N+1-version Differential Testing

ECMA-262

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JEST - N+1-version Differential Testing

ECMA-262

Synthesize

Test

test

test

test

test

JavaScript Engines

An engine bug in

JEST - N+1-version Differential Testing

ECMA-262

Synthesize

Test

test

test

test

test

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JavaScript
Engines

JEST - N+1-version Differential Testing

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JavaScript
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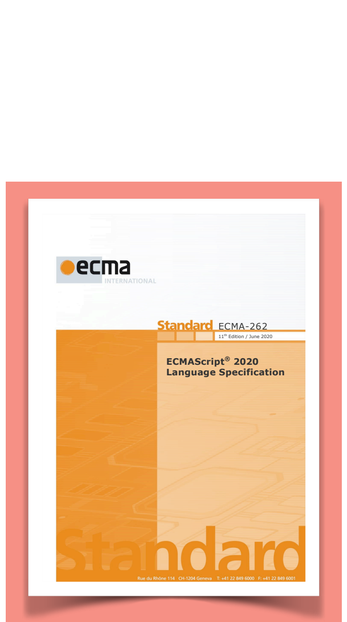
JEST - N+1-version Differential Testing



ECMA-262

Synthesize

Test

test

test

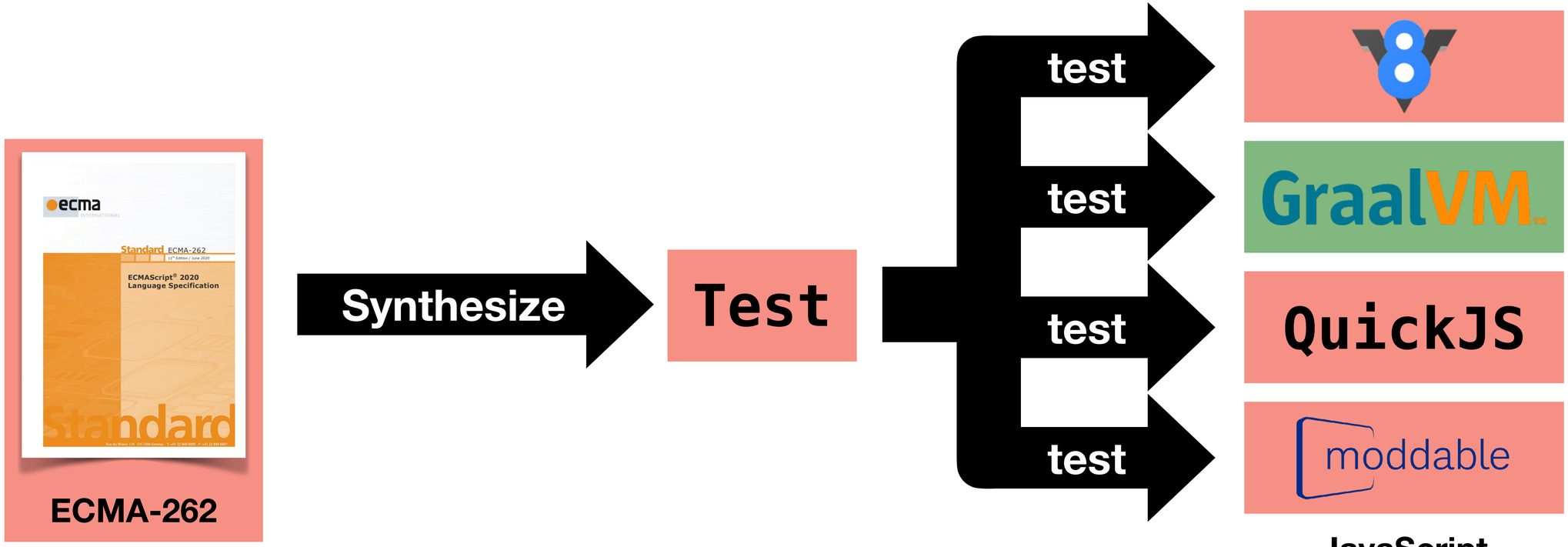
test

test

JavaScript
Engines

A specification bug in ECMA-262

JEST - N+1-version Differential Testing

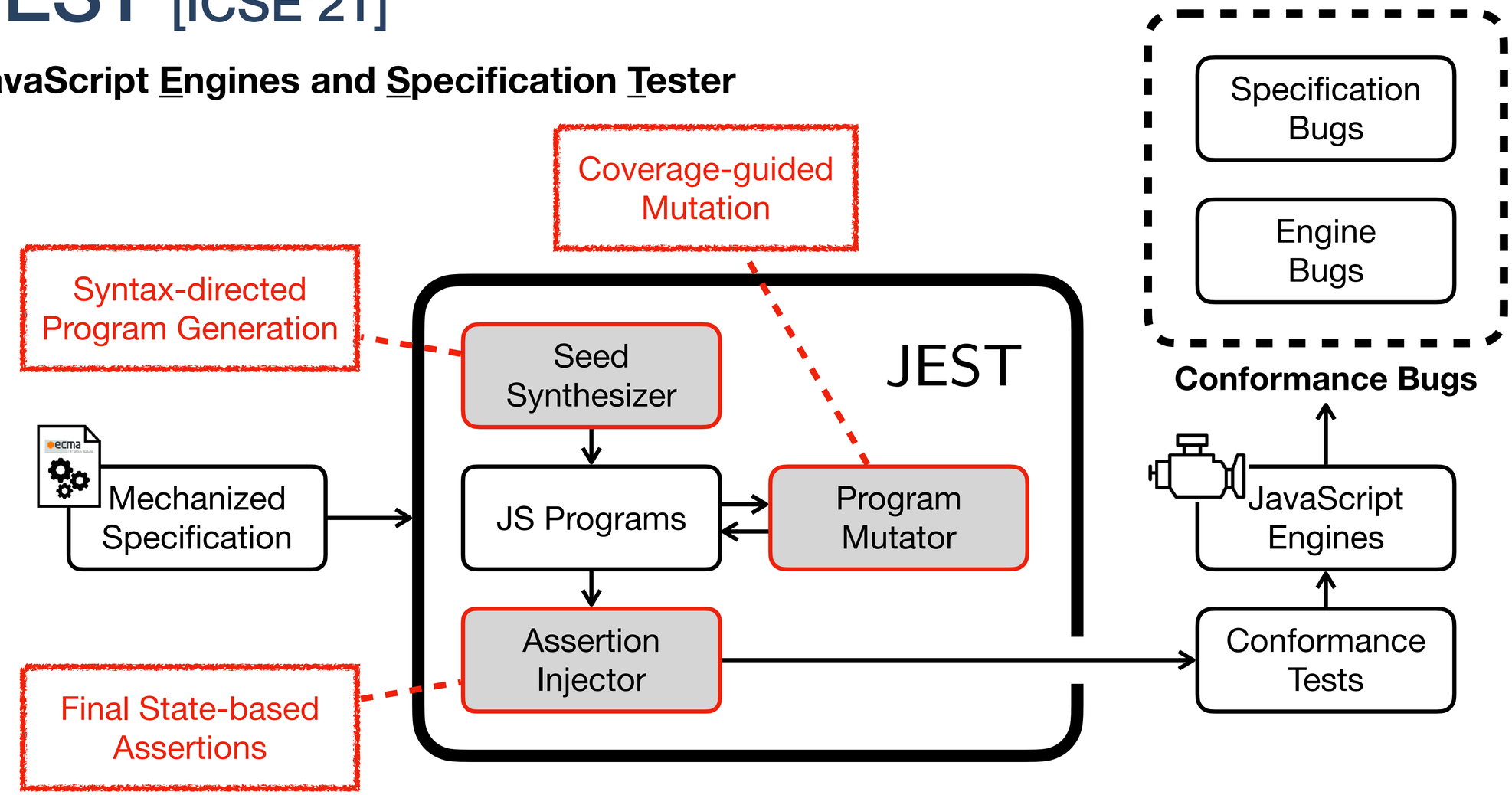


A <u>specification</u> bug in ECMA-262

An <u>engine</u> bug in GraalVM

JEST [ICSE'21]

JavaScript Engines and Specification Tester



JEST - Assertion Injector (7 Kinds)

```
var x = 1 + 2;
```

JEST - Assertion Injector (7 Kinds)

```
  var x = 1 + 2;

+ $assert.sameValue(x, 3);
```

JEST - Assertion Injector (7 Kinds)

1. **Exceptions (`Exc`)**

```
+ // Throw
  let x = 42;
  function x() {};
```

---

2. **Aborts (`Abort`)**

```
+ // Abort
  var x = 42; x++;
```

---

3. **Variable Values (`Var`)**

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

---

4. **Object Values (`Obj`)**

```
  var x = {}, y = {}, z = { p: x, q: y };
+ $assert.sameValue(z.p, x);
+ $assert.sameValue(z.q, y);
```

JEST - Assertion Injector (7 Kinds)

5. **Object Properties (`Desc`)**

```
  var x = { p: 42 };
+ $verifyProperty(x, "p", {
+   value: 42.0, writable: true,
+   enumerable: true, configurable: true
+ });
```

---

6. **Property Keys (`Key`)**

```
  var x = {[Symbol.match]: 0, p: 0, 3: 0, q: 0, 1: 0}
+ $assert.compareArray(
+   Reflect.ownKeys(x),
+   ["1", "3", "p", "q", Symbol.match]
+ );
```

---

7. **Internal Methods and Slots (`In`)**

```
  function f() {}
+ $assert.sameValue(Object.getPrototypeOf(f),
+                   Function.prototype);
+ $assert.sameValue(Object.isExtensible(x), true);
+ $assert.callable(f);
+ $assert.constructable(f);
```

JEST - Evaluation

44 Bugs in Engines

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
GraalJS	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

