PLRG
Programming Language
Research Group

JavaScript Static Analysis for Evolving Language Specifications

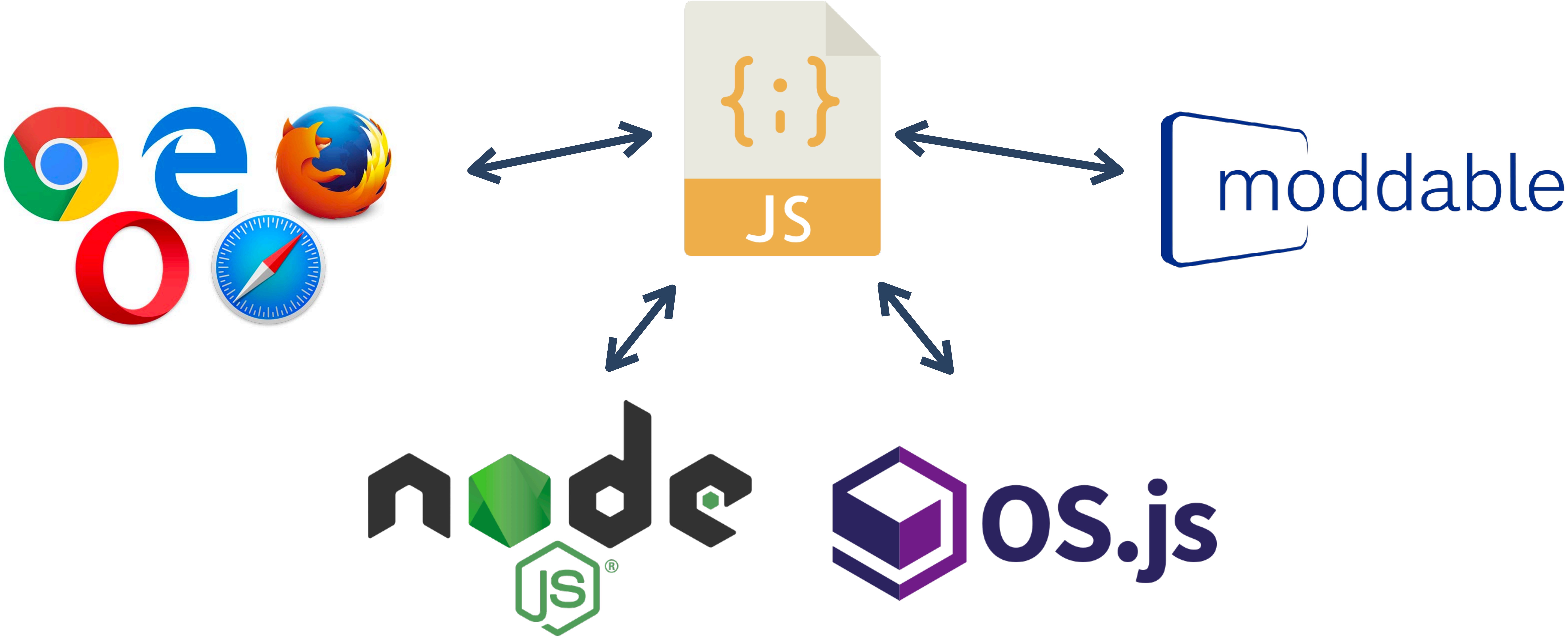
Seminar at le Département d'Informatique de l'ENS (DI ENS)

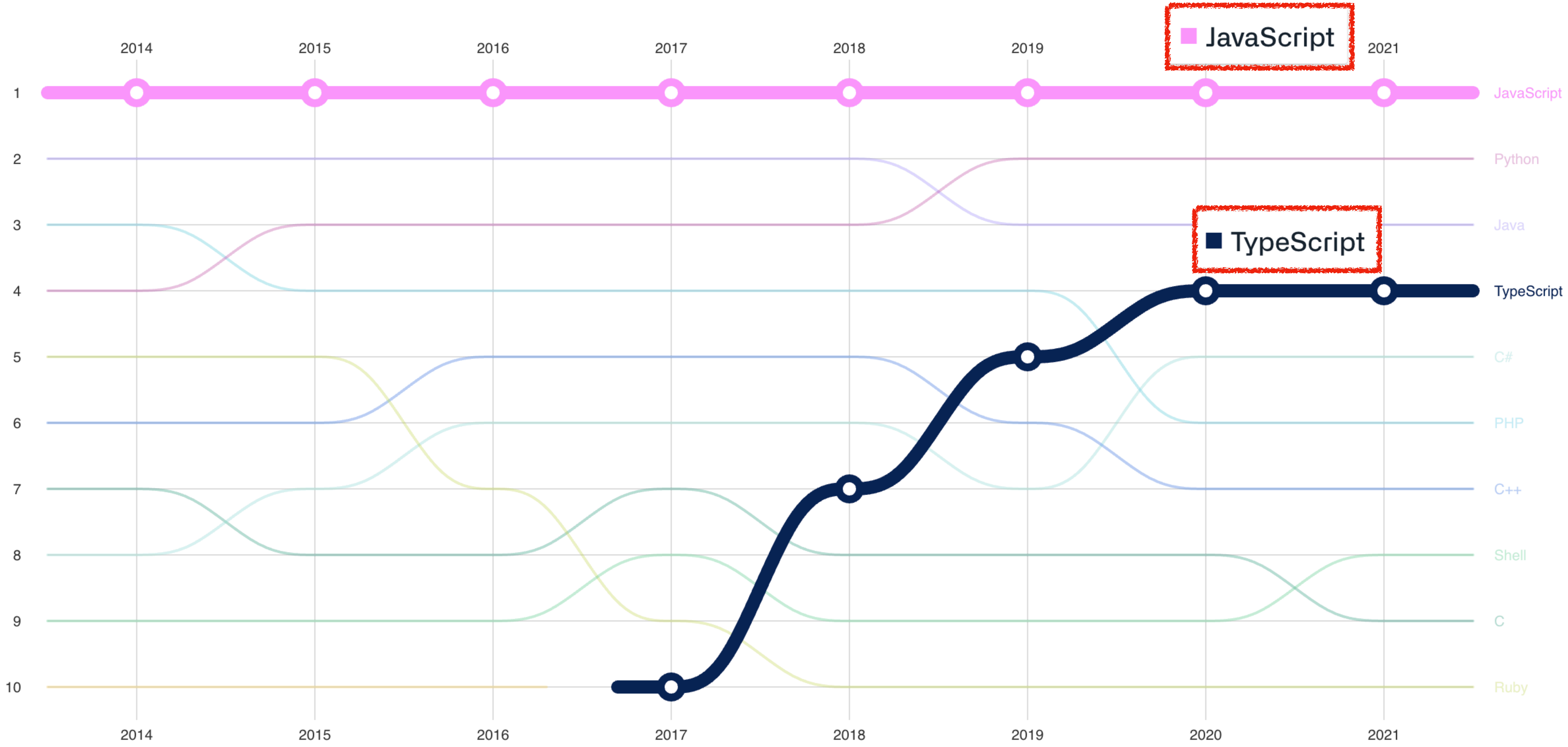
Jihyeok Park

PLRG @ KAIST

December 15, 2021

JavaScript Is Everywhere





https://octoverse.github.com/

JavaScript Complex Semantics

```
function f(x) { return x == !x; }
```

Always return `false`?

NO!!

```
f([]) -> [] == ![]
      -> [] == false
      -> +[] == +false
      -> 0 == 0
      -> true
```

ECMAScript: JavaScript Specification

Syntax

ArrayLiteral$_{\texttt{[Yield, Await]}}$:

[*Elision*$_{\texttt{opt}}$]

[*ElementList*$_{\texttt{[?Yield, ?Await]}}$]

[*ElementList*$_{\texttt{[?Yield, ?Await]}}$, *Elision*$_{\texttt{opt}}$]