27 Bugs in Spec.

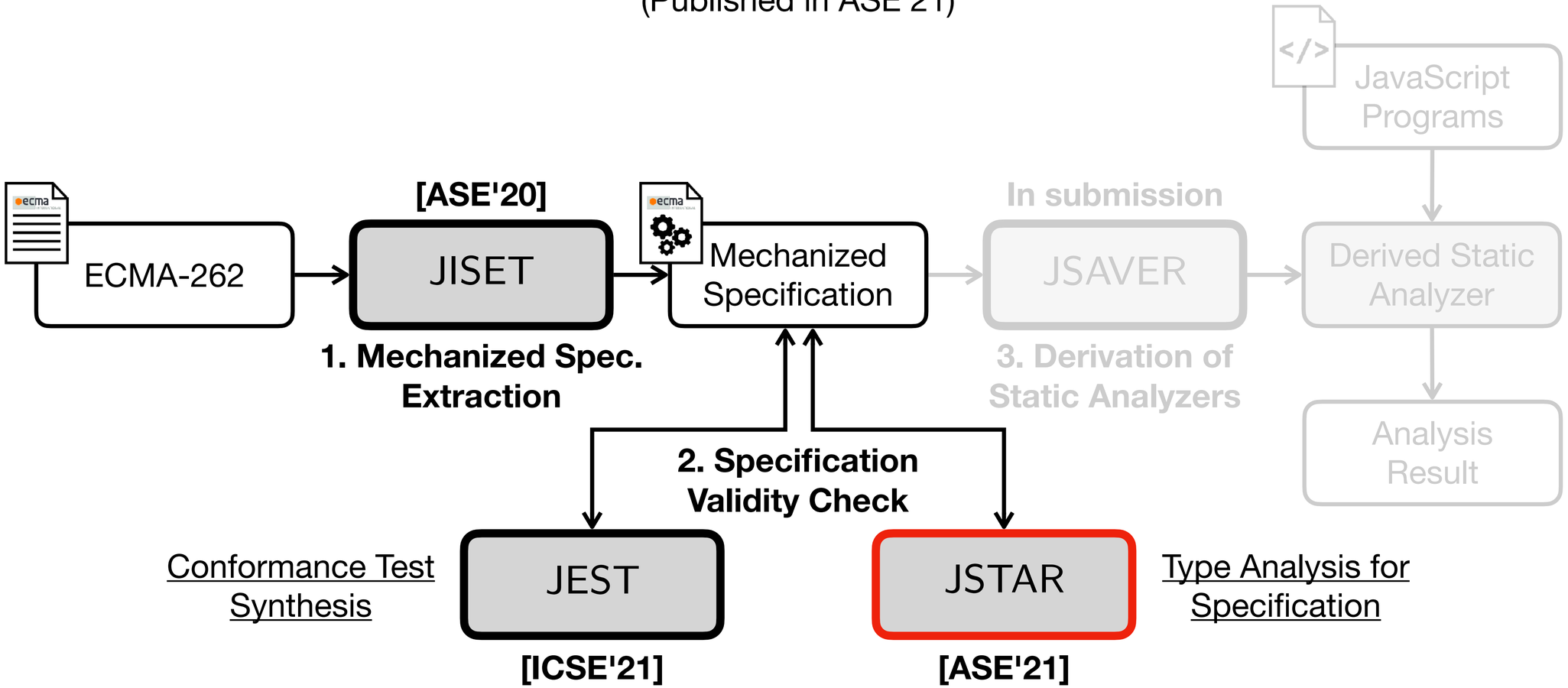
TABLE III: Specification bugs in ECMAScript 2020 (ES11) detected by JEST

Name	Feature	#	Assertion	Known	Created	Resolved	Existed
ES11-1	Function	12	Key	O	2019-02-07	2020-04-11	429 days
ES11-2	Function	8	Key	O	2015-06-01	2020-04-11	1,776 days
ES11-3	Loop	1	Exc	O	2017-10-17	2020-04-30	926 days
ES11-4	Expression	4	Abort	O	2019-09-27	2020-04-23	209 days
ES11-5	Expression	1	Exc	O	2015-06-01	2020-04-28	1,793 days
ES11-6	Object	1	Exc	X	2019-02-07	2020-11-05	637 days

JSTAR: JavaScript Specification Type Analyzer using Refinement

Jihyeok Park, Seungmin An, Wonho Shin, Yusung Sim, and Sukyoung Ryu

(Published in ASE'21)



JSTAR - Types in Specification

20.3.2.28 Math.round (*x*)

1. Let *n* be ? ToNumber(*x*).
2. If *n* is an integral Number, return *n*.
3. If $x < 0.5$ and $x > 0$, return **+0**.
4. If $x < 0$ and $x \geq -0.5$, return **-0**.

...

https://github.com/tc39/ecma262/tree/575149cfd77aebcf3a129e165bd89e14caafc31c

JSTAR - Types in Specification

20.3.2.28 Math.round (*x*) `x: (String v Boolean v Number v Object v ...)`

1. Let *n* be ? ToNumber(*x*).
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JSTAR - Types in Specification

20.3.2.28 Math.round (*x*) `x: (String v Boolean v Number v Object v ...)`

1. Let *n* be ? ToNumber(*x*). `ToNumber(x): (Number v Exception)`
2. If *n* is an integral Number, return *n*.
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JSTAR - Types in Specification

20.3.2.28 Math.round (*x*) `x: (String v Boolean v Number v Object v ...)`

1. Let *n* be ? ToNumber(*x*). `ToNumber(x): (Number v Exception) ∧ n: (Number)`
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`Type Mismatch for numeric operator `>``

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...

Type Mismatch for numeric operator `>`

```
Math.round(true)  = ???
Math.round(false) = ???
```

https://github.com/tc39/ecma262/tree/575149cfd77aebcf3a129e165bd89e14caafc31c

JSTAR - Types in Specification

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4. If $x < 0$ and $x \geq -0.5$, return **-0**.

...

Type Mismatch for numeric operator `>`

```
Math.round(true)  = ???
Math.round(false) = ???
```

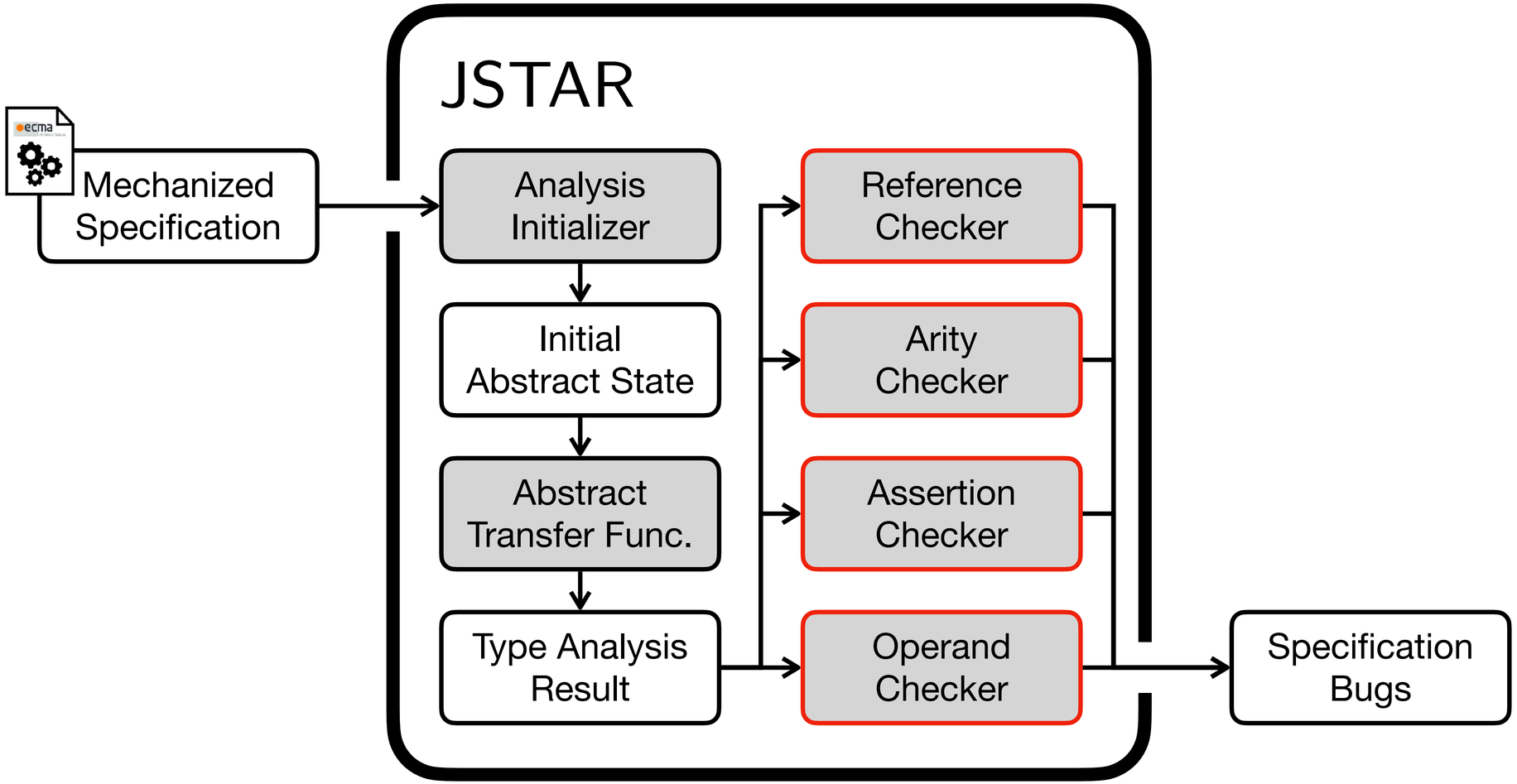
3. If $n < 0.5$ and $n > 0$, return **+0**.
4. If $n < 0$ and $n \geq -0.5$, return **-0**.

```
Math.round(true)  = 1
Math.round(false) = 0
```

https://github.com/tc39/ecma262/tree/575149cfd77aebcf3a129e165bd89e14caafc31c

JSTAR [ASE'21]