The production of *ArrayLiteral* in ES12

Semantics

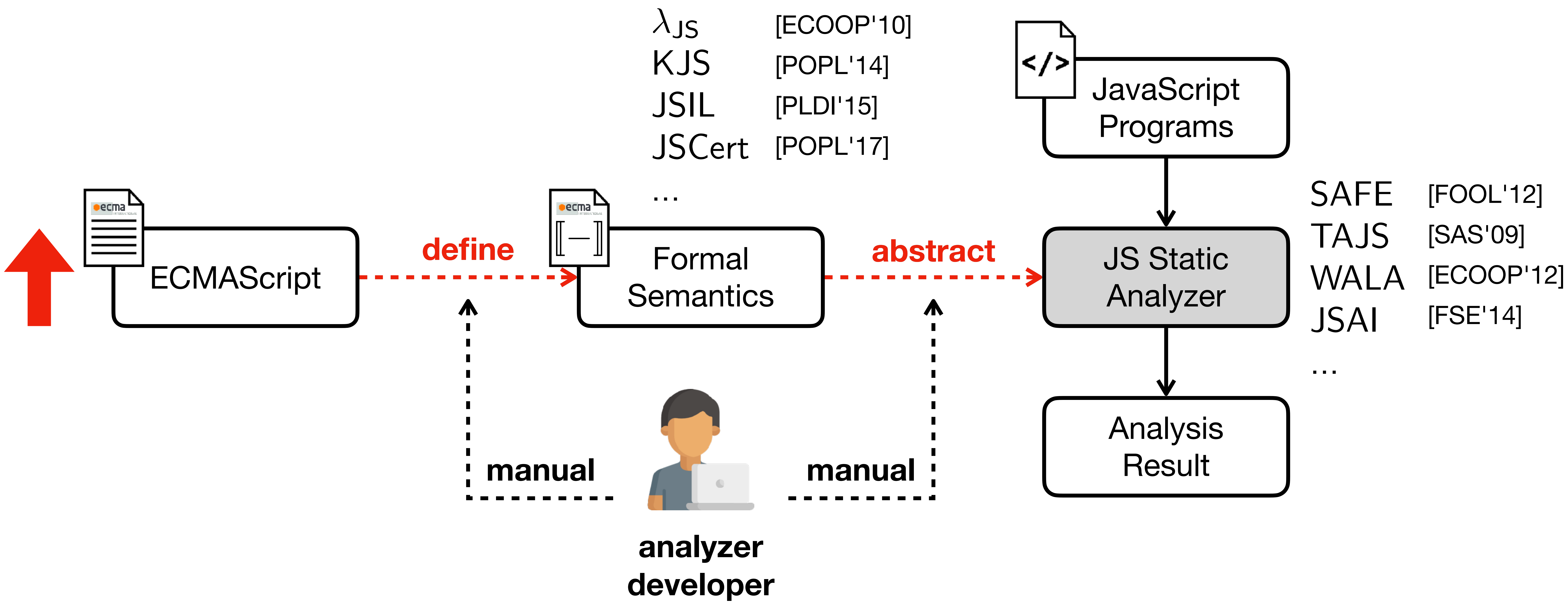
13.2.5.2 Runtime Semantics: Evaluation

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

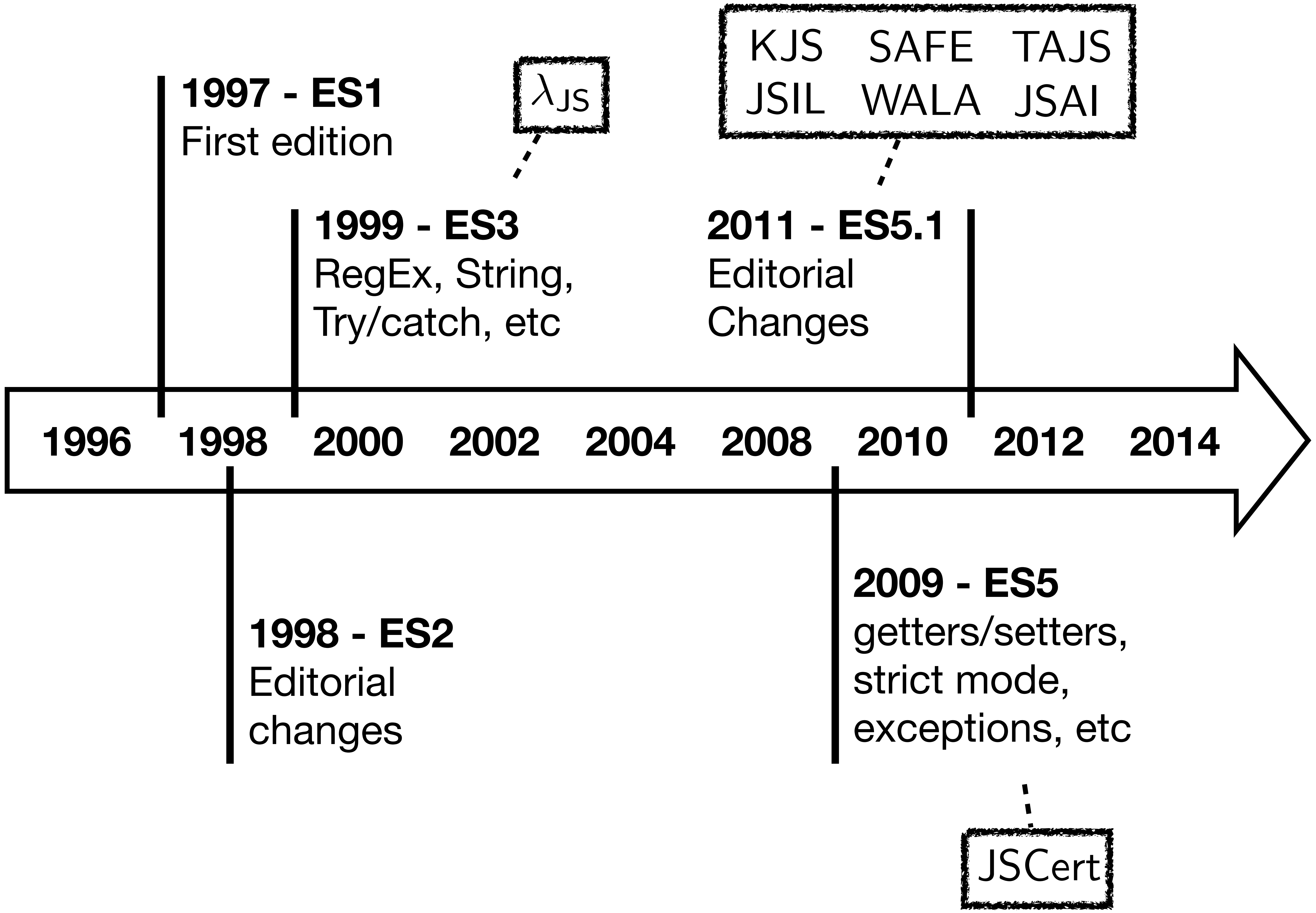
1. Let *array* be ! ArrayCreate(0).
2. Let *nextIndex* be the result of performing ArrayAccumulation for *ElementList* with arguments *array* and 0.
3. ReturnIfAbrupt(*nextIndex*).
4. If *Elision* is present, then
   a. Let *len* be the result of performing ArrayAccumulation for *Elision* with arguments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

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

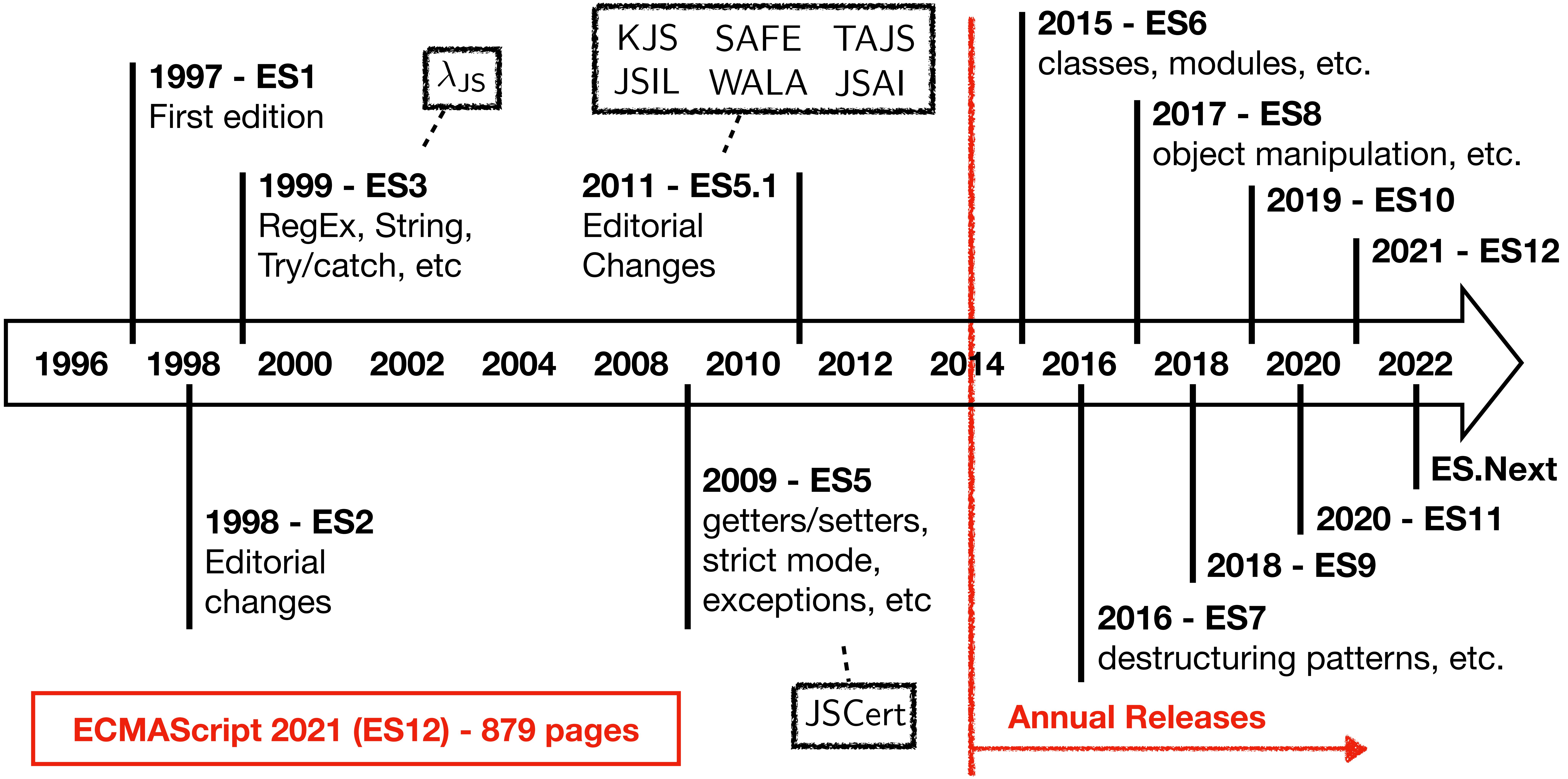
Problem: Manual JavaScript Static Analyzer



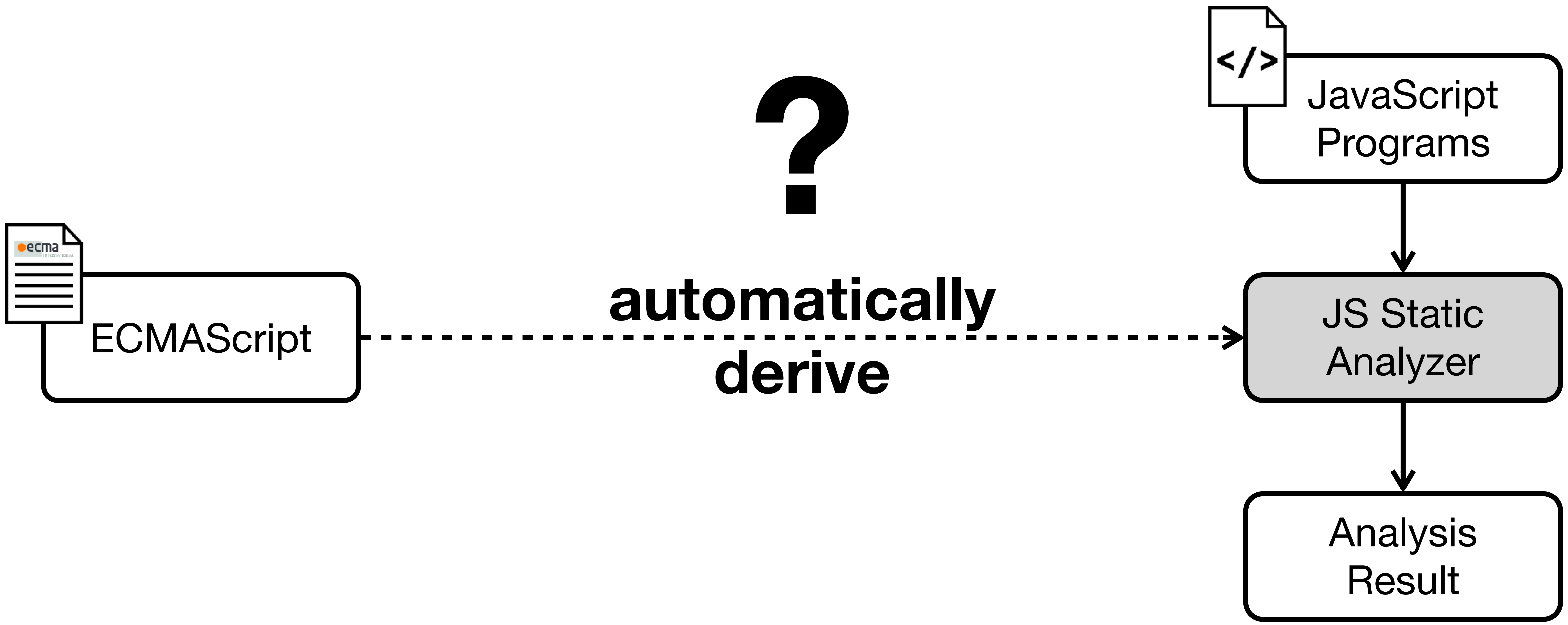
Problem: Fast Evolving JavaScript



Problem: Fast Evolving JavaScript



Main Idea: Deriving Static Analyzer from Spec.



JavaScript Static Analysis for Evolving Language Specifications

by 1) extracting mechanized specifications,

↳ JISET [ASE'20]

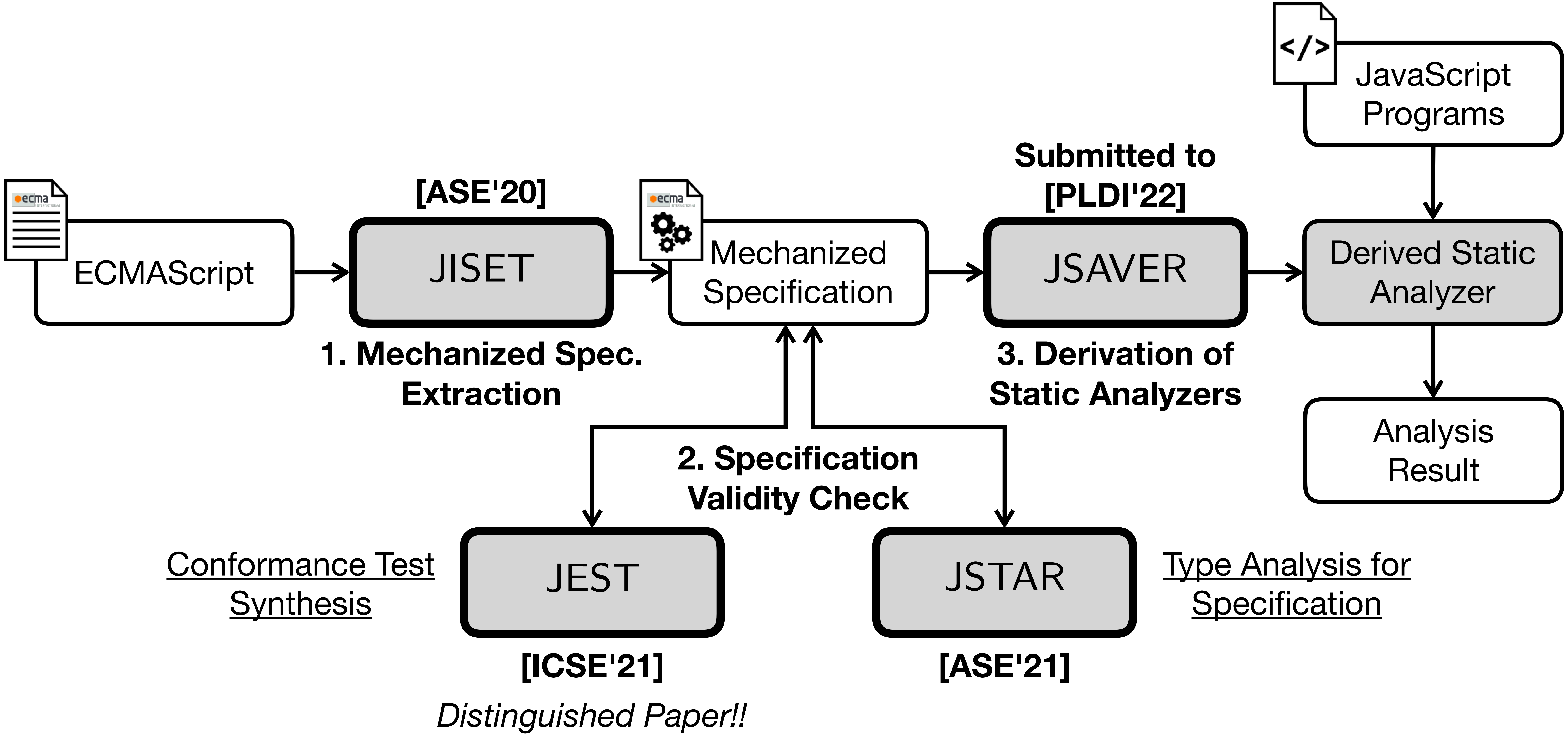
2) checking the validity of specifications,

↳ JEST [ICSE'21] ↳ JSTAR [ASE'21]

and 3) deriving static analyzers

↳ JSAVER (On going work)

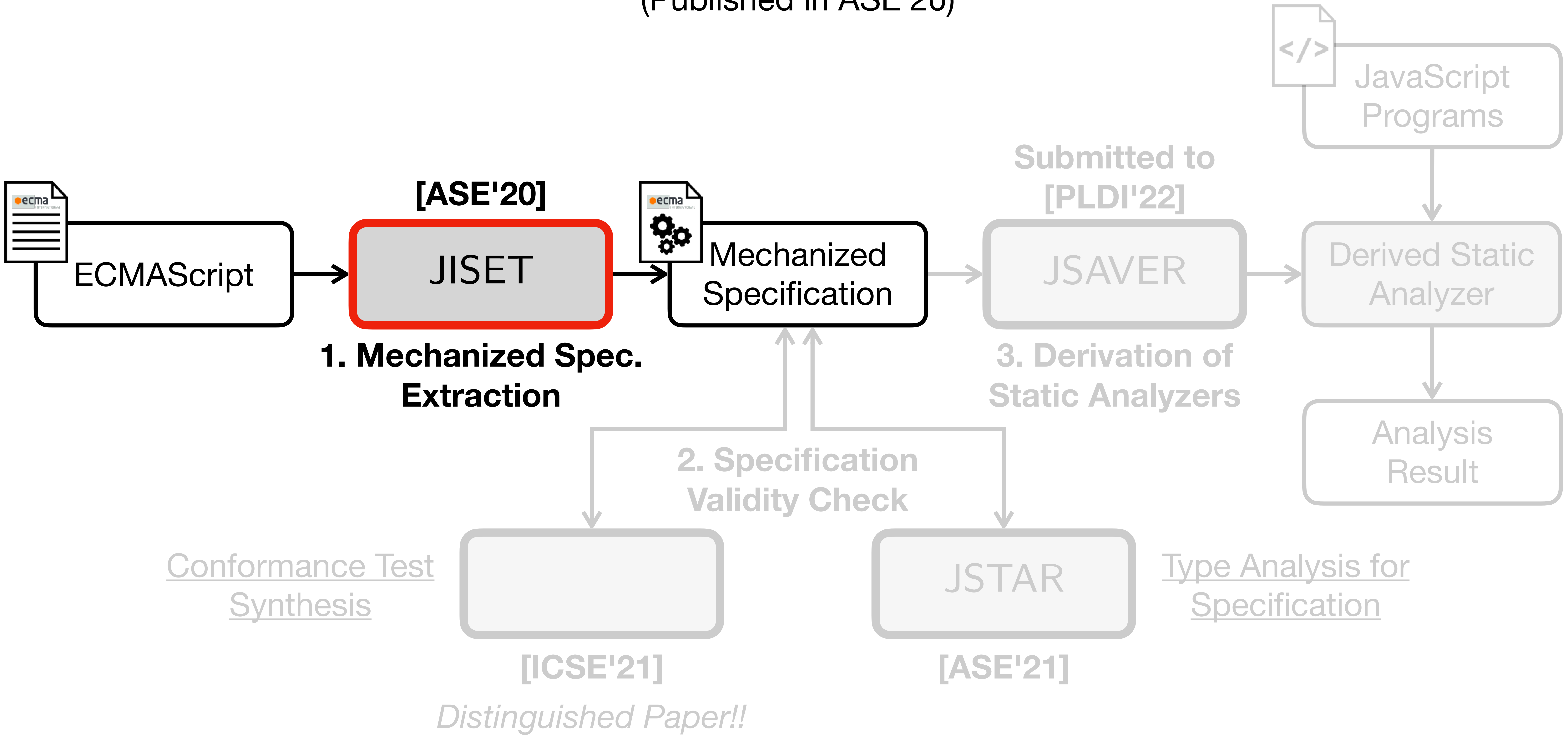
Overall Structure



JISET: JavaScript IR-based Semantics Extraction Toolchain

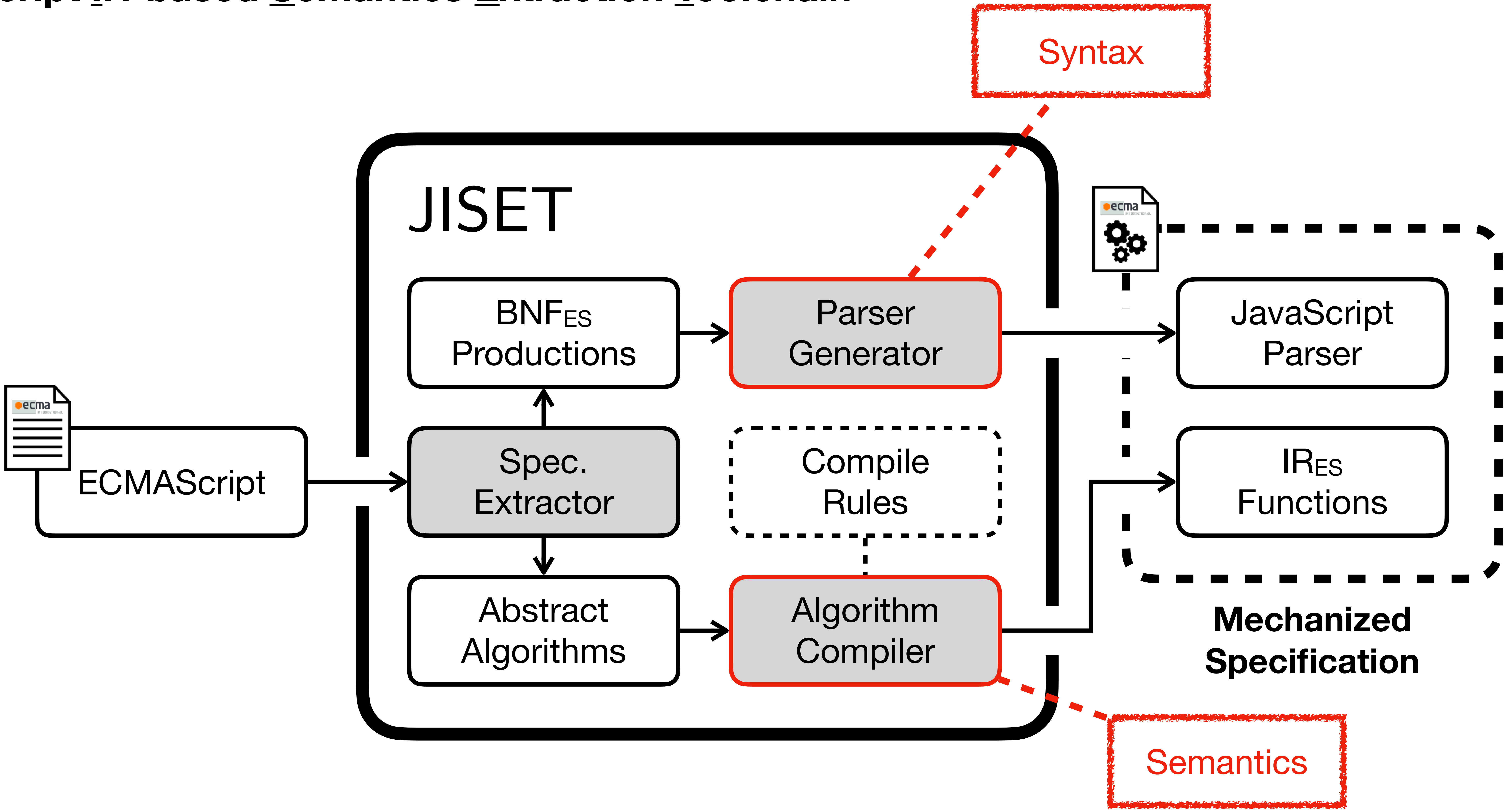
Jihyeok Park, Jihee Park, Seungmin An, and Sukyoung Ryu

(Published in ASE'20)



JISET [ASE'20]

JavaScript IR-based Semantics Extraction Toolchain



JISET - Parser Generator (Syntax)

```
ArrayLiteral[Yield, Await] :
    [ Elision_opt ]
    [ ElementList[?Yield, ?Await] ]
    [ ElementList[?Yield, ?Await] , Elision_opt ]
```

<u>Parsing Expression Grammar</u>
(+ 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"

- **Context-Free Grammar (CFG)**
  - Unordered Choices

$$A ::= B\,\texttt{;} \mid B + B\,\texttt{;} \qquad \texttt{xy;}\ ✓$$
$$B ::= \texttt{x} \mid \texttt{xy} \qquad \texttt{x+x;}\ ✓$$

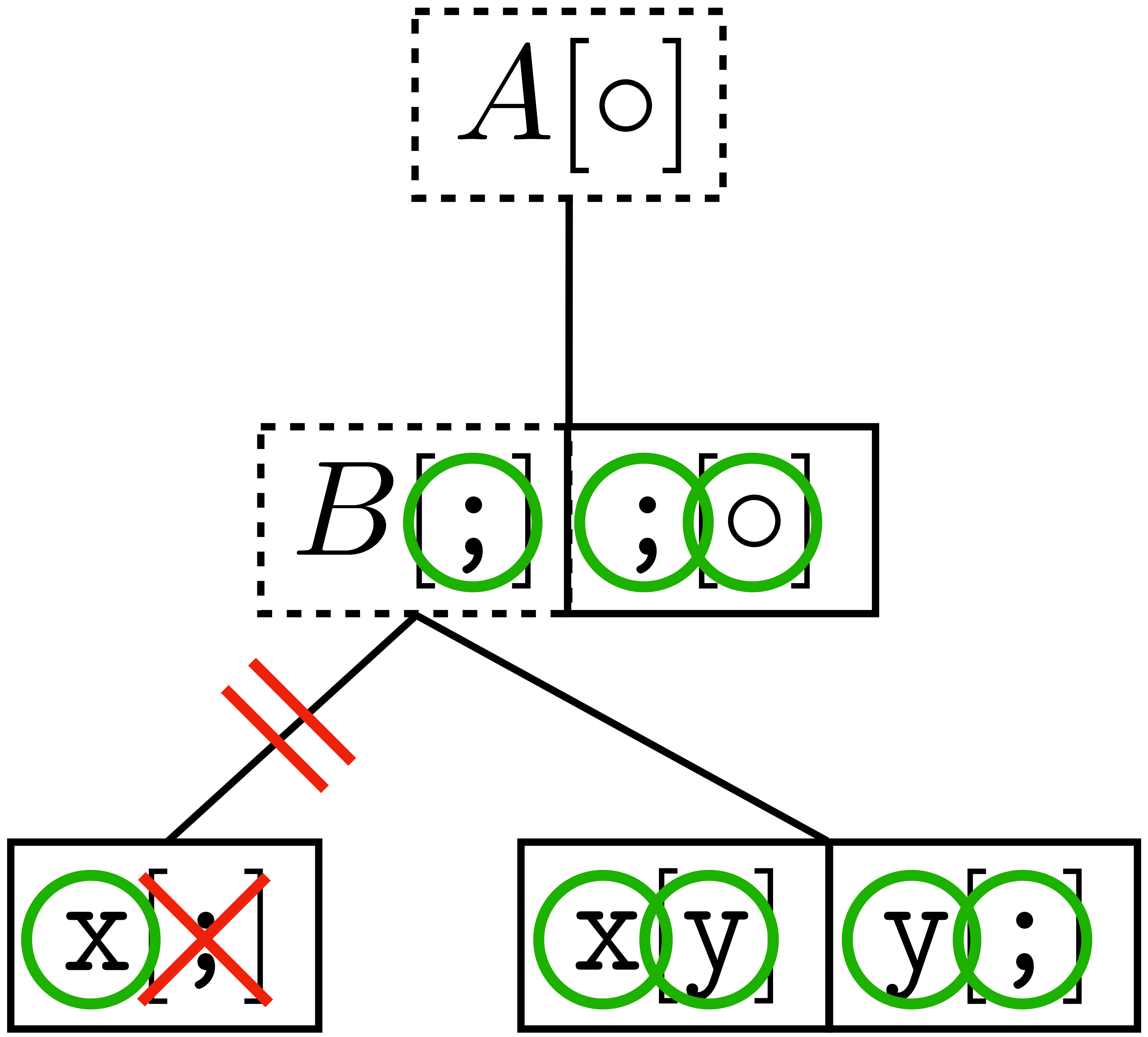
- **Parsing Expression Grammar (PEG)**
  - Ordered Choices