JavaScript Specification Type Analyzer using Refinement



JSTAR - Evaluation

- **Type Analysis for 864 versions of ECMA-262**

59.2% Precision

93 Bugs Detected

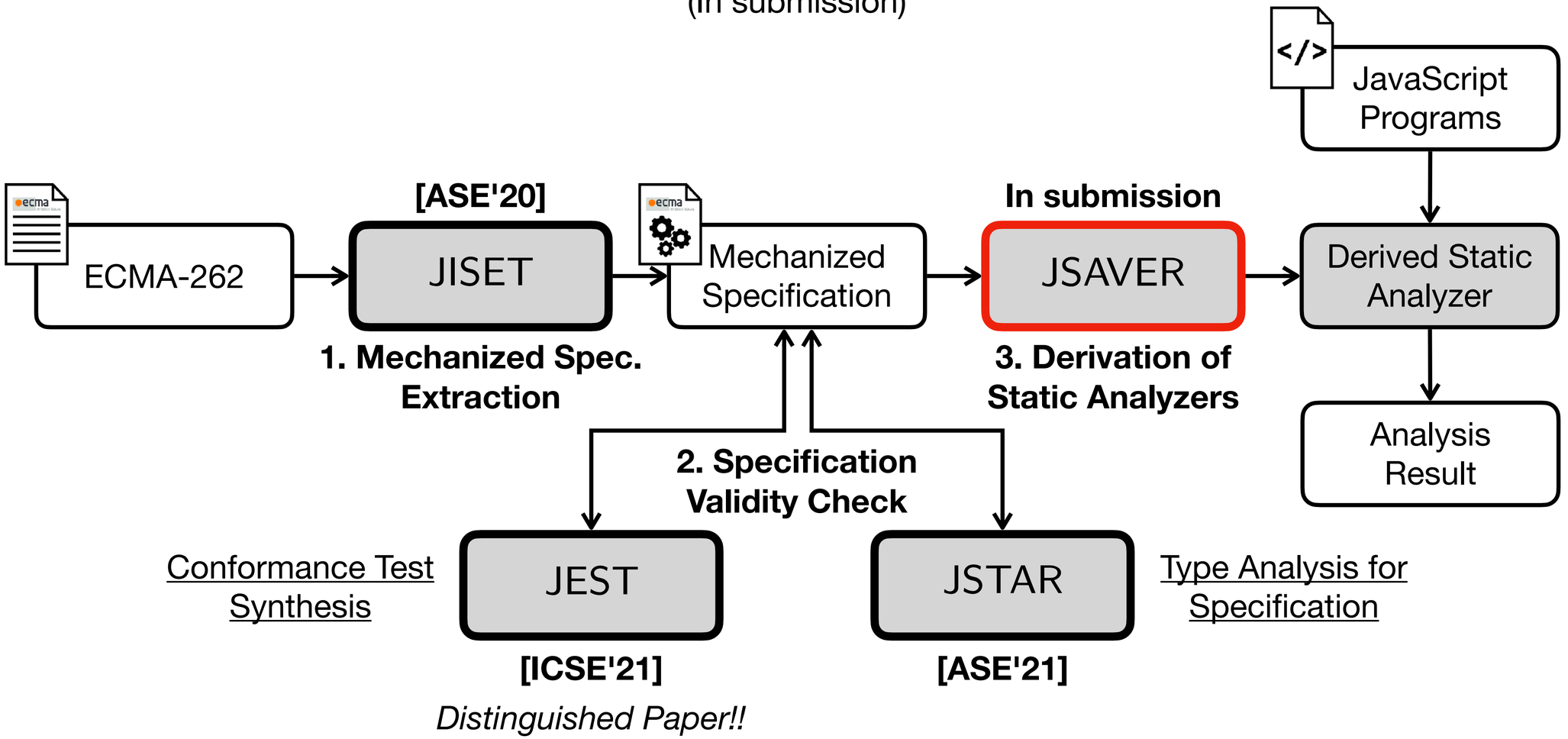
Checker	Bug Kind	Precision = (# True Bugs) / (# Detected Bugs)					
		no-refine		refine		Δ	
Reference	UnknownVar	62 / 106	17 / 60	63 / 78	17 / 31	+1 / -28	/ -29
	DuplicatedVar		45 / 46		46 / 47		+1 / +1
Arity	MissingParam	4 / 4	4 / 4	4 / 4	4 / 4	/	/
Assertion	Assertion	4 / 56	4 / 56	4 / 31	4 / 31	/ -25	/ -25
Operand	NoNumber	22 / 113	2 / 65	22 / 44	2 / 6	/ -69	/ -59
	Abrupt		20 / 48		20 / 38		/ -10
Total		92 / 279 (33.0%)		93 / 157 (59.2%)		+1 / -122 (+26.3%)	

Name	Feature	#	Checker	Created	Life Span
ES12-1	Switch	3	Reference	2015-09-22	1,996 days
ES12-2	Try	3	Reference	2015-09-22	1,996 days
ES12-3	Arguments	1	Reference	2015-09-22	1,996 days
ES12-4	Array	2	Reference	2015-09-22	1,996 days
ES12-5	Async	1	Reference	2015-09-22	1,996 days
ES12-6	Class	1	Reference	2015-09-22	1,996 days
ES12-7	Branch	1	Reference	2015-09-22	1,996 days
ES12-8	Arguments	2	Operand	2015-12-16	1,910 days

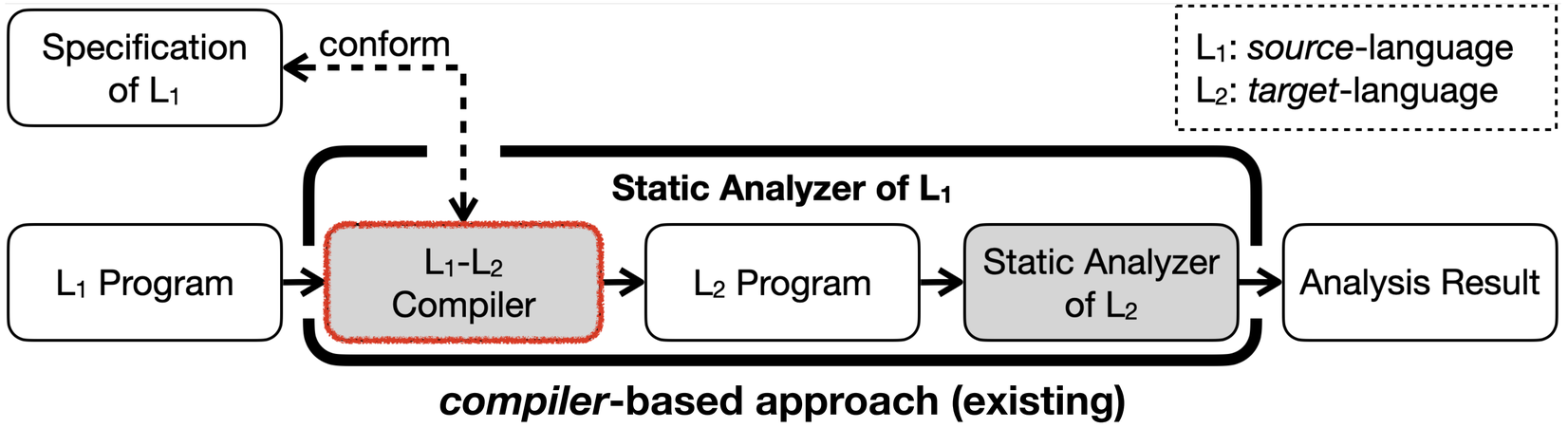
14 Bugs in ES12

Automatically Deriving JavaScript Static Analyzers from Language Specifications

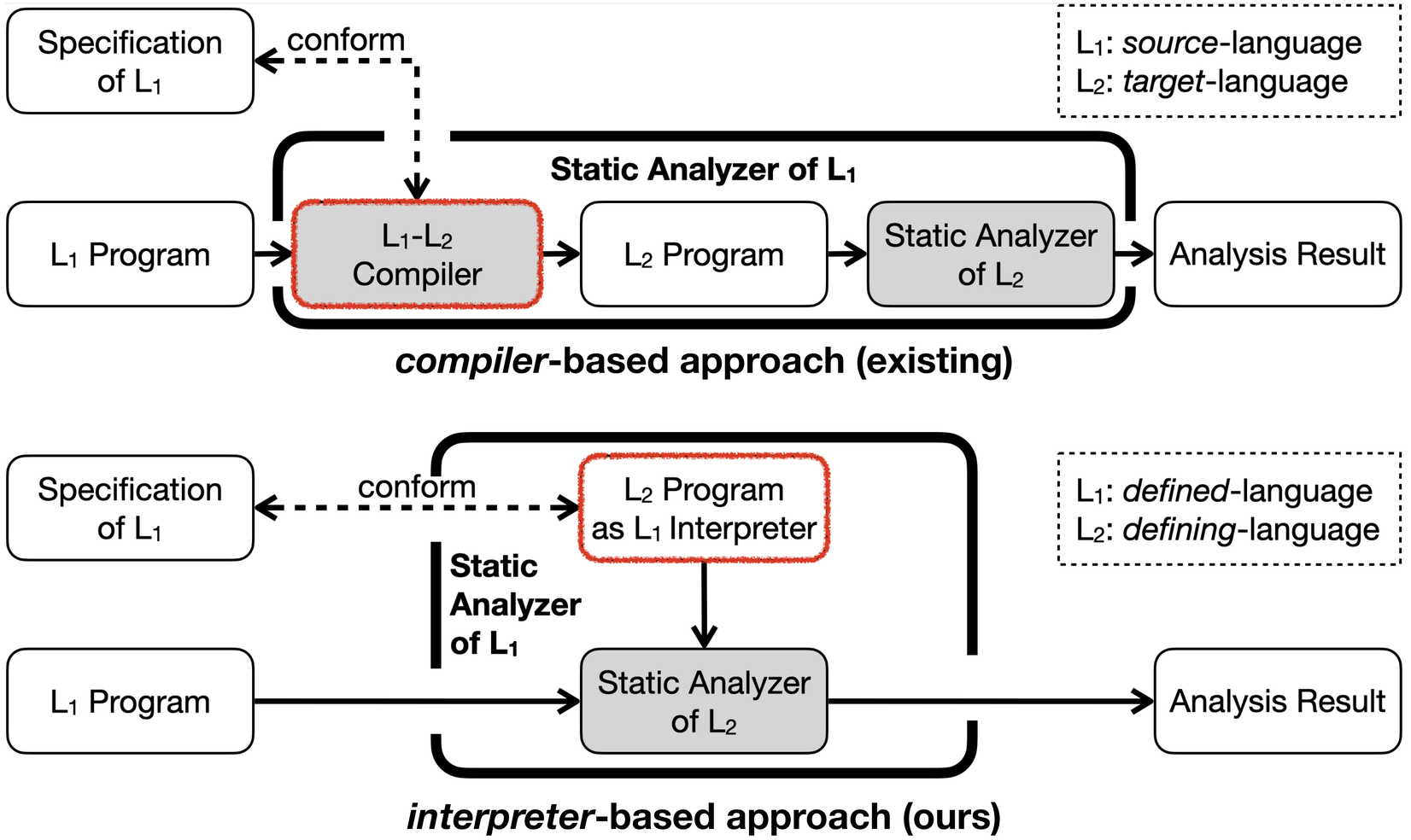
Jihyeok Park, Seungmin An, and Sukyoung Ryu
(In submission)