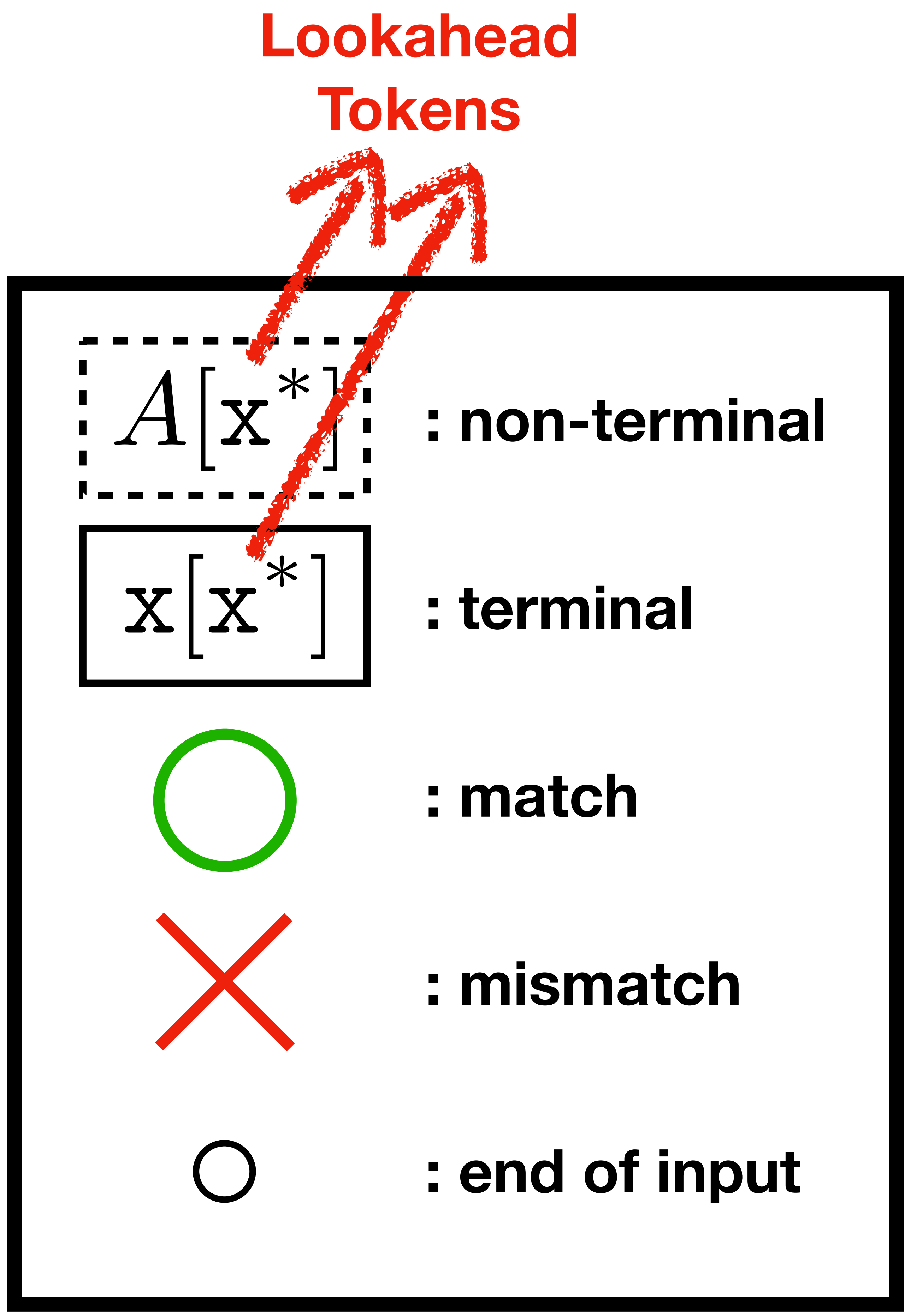
$$A ::= B\,\texttt{;}\ /\ B + B\,\texttt{;} \qquad \texttt{xy;}\ ✗$$
$$B ::= \texttt{x}\ /\ \boxed{\texttt{xy}} \qquad \texttt{x+x;}\ ✓$$

always ignored

- **PEG with *Lookahead Parsing***
  - Ordered Choices with *Lookahead Tokens*

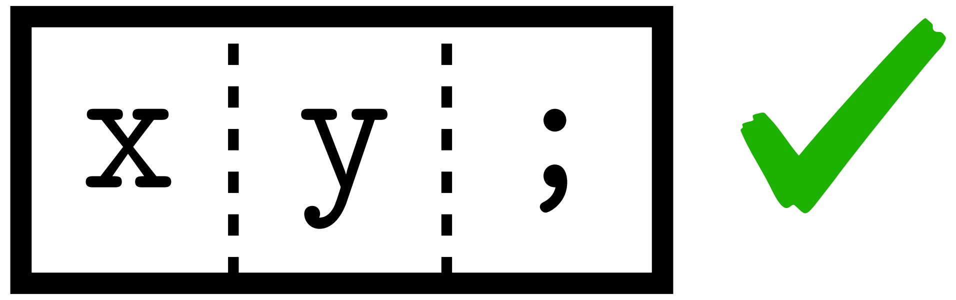
$$A ::= B\,\texttt{;}\ /\ B + B\,\texttt{;} \qquad \texttt{xy;}\ ✓$$
$$B ::= \texttt{x}\ /\ \texttt{xy} \qquad \texttt{x+x;}\ ✓$$





$$A ::= B\,; \;/\; B + B\,;$$
$$B ::= \mathrm{x} \;/\; \mathrm{xy}$$

input :



$$
\begin{aligned}
\mathbf{first}_\alpha(s_1 \cdots s_n) &= \mathbf{first}_s(s_1) :\!+ \mathbf{first}_s(s_2 \cdots s_n) \\
&\quad \text{where } x :\!+ y = \begin{cases} x \cup y & \text{if } \circ \in x \\ x & \text{otherwise} \end{cases} \\
\mathbf{first}_s(\epsilon) &= \{\circ\} \\
\mathbf{first}_s(\mathsf{a}) &= \{\mathsf{a}\} \\
\mathbf{first}_s(A(a_1, \cdots, a_k)) &= \mathbf{first}_\alpha(\alpha_1) \cup \cdots \cup \mathbf{first}_\alpha(\alpha_n) \\
&\quad \text{where } A(a_1, \cdots, a_k) = \alpha_1 \mid \cdots \mid \alpha_n \\
\mathbf{first}_s(s?) &= \mathbf{first}_s(s) \cup \{\circ\} \\
\mathbf{first}_s(+s) &= \mathbf{first}_s(s) \\
\mathbf{first}_s(-s) &= \{\circ\} \\
\mathbf{first}_s(s \setminus s') &= \mathbf{first}_s(s) \\
\mathbf{first}_s(\langle \neg \mathsf{LT} \rangle) &= \{\circ\}
\end{aligned}
$$

Algorithm for first tokens of BNFES

Algorithm for lookahead parsing

$$
\begin{aligned}
(s_1 \cdots s_n)[L] &= s_1[\mathbf{first}_s(s_2 \cdots s_n) :\!+ L]\ (s_1 \cdots s_n)[L] \\
\epsilon[L] &= +\mathbf{get}_s(L) \\
\mathsf{a}[L] &= \mathsf{a}\ \ + \mathbf{get}_s(L) \\
A(a_1, \cdots, a_k)[L] &= \alpha_1[L] \mid \cdots \mid \alpha_n[L] \\
&\quad \text{where } A(a_1, \cdots, a_k) = \alpha_1 \mid \cdots \mid \alpha_n \\
s?[L] &= s[L] \mid \epsilon[L] \\
(\pm s)[L] &= \pm(s[L]) \\
(s \setminus s')[L] &= s[L] \setminus s' \\
\langle \neg \mathsf{LT} \rangle &= \langle \neg \mathsf{LT} \rangle\ + \mathbf{get}_s(L)
\end{aligned}
$$

JISET - Algorithm Compiler (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*.

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
}
```

Parsing rules — Conversion Rules

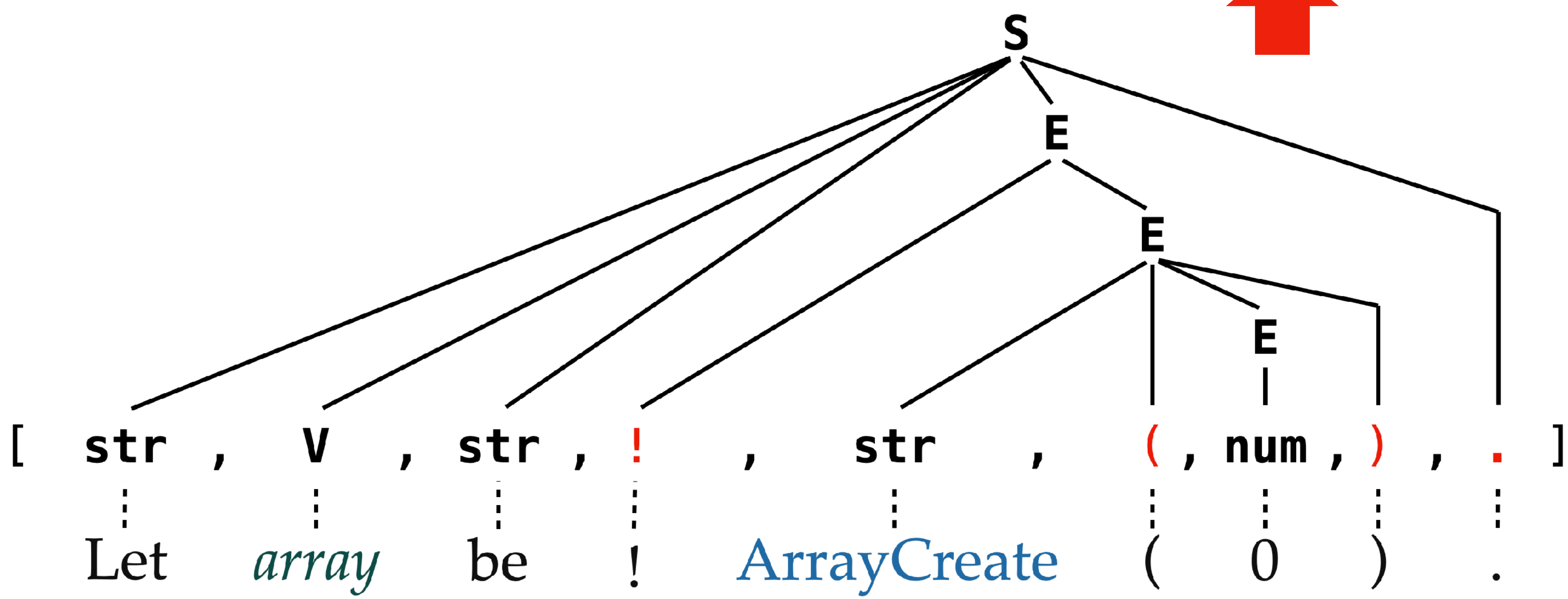
```
S = // statements
  Let ~ V ~ be ~ E ~ .   ^^ ILet

E = // expressions
  ! E                    ^^ EAbruptCheck |
  str ~ ( ~ E ~ )        ^^ ECall        |
  num                    ^^ _.toDouble
```

Simplified compile rules

```
let array = ! (ArrayCreate 0)
```

```
ILet(array, EAbruptCheck(
  ECall("ArrayCreate", 0)))
```



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%)
		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%)

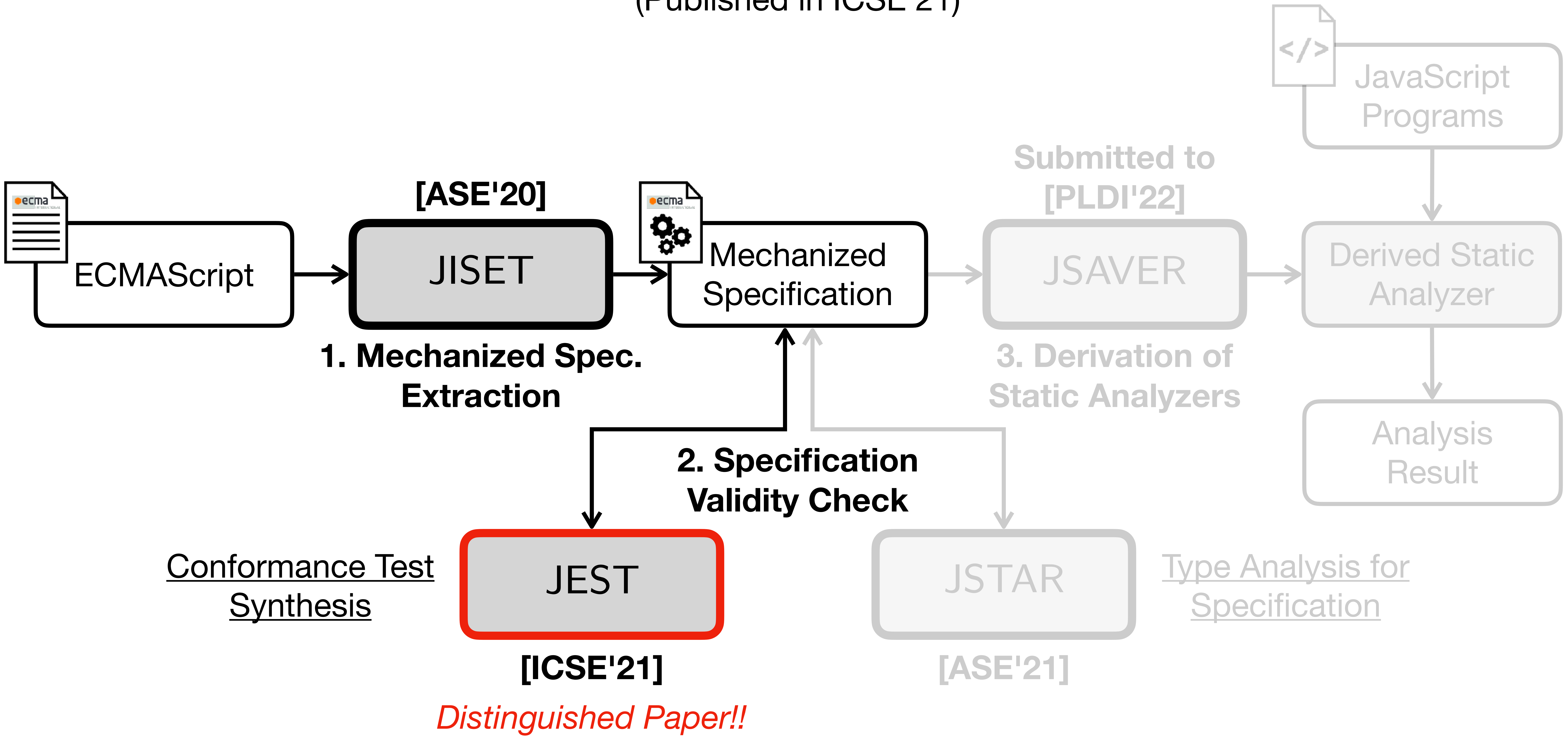
Complete Missing Parts

- **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

ECMAScript

?

Conform

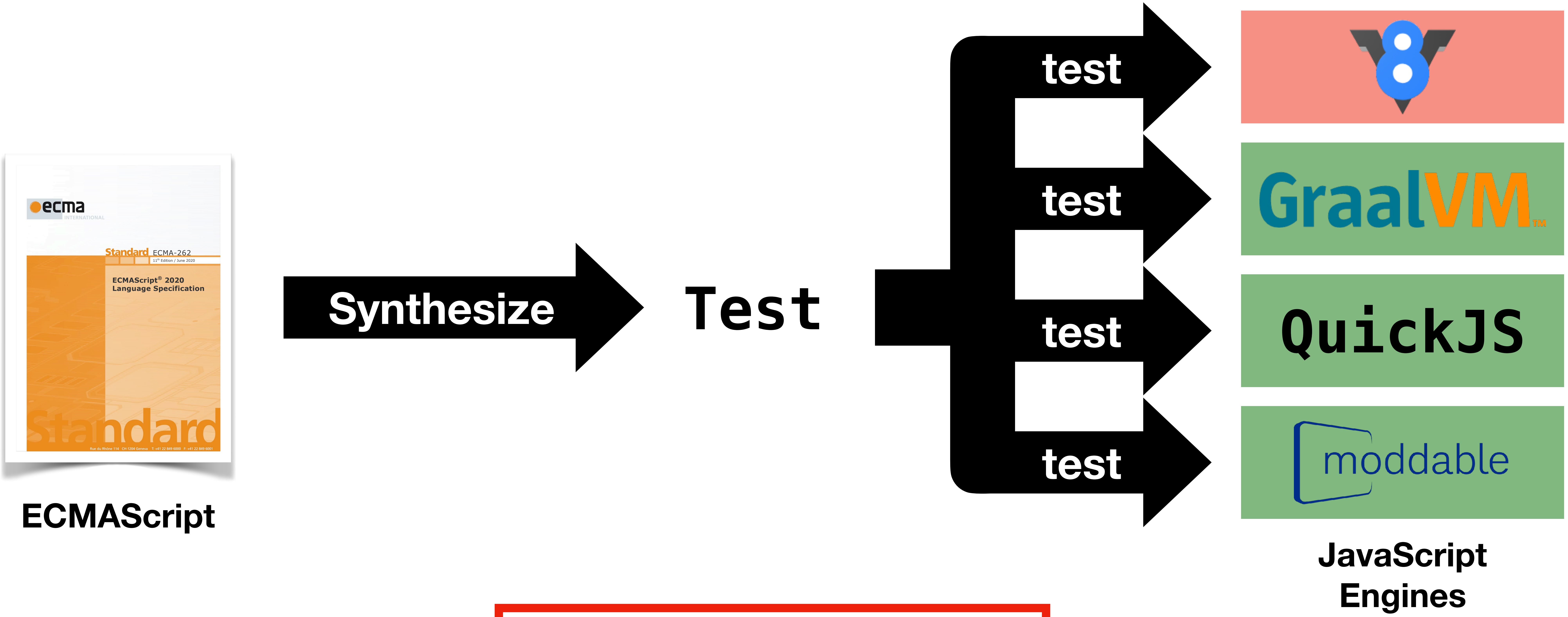
GraalVM

QuickJS

moddable

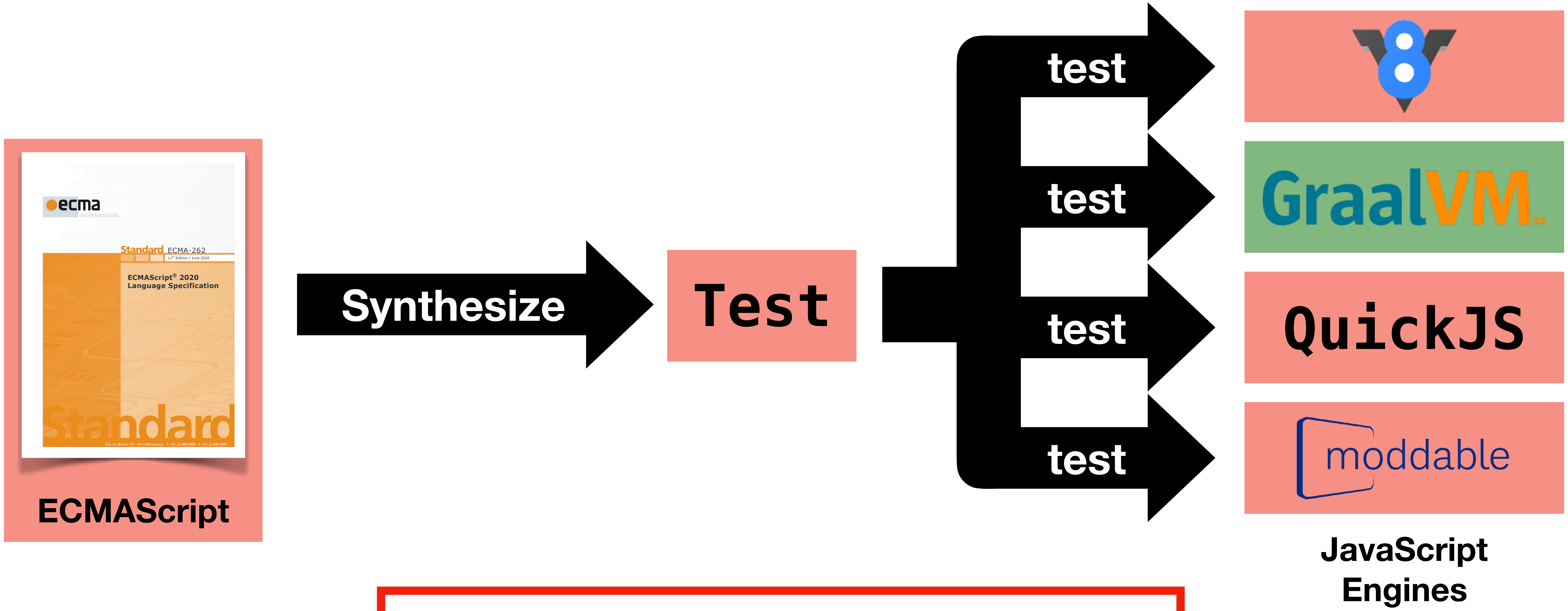
JavaScript
Engines

JEST - N+1-version Differential Testing



An engine bug in V8

JEST - N+1-version Differential Testing

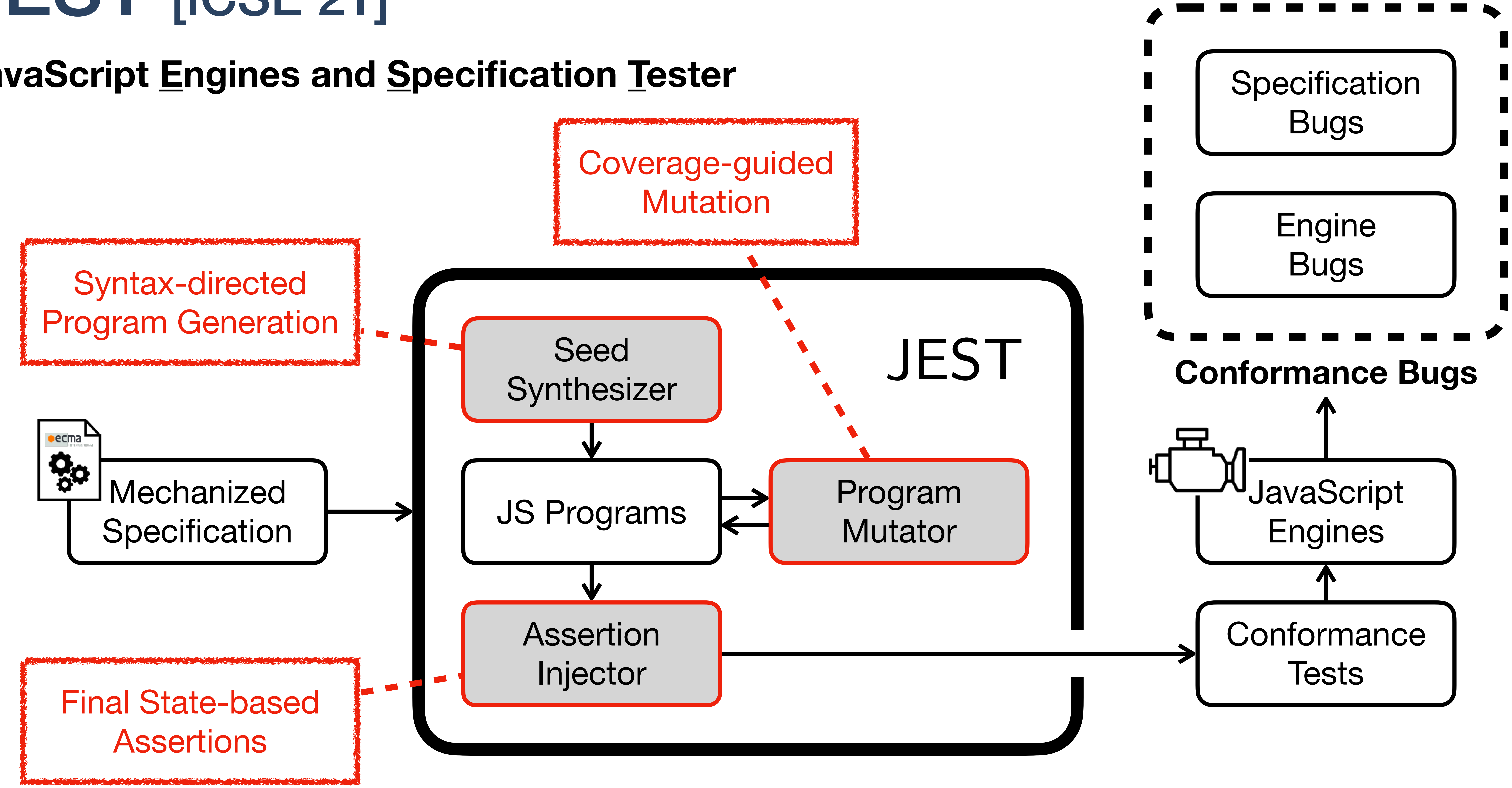


A specification bug in ECMAScript

An engine bug in GraalVM

JEST [ICSE'21]

JavaScript Engines and Specification Tester



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.

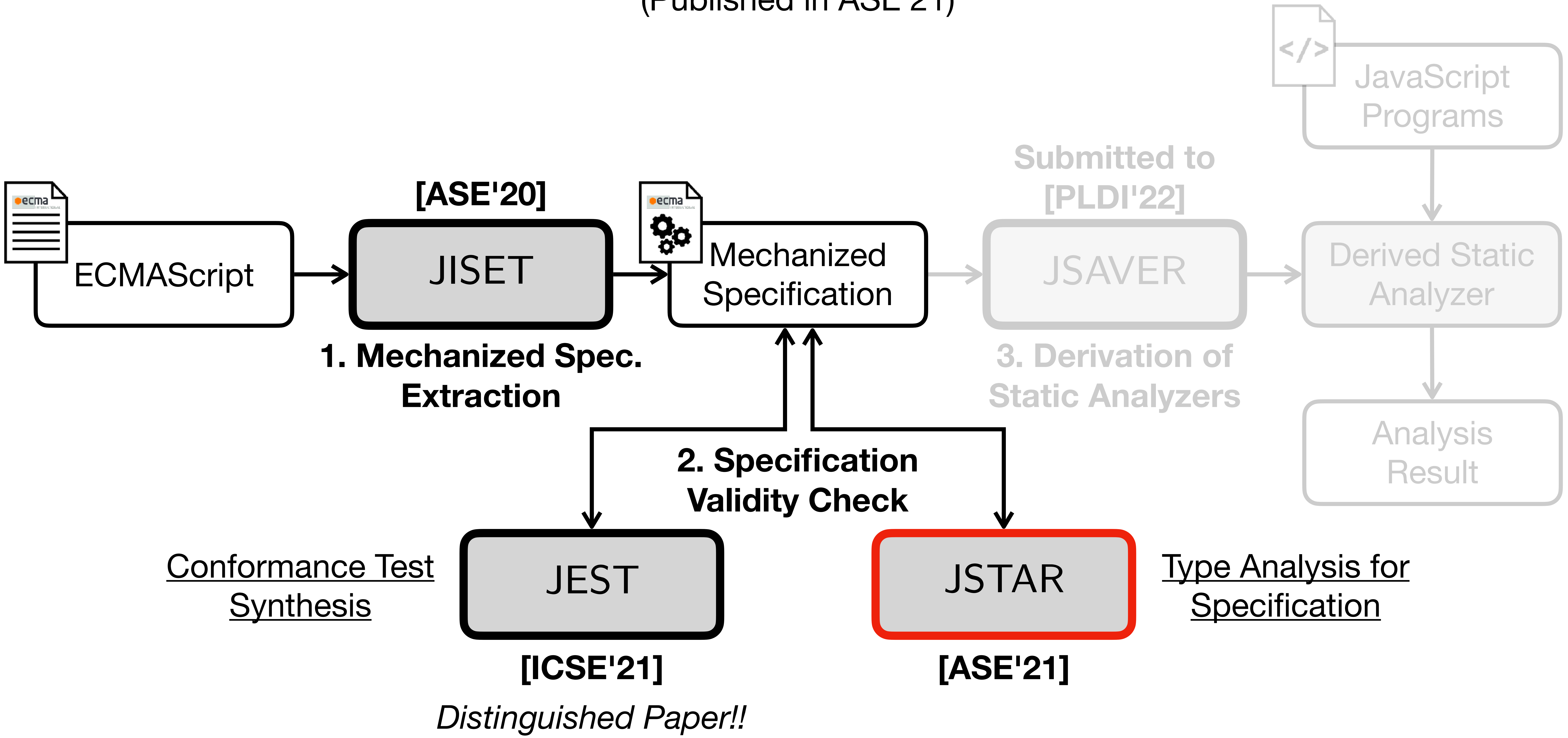
TABLE III: Specification bugs in ECMAScript 2020 (ES11) detected by JEST

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) `x: (String ∨ Boolean ∨ Number ∨ Object ∨ ...)`

1. Let n be ? ToNumber(x). `n: (Number) ∧ ToNumber(x): (Number ∨ Exception)`