JSAVER - Meta-Level Static Analysis



JSAVER - Meta-Level Static Analysis



JSAVER - Meta-Level Static Analysis

***defined*-language**
(JavaScript)

```
x ||= y
```

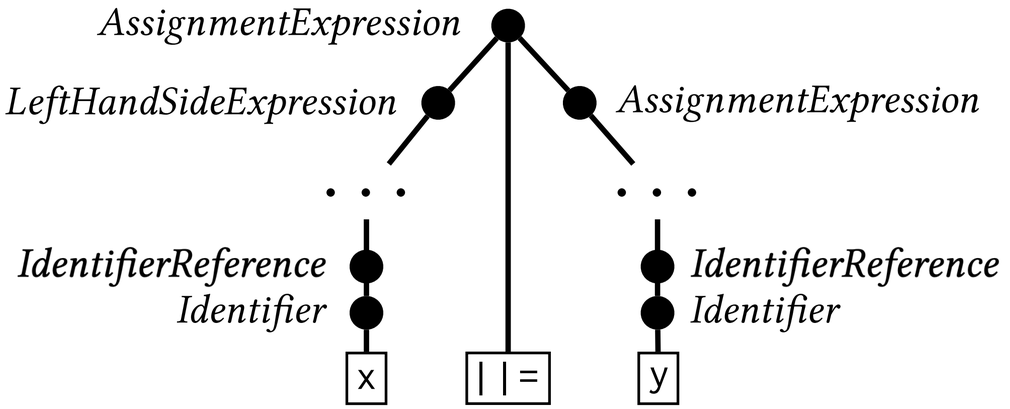
***defining*-language**
(IR_{ES})

JSAVER - Meta-Level Static Analysis

***defined*-language**
(JavaScript)

x ||= y

parse



***defining*-language**
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JSAVER - Meta-Level Static Analysis

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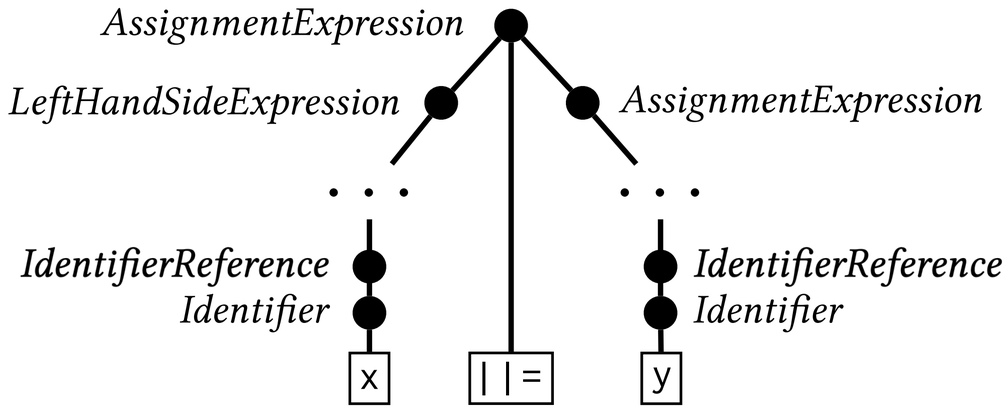


***defining*-language**
(IR_{ES})

```
syntax def AssignmentExpression[8].Evaluation(
  this, LeftHandSideExpression, AssignmentExpression
) {
  let lref = (LeftHandSideExpression.Evaluation)
  let lval = [? (GetValue lref)]
  let lbool = [! (ToBoolean lval)]
  if (= lbool true) return lval
  ...
}
```

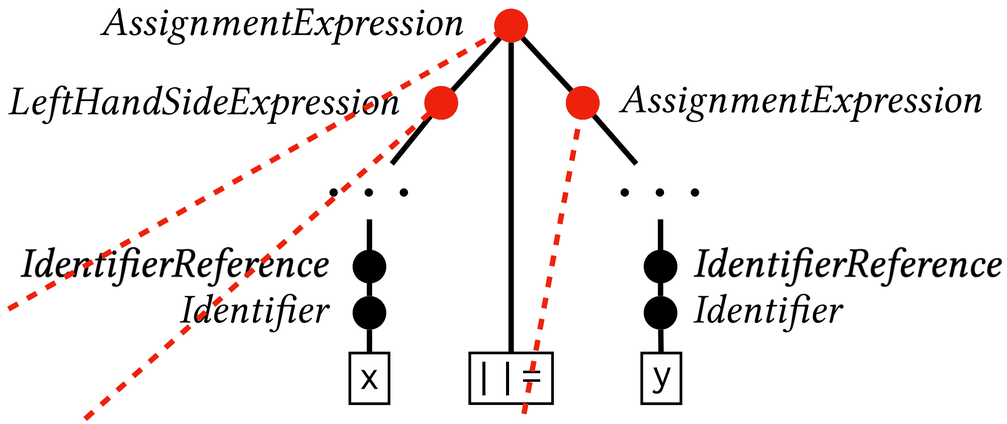
A mechanized specification from ES12
= A JavaScript interpreter
= An IR_{ES} program