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**.

...

Type Mismatch for numeric operator `>`

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

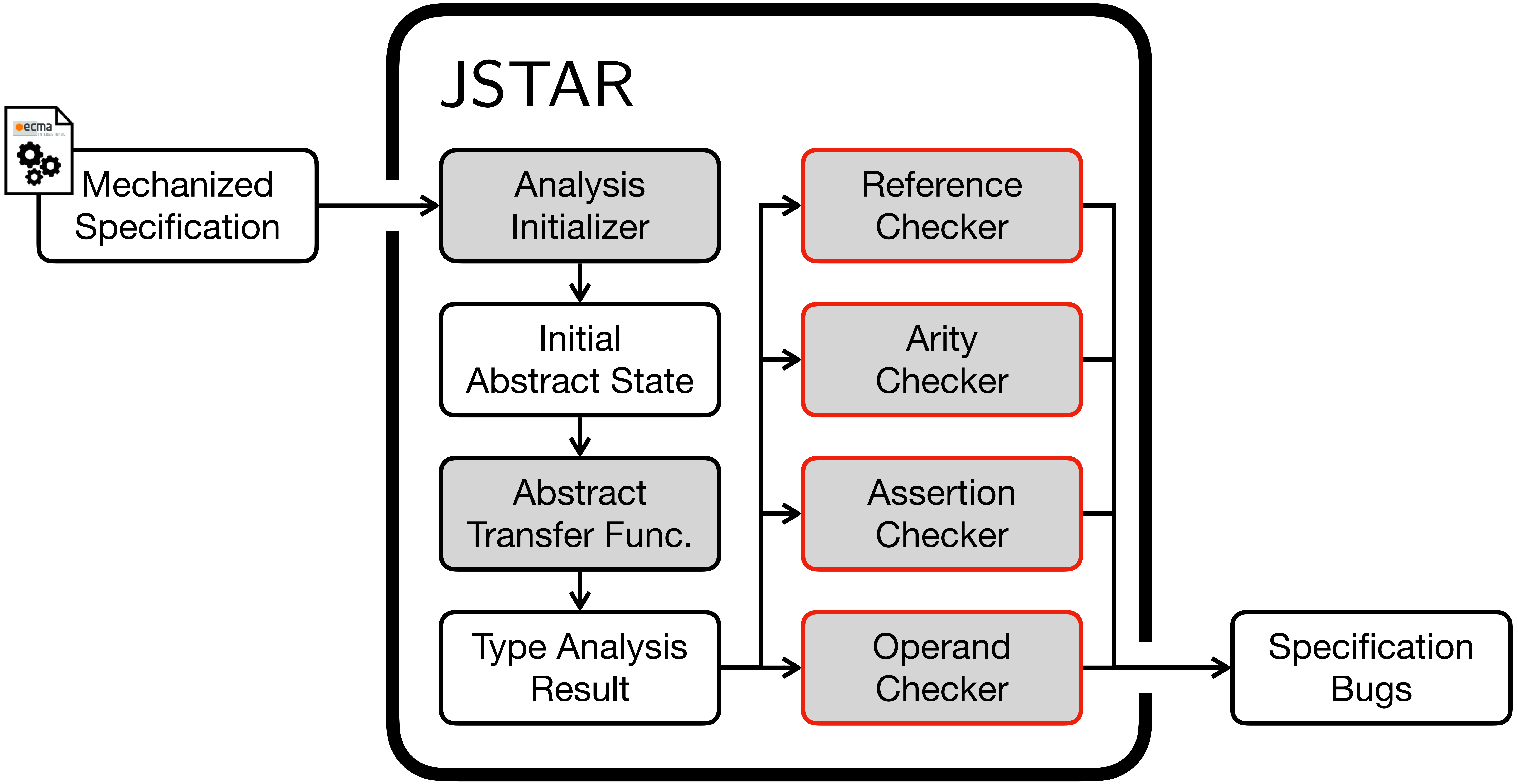
3. If $n < 0.5$ and $n > 0$, return **+0**.
4. If $n < 0$ and $n \geq$ -0.5, return **-0**.

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

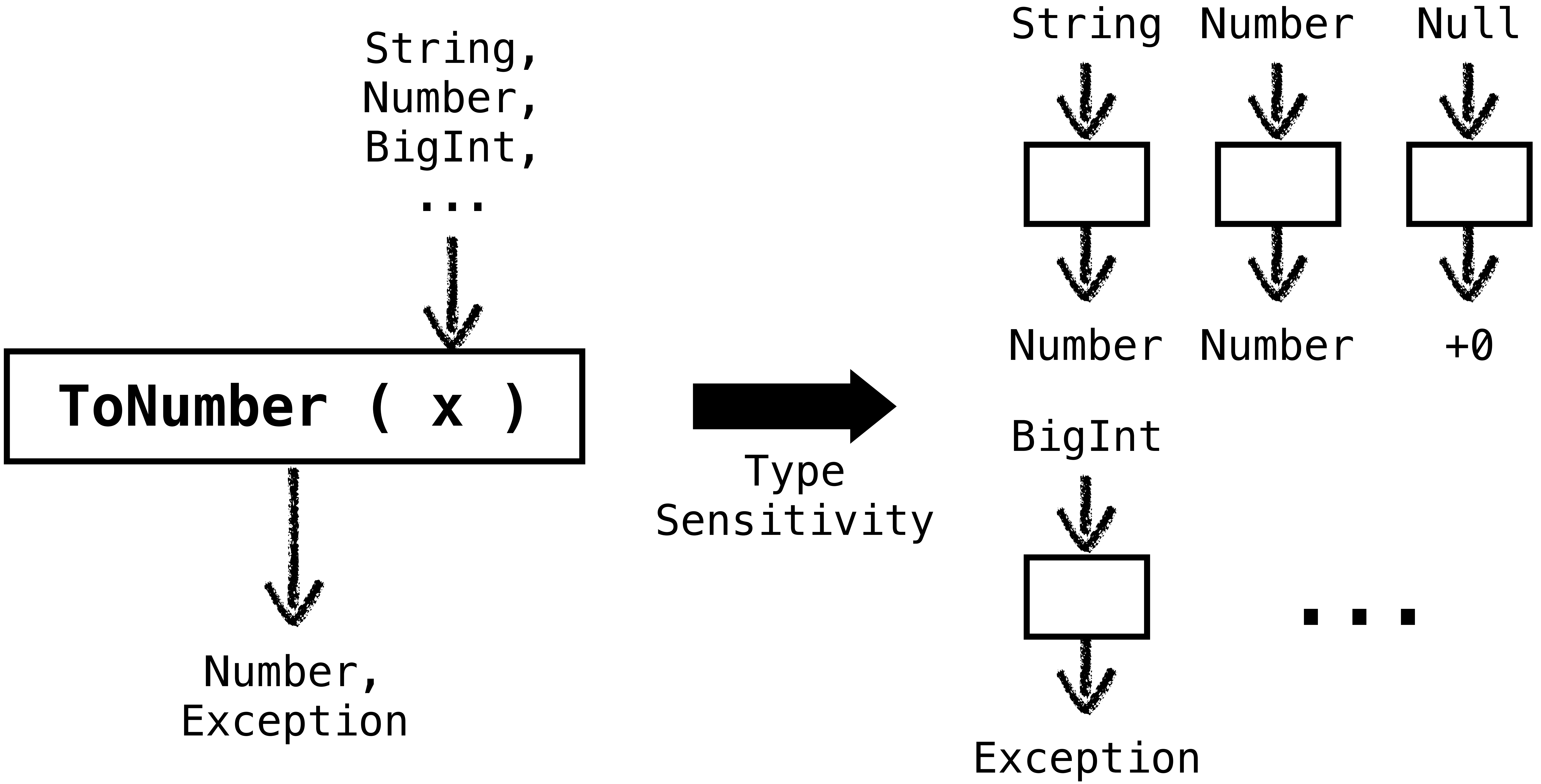
https://github.com/tc39/ecma262/tree/575149cfd77aebcf3a129e165bd89e14caafc31c

JSTAR [ASE'21]

JavaScript Specification Type Analyzer using Refinement



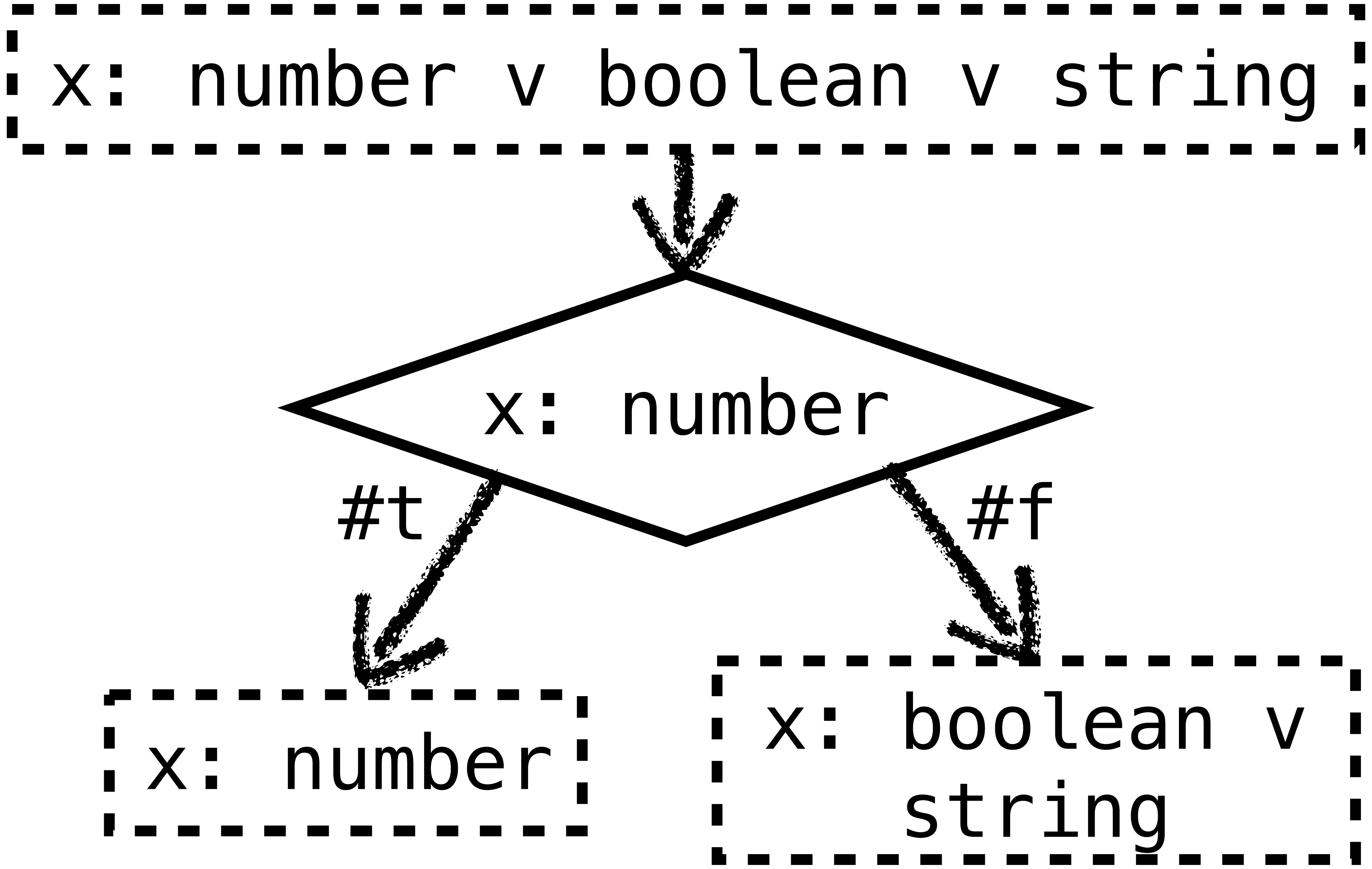
JSTAR - Type Sensitivity



JSTAR - Condition-based 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.



JSTAR - Evaluation

- **Type Analysis for 864 versions of ECMAScript**

26.3% more precise

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%)	

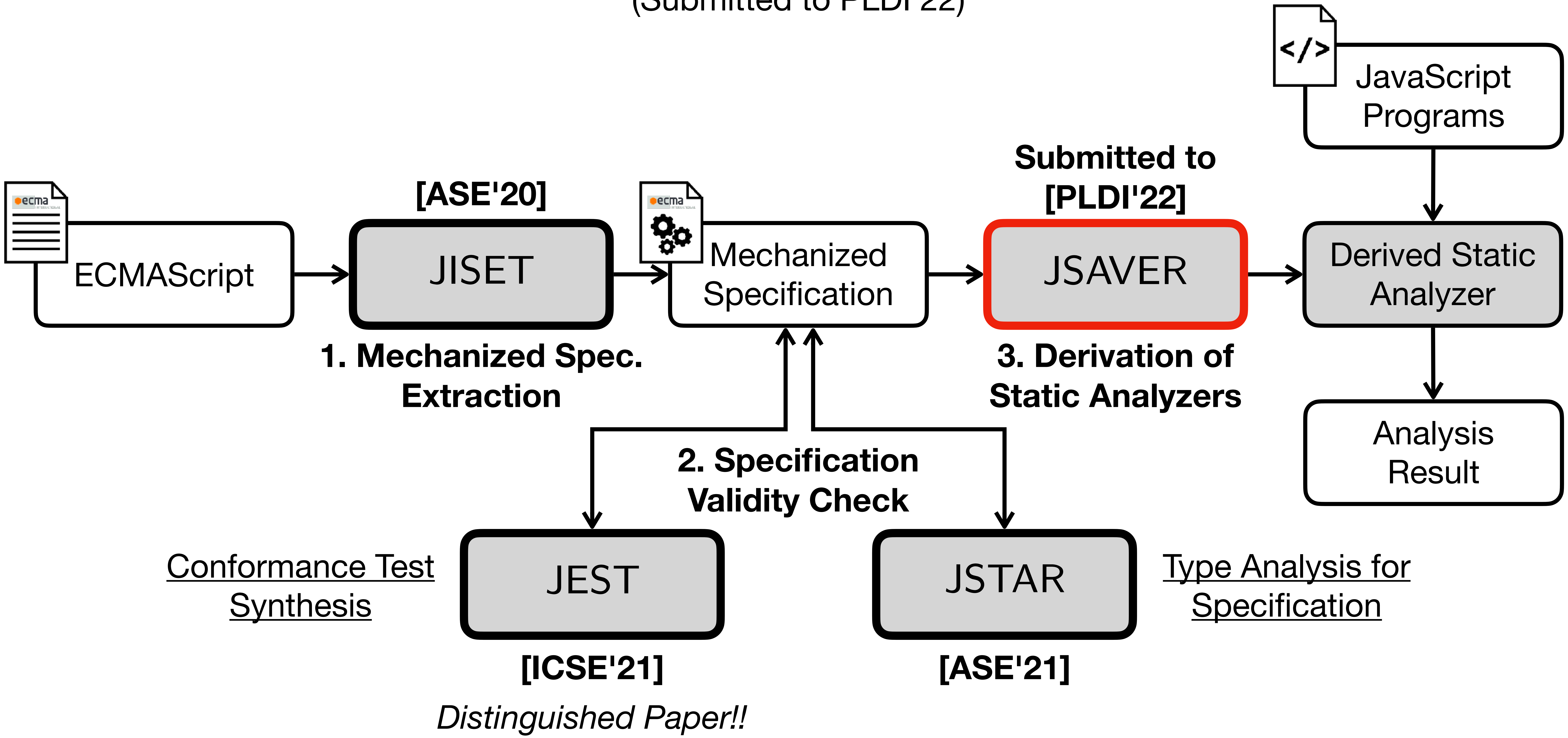
Name	Feature	#	Checker	Created	Life Span
ES12-1	Switch	3	Reference	2015-09-22	1,996 days
ES12-2	Try	3	Reference	2015-09-22	1,996 days
ES12-3	Arguments	1	Reference	2015-09-22	1,996 days
ES12-4	Array	2	Reference	2015-09-22	1,996 days