JSAVER - Meta-Level Static Analysis

***defined*-language**
(JavaScript)

x ||= y

parse



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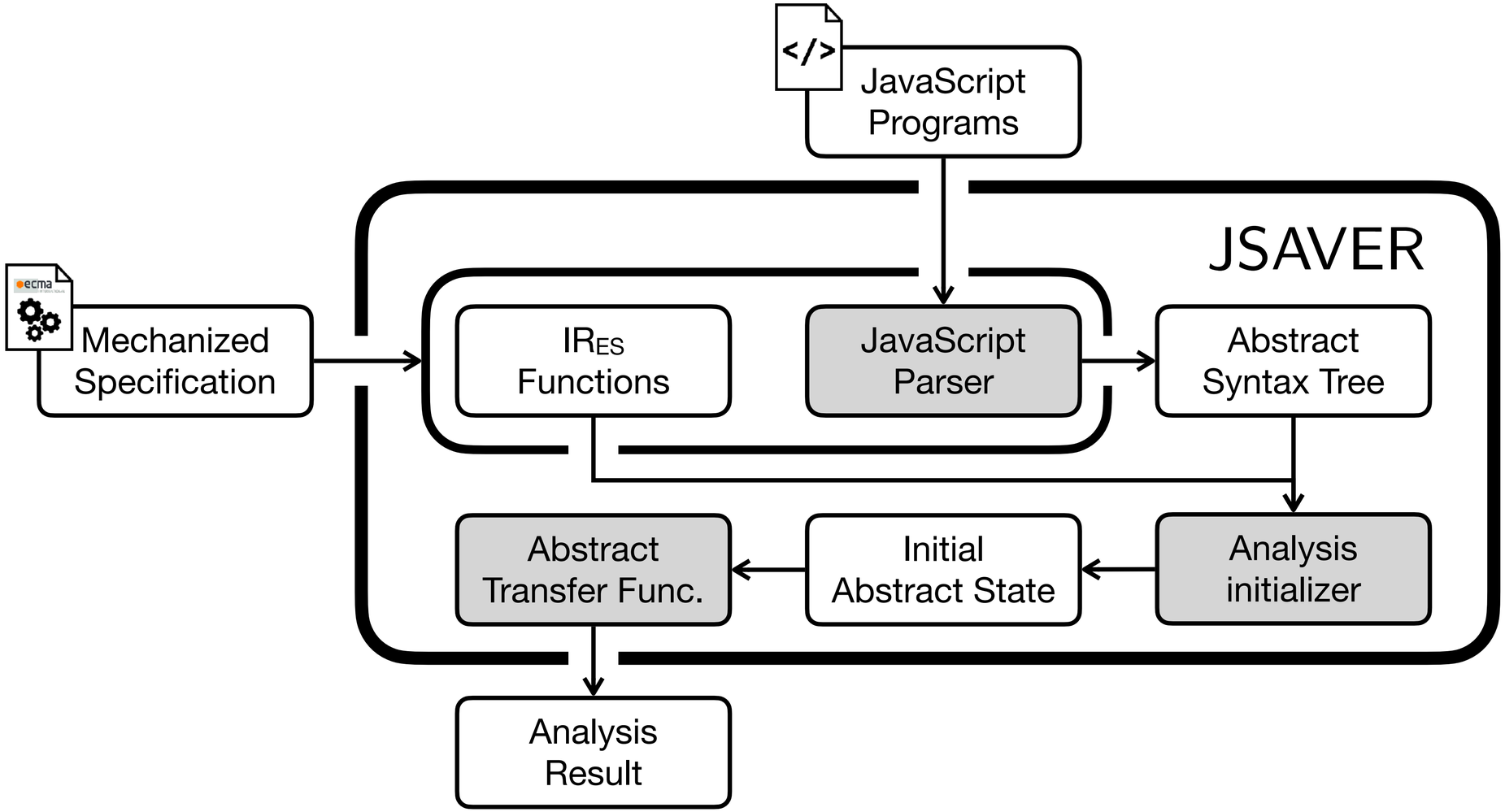
```

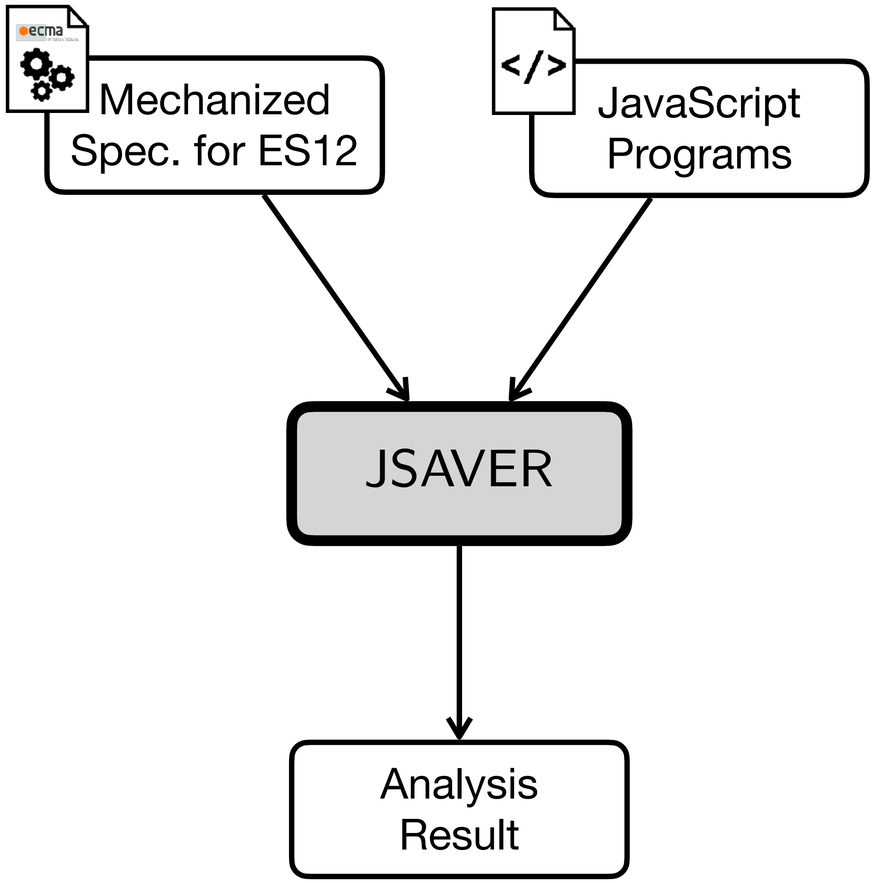
A mechanized specification from ES12
= A JavaScript interpreter
= An IR_{ES} program

JSAVER In submission

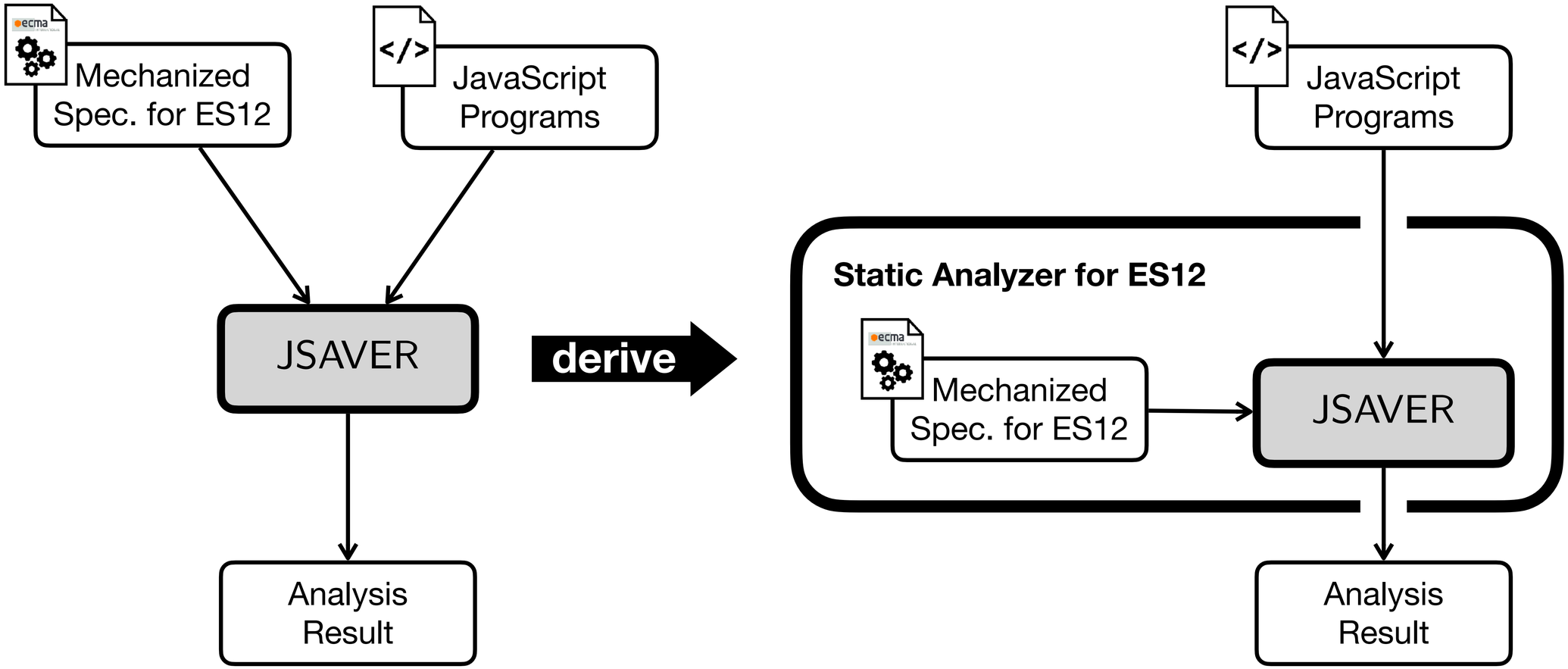
JavaScript Static Analyzer via ECMAScript Representation



JSAVER - Static Analyzer Derivation

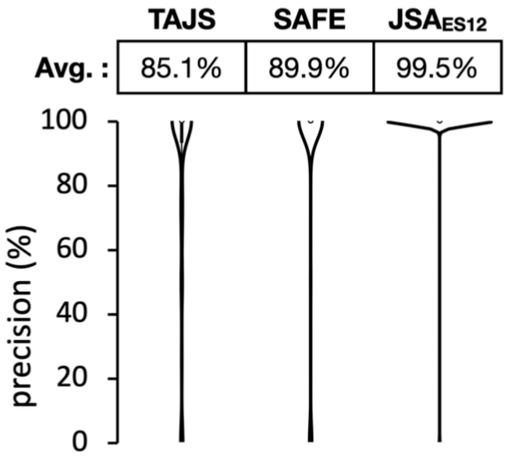


JSAVER - Static Analyzer Derivation

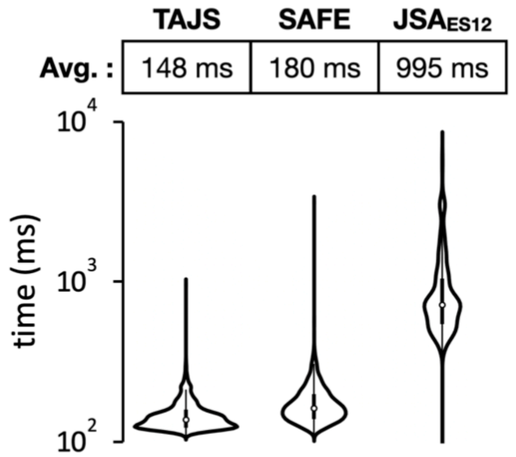


JSAVER - Evaluation

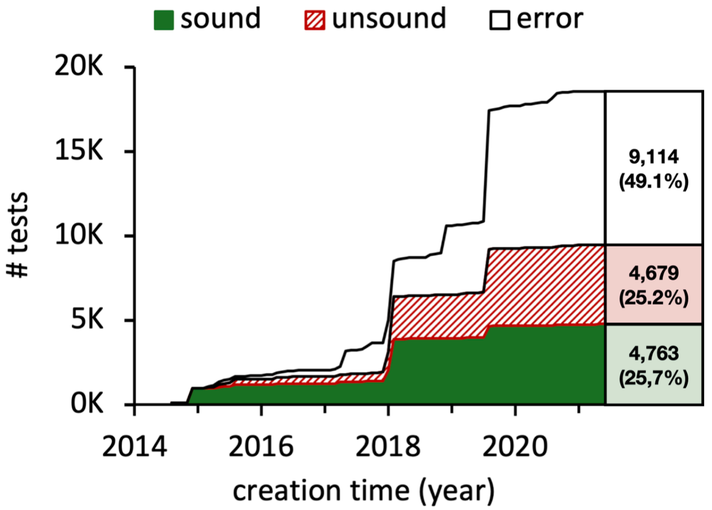
- **Soundness / Precision / Performance**
  - 18,556 applicable tests in Test262
  - 3,903 tests analyzable by all the three analyzers



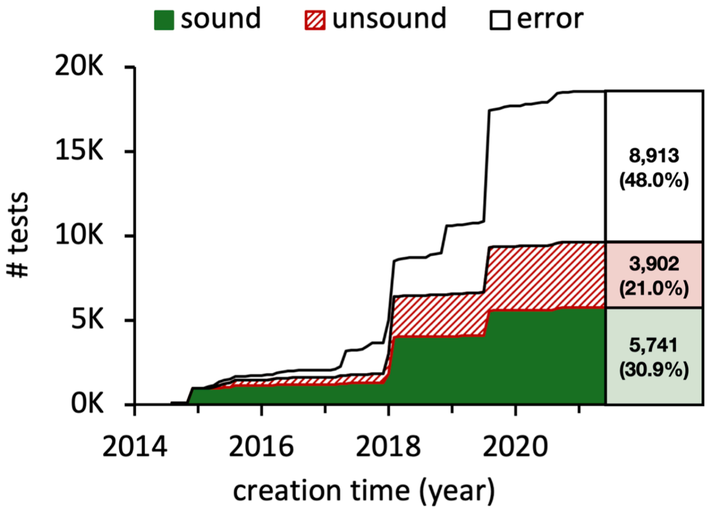
(a) The analysis precision



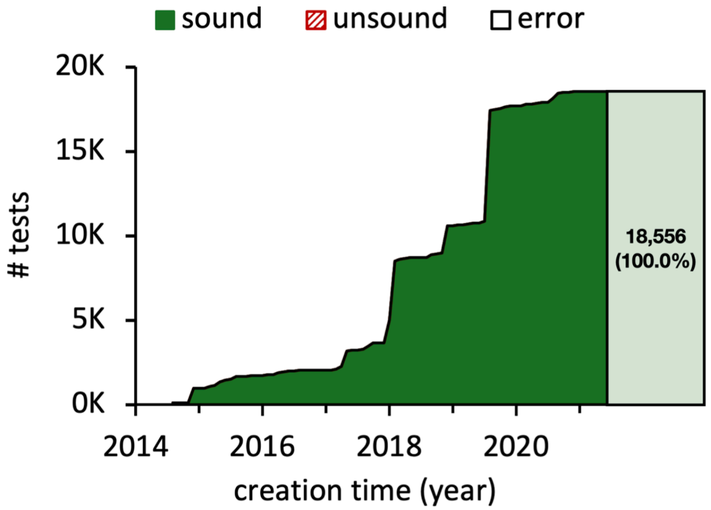
(b) The analysis performance



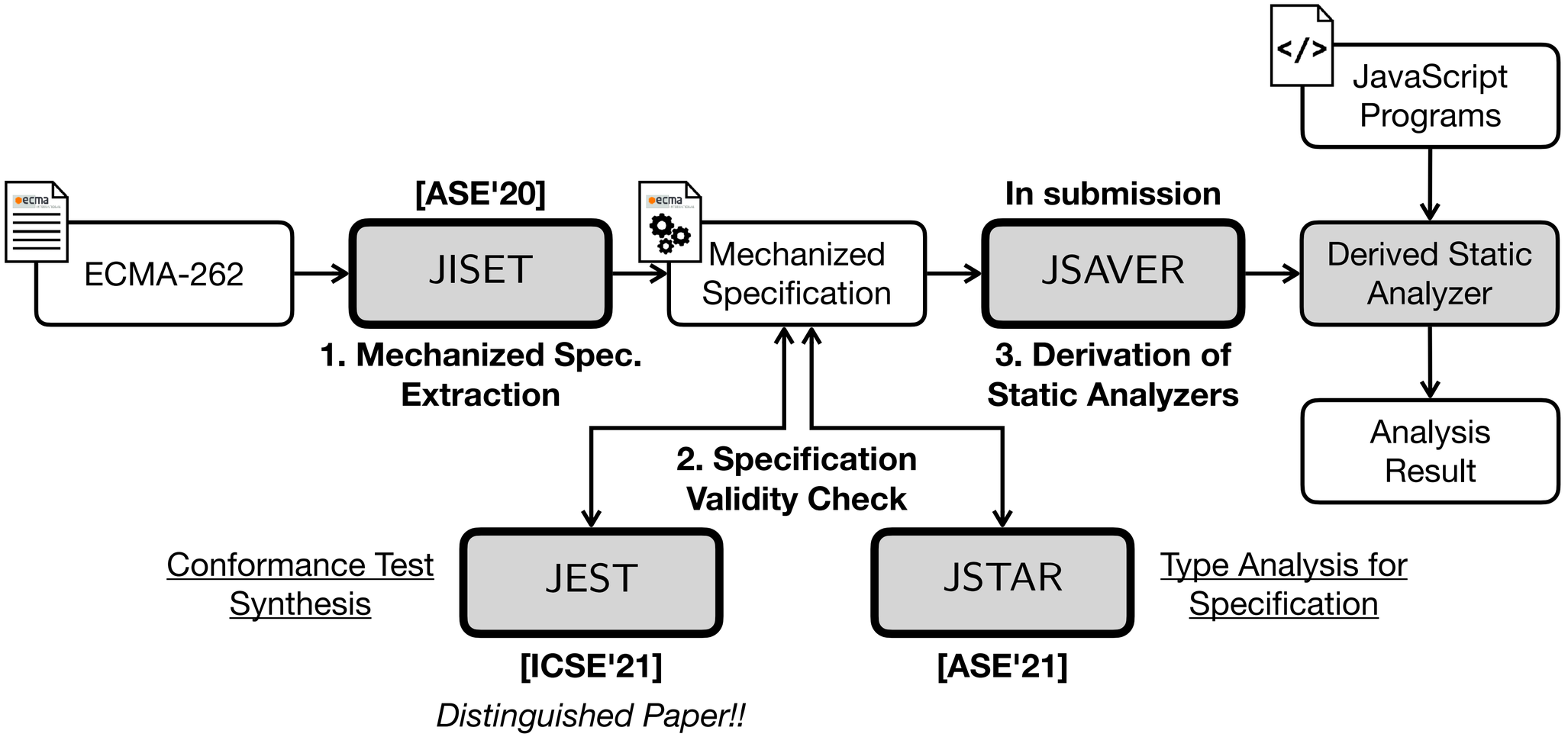
(a) Analysis results of TAJS

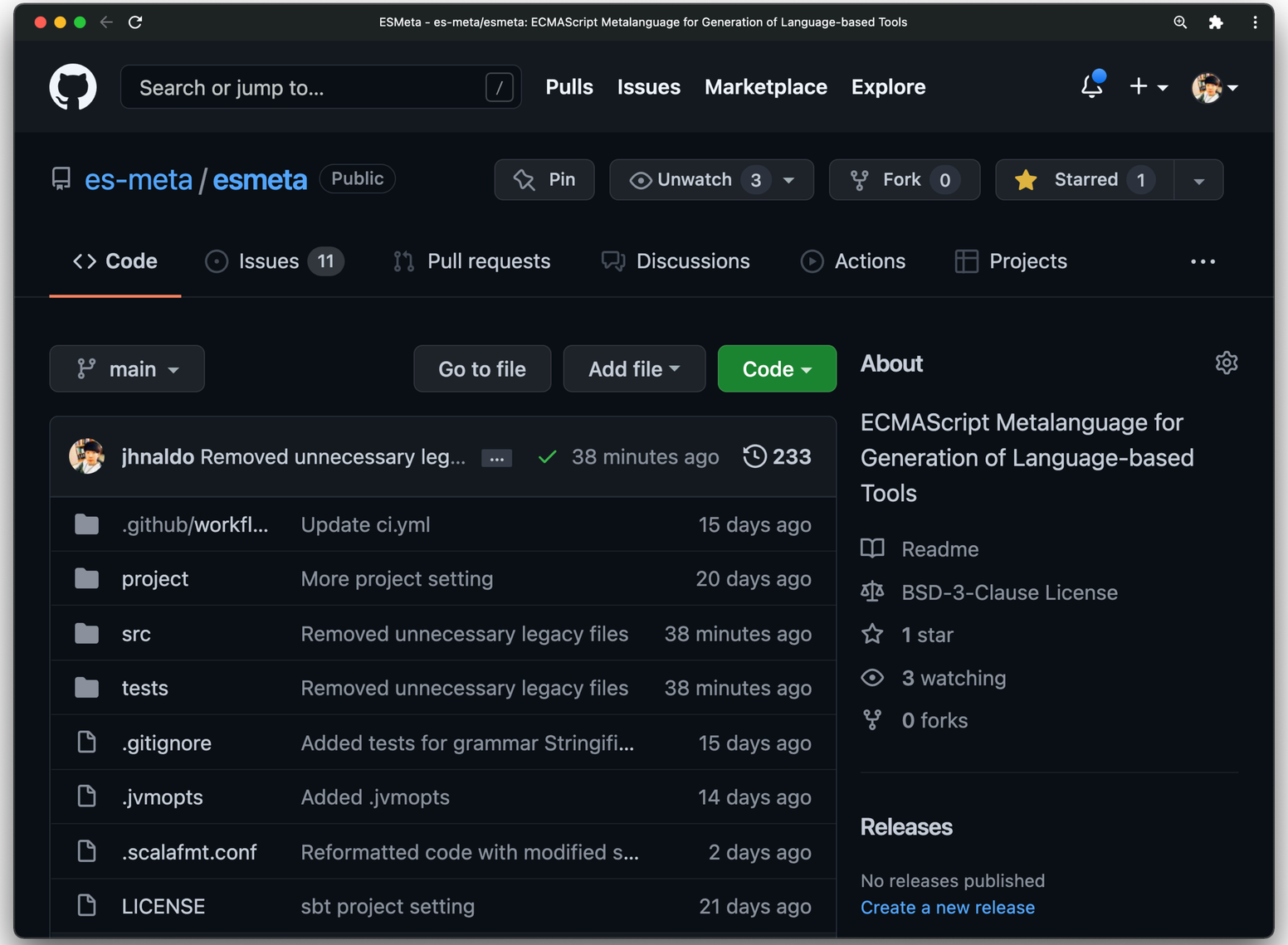


(b) Analysis results of SAFE



(c) Analysis results of JSA$_{ES12}$


JavaScript Programs
ECMA-262
[ASE'20]
JISET
Mechanized Specification
In submission
JSAVER
Derived Static Analyzer
1. Mechanized Spec. Extraction
3. Derivation of Static Analyzers
Analysis Result
2. Specification Validity Check
Conformance Test Synthesis
JEST
JSTAR
Type Analysis for Specification
[ICSE'21]
[ASE'21]
Distinguished Paper!!



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

ECMAScript Debugger

RUN | CANCEL | STEP | STEP-OVER | STEP-OUT | JS-STEP | JS-STEP-OVER | JS-STEP-OUT | CONTINUE

JavaScript