ES12-5	Async	1	Reference	2015-09-22	1,996 days
ES12-6	Class	1	Reference	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 Spec.

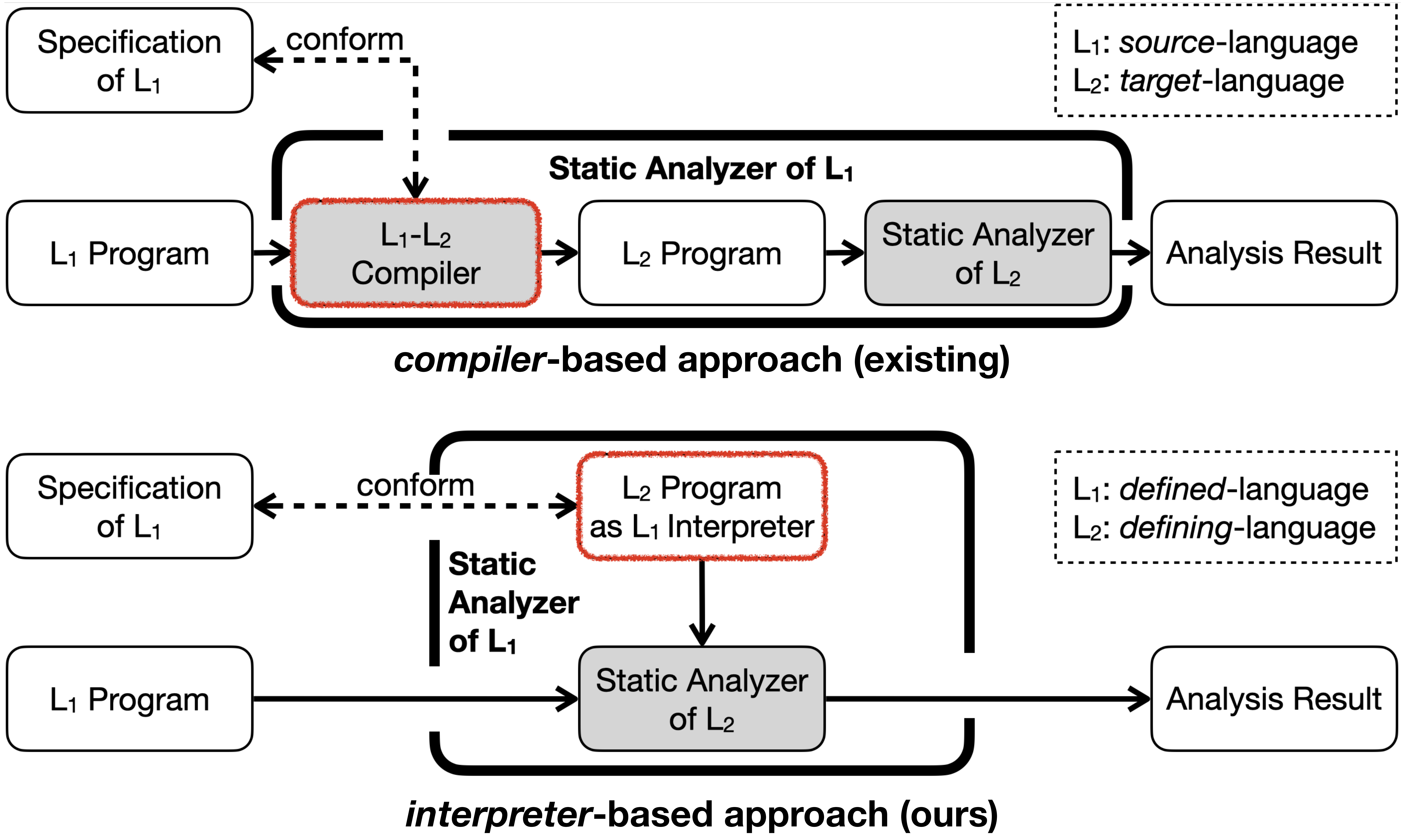
Automatically Deriving JavaScript Static Analyzers from Language Specifications

Jihyeok Park, Seungmin An, and Sukyoung Ryu

(Submitted to PLDI'22)



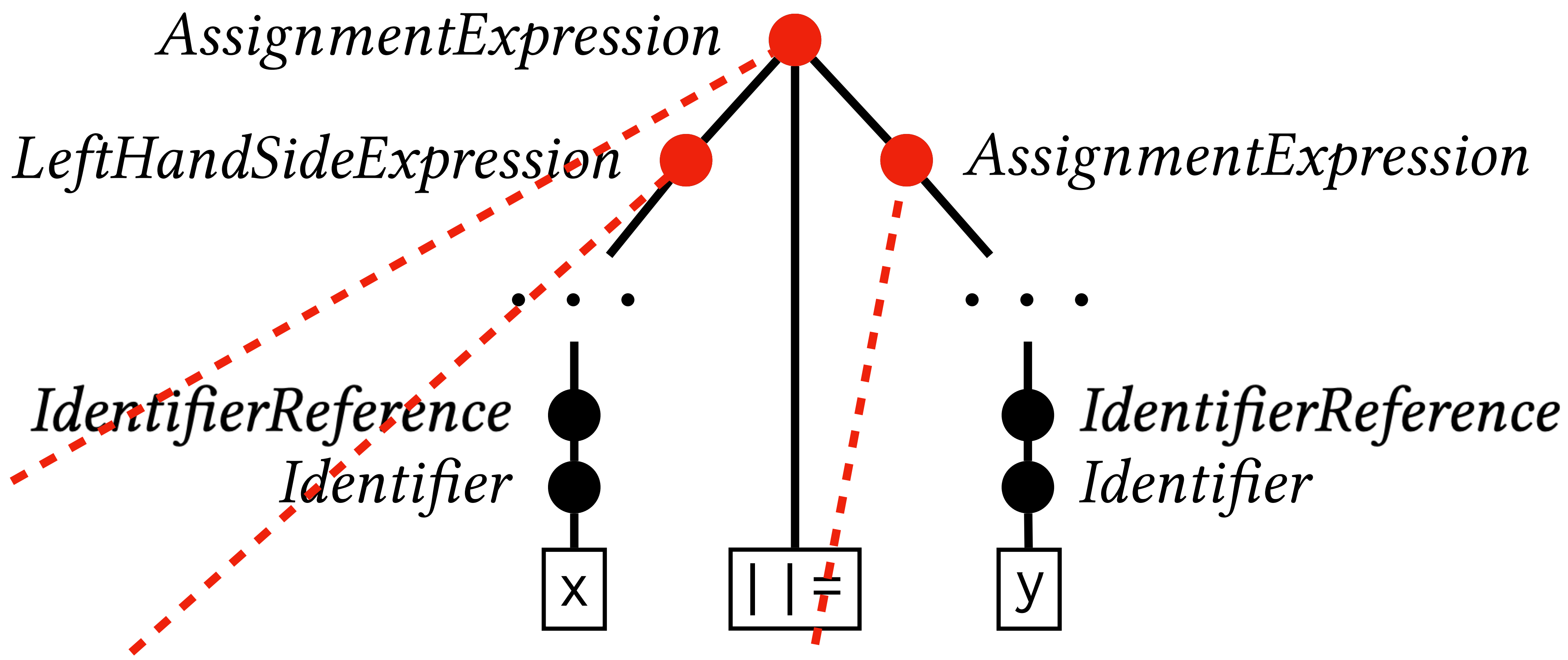
JSAVER - Meta-Level Static Analysis



JSAVER - Meta-Level Static Analysis

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

x ||= y **parse**



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

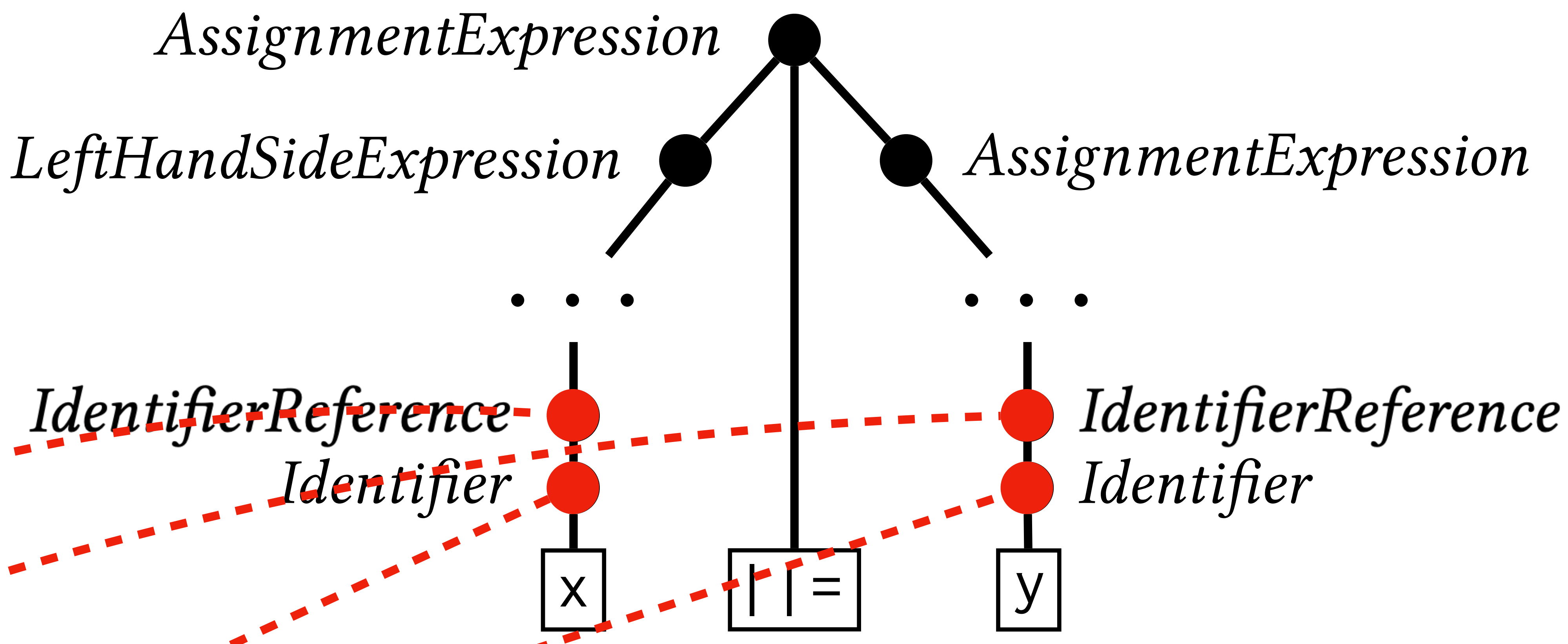
```
syntax def AssignmentExpression[8].Evaluation(
  this, LeftHandSideExpression, AssignmentExpression
) {
  let lref = (LeftHandSideExpression.Evaluation)
  let lval = [? (GetValue lref)]
  let lbool = [! (ToBoolean lval)]
  if (= lbool true) return lval
  ...
}
```

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

JSAVER - AST Sensitivity

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

x ||= y **parse**



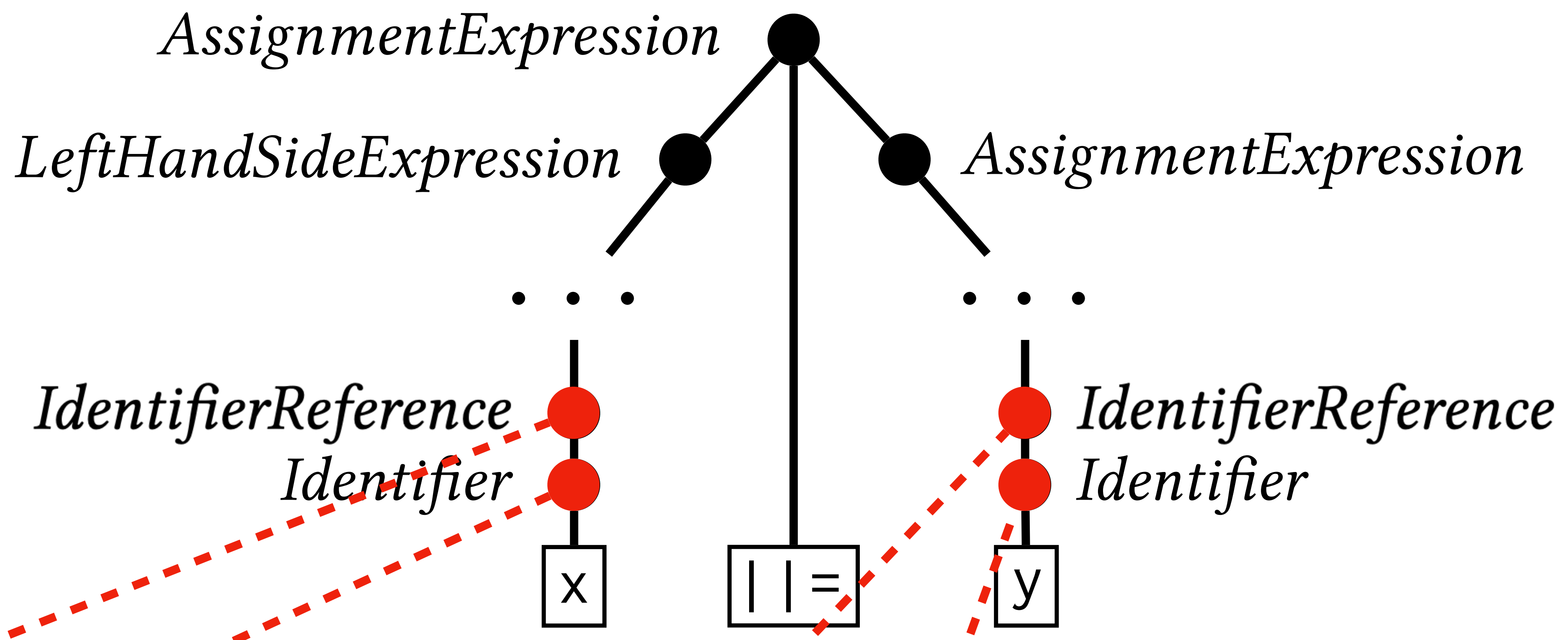
***defining*-language**
(IR_{ES})