```
1 | let f = x => x == !x;
2 | let a = f(true);
3 | let b = f([]);
```

ECMAScript Specification

AbstractEqualityComparison [x, y]

1. If Type(x) is the same as Type(y), then
   1. Return the result of performing Strict Equality Comparison x === y.
2. If x is **null** and y is **undefined**, return **true**.
3. If x is **undefined** and y is **null**, return **true**.
4. NOTE: This step is replaced in section sec-IsHTMLDDA-internal-slot-aec .
5. If Type(x) is Number and Type(y) is String, return the result of the comparison x == ! ToNumber(y).
6. If Type(x) is String and Type(y) is Number, return the result of the comparison ! ToNumber(x) == y.
7. If Type(x) is BigInt and Type(y) is String, then
   1. Let n be ! StringToBigInt(y).
   2. If n is **NaN**, return **false**.
   3. Return the result of the comparison x == n.
8. If Type(x) is String and Type(y) is BigInt, return the result of the comparison y == x.
9. If Type(x) is Boolean, return the result of the comparison ! ToNumber(x) == y.
10. If Type(y) is Boolean, return the result of the comparison x == ! ToNumber(y).

ECMAScript Call Stack

#	name
0	5 @ AbstractEqualityComparisor
1	4 @ EqualityExpression[1,0] Eva

ECMAScript Environment

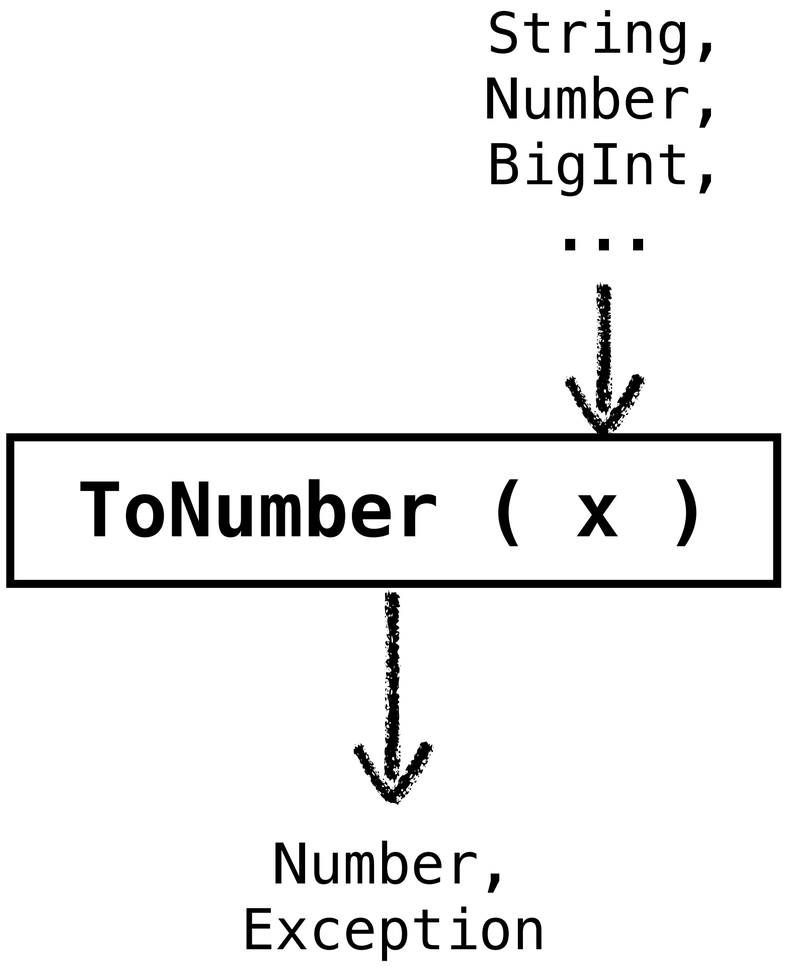
name	value
x	false
y	#94

ECMAScript Heap

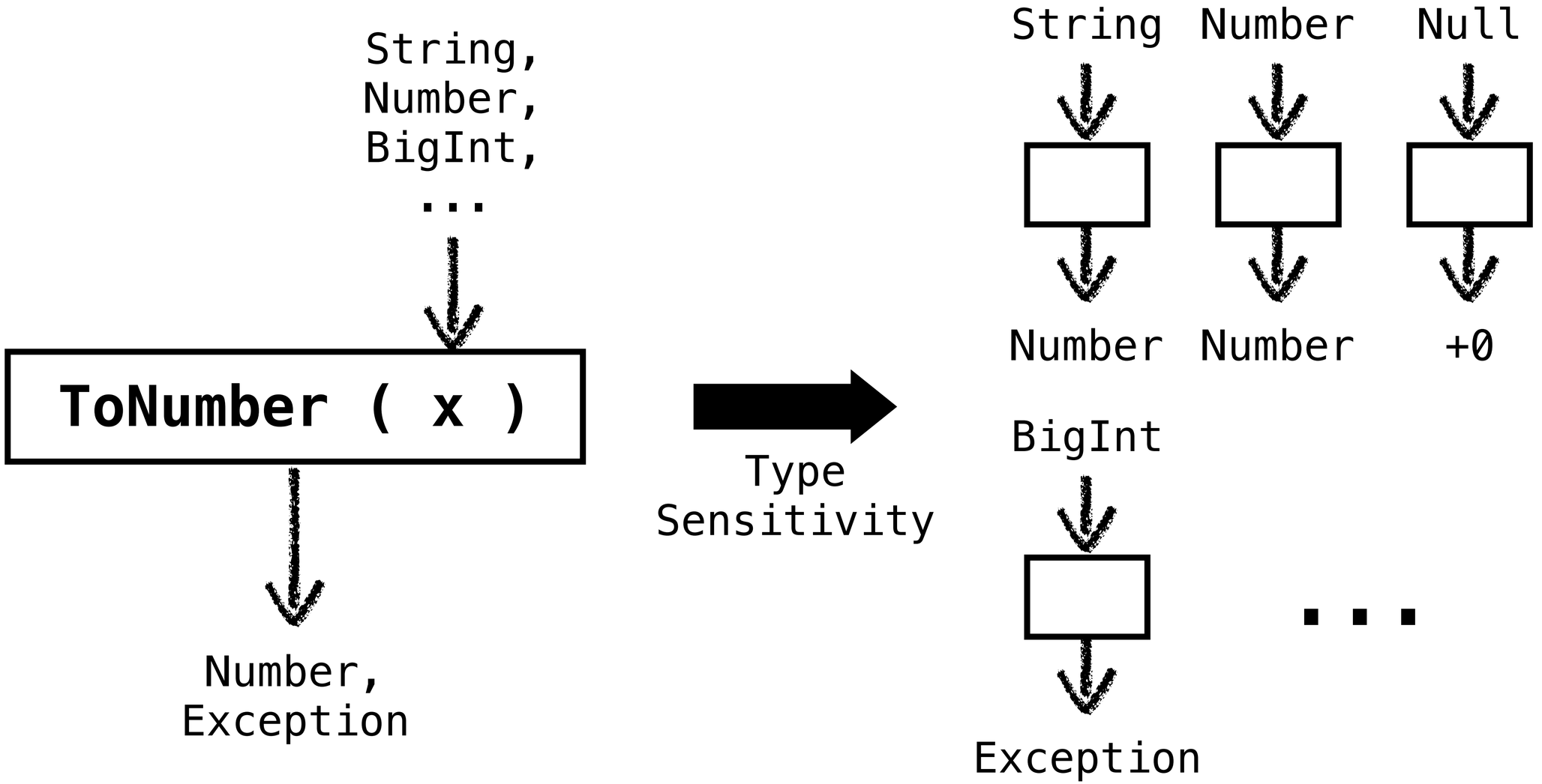
ECMAScript Breakpoints

Backup Slides

JSTAR - Precision ⇧ - 1) Type Sensitivity



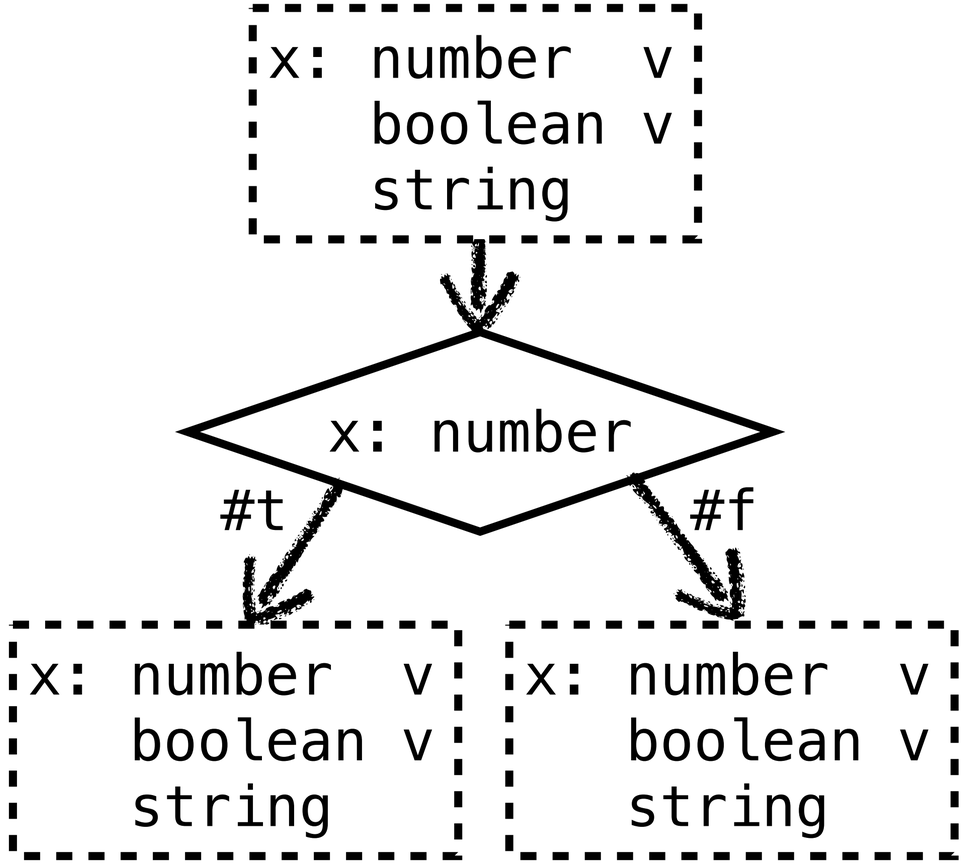
JSTAR - Precision ⇧ - 1) Type Sensitivity



JSTAR - Precision ⇧ - 2) Type Refinement

$$
\begin{aligned}
\texttt{refine}(!e, b)(\sigma^\sharp) &= \texttt{refine}(e, \neg b)(\sigma^\sharp) \\
\texttt{refine}(e_0 \texttt{ || } e_1, b)(\sigma^\sharp) &= \begin{cases} \sigma_0^\sharp \sqcup \sigma_1^\sharp & \text{if } b \\ \sigma_0^\sharp \sqcap \sigma_1^\sharp & \text{if } \neg b \end{cases} \\
\texttt{refine}(e_0 \texttt{ \&\& } e_1, b)(\sigma^\sharp) &= \begin{cases} \sigma_0^\sharp \sqcap \sigma_1^\sharp & \text{if } b \\ \sigma_0^\sharp \sqcup \sigma_1^\sharp & \text{if } \neg b \end{cases} \\
\texttt{refine}(\texttt{x.Type} == c_{\texttt{normal}}, \texttt{\#t})(\sigma^\sharp) &= \sigma^\sharp[\texttt{x} \mapsto \tau_{\texttt{x}}^\sharp \sqcap \texttt{normal}(\mathbb{T})] \\
\texttt{refine}(\texttt{x.Type} == c_{\texttt{normal}}, \texttt{\#f})(\sigma^\sharp) &= \sigma^\sharp[\texttt{x} \mapsto \tau_{\texttt{x}}^\sharp \sqcap \{\texttt{abrupt}\}] \\
\texttt{refine}(\texttt{x} == e, \texttt{\#t})(\sigma^\sharp) &= \sigma^\sharp[\texttt{x} \mapsto \tau_{\texttt{x}}^\sharp \sqcap \tau_e^\sharp] \\
\texttt{refine}(\texttt{x} == e, \texttt{\#f})(\sigma^\sharp) &= \sigma^\sharp[\texttt{x} \mapsto \tau_{\texttt{x}}^\sharp \setminus \lfloor \tau_e^\sharp \rfloor] \\
\texttt{refine}(\texttt{x} : \tau, \texttt{\#t})(\sigma^\sharp) &= \sigma^\sharp[\texttt{x} \mapsto \tau_{\texttt{x}}^\sharp \sqcap \{\tau\}] \\
\texttt{refine}(\texttt{x} : \tau, \texttt{\#f})(\sigma^\sharp) &= \sigma^\sharp[\texttt{x} \mapsto \tau_{\texttt{x}}^\sharp \setminus \{\tau' \mid \tau' <: \tau\}] \\
\texttt{refine}(e, b)(\sigma^\sharp) &= \sigma^\sharp
\end{aligned}
$$

where $\sigma_j^\sharp = \texttt{refine}(e_j, b)(\sigma^\sharp)$ for $j = 0, 1$, $\tau_e^\sharp = [\![e]\!]_e^\sharp(\sigma^\sharp)$, and $\lfloor \tau^\sharp \rfloor$ returns $\{\tau\}$ if $\tau^\sharp$ denotes a singleton type τ, or returns $\varnothing$, otherwise.



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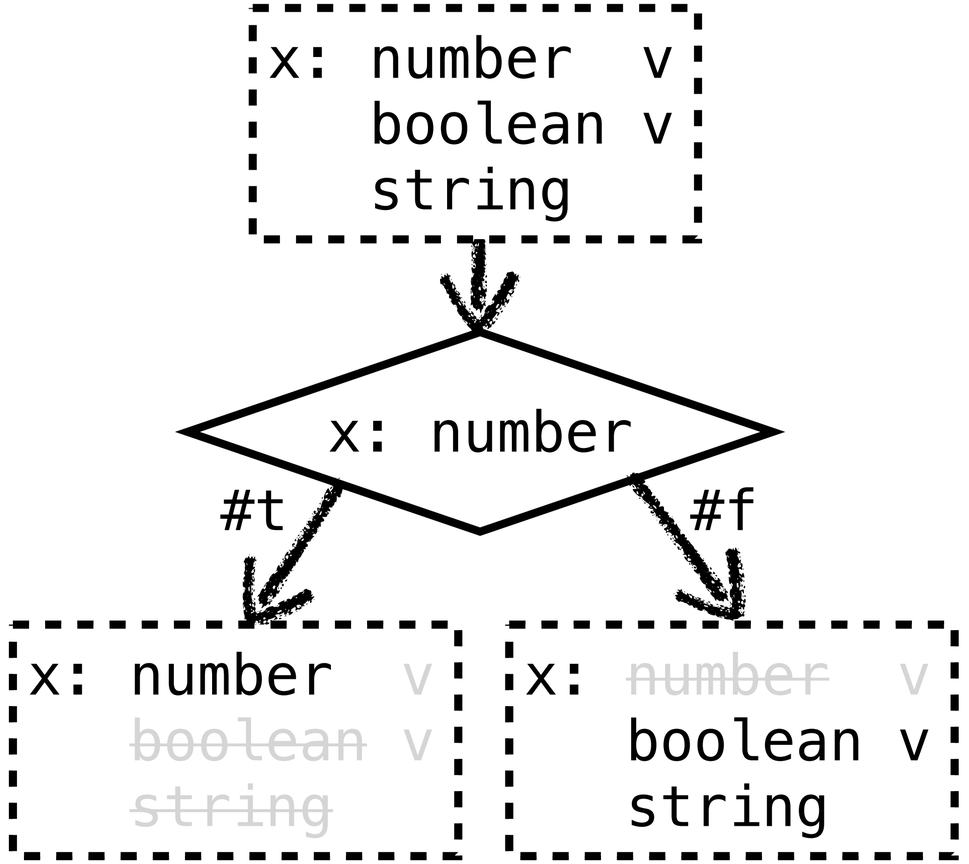
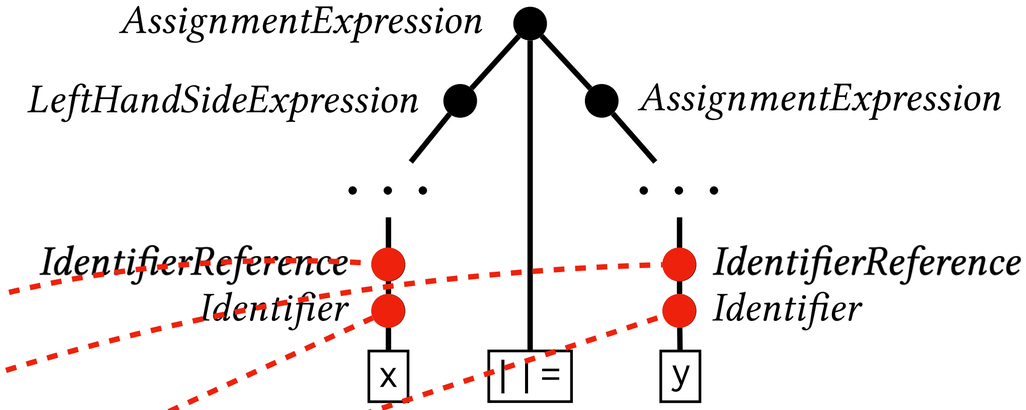


JSAVER - AST Sensitivity

***defined*-language**
(JavaScript)

x ||= y

parse



***defining*-language**
(IR$_{ES}$)

```
syntax def IdentifierReference[0]
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) {
  return [?
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}
```

JSAVER - AST Sensitivity

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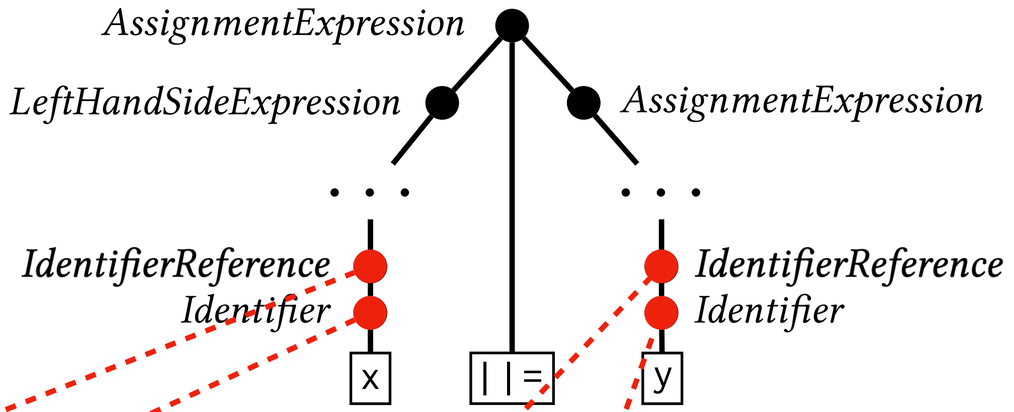
parse



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```

`this = AST of `x``

```
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) {
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      (Identifier.StringValue))]
}
```
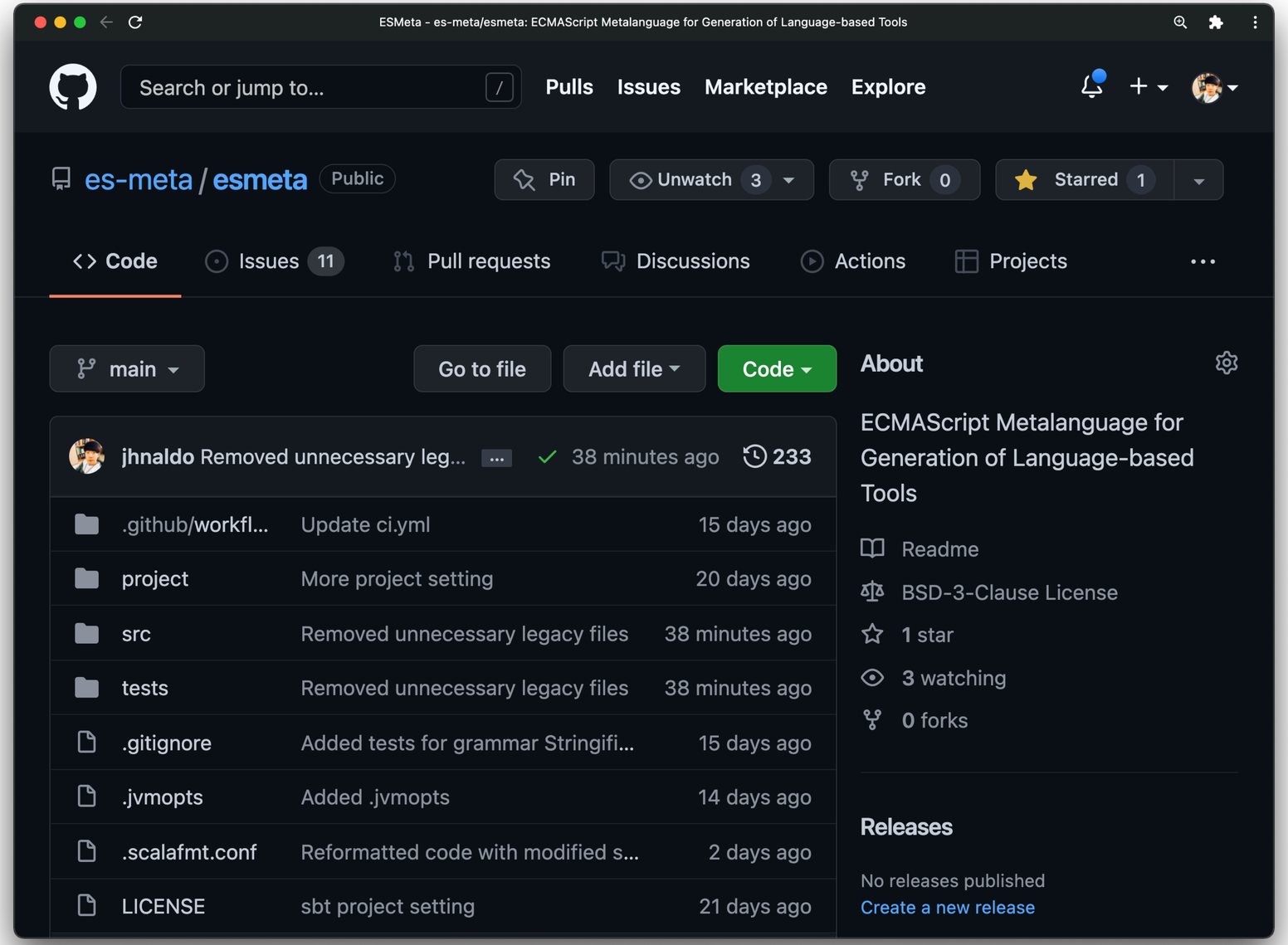

`this = AST of `y``

JSAVER - AST Sensitivity

defined-language (JavaScript)	**defining-language** (IR_{ES})
flow-sensitivity	$\delta^{\text{js-flow}}(t_\perp) = \{\sigma = (\_, \_, \bar{c}, \_) \in \mathbb{S} \mid \text{ast}(\bar{c}) = t_\perp\}$
k-callsite sensitivity	$\delta^{\text{js-}k\text{-cfa}}([t_1, \cdots, t_n]) = \{\sigma = (\_, \_, \bar{c}, \_) \in \mathbb{S} \mid n \leq k \wedge (n = k \vee \text{js-ctxt}^{n+1}(\bar{c}) = \perp) \wedge \forall 1 \leq i \leq n.\ \text{ast} \circ \text{js-ctxt}^{i}(\bar{c}) = t_i\}$



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