```
syntax def IdentifierReference[0]
  .Evaluation(
  this, Identifier
) {
  return [?
    (ResolveBinding
      (Identifier.StringValue))]
}
```

JSAVER - AST Sensitivity

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

`x ||= y` **parse**



***defining*-language**
(IRES)

```
syntax def IdentifierReference[0]
  .Evaluation(
  this, Identifier
) {
  return [?
    (ResolveBinding
      (Identifier.StringValue))]
}
```

`this = AST of `x``

```
syntax def IdentifierReference[0]
  .Evaluation(
  this, Identifier
) {
  return [?
    (ResolveBinding
      (Identifier.StringValue))]
}
```

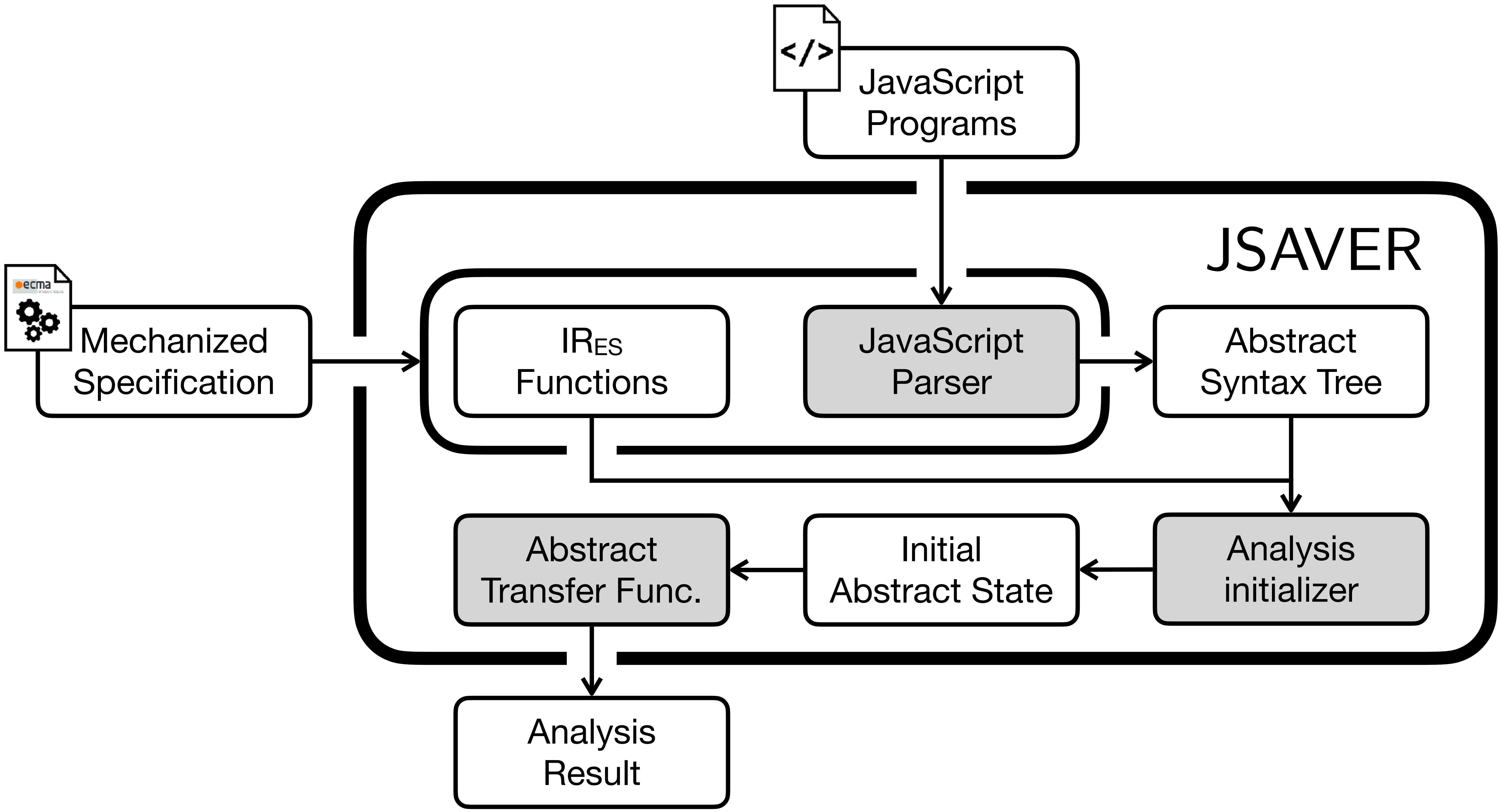
`this = AST of `y``

JSAVER - AST Sensitivity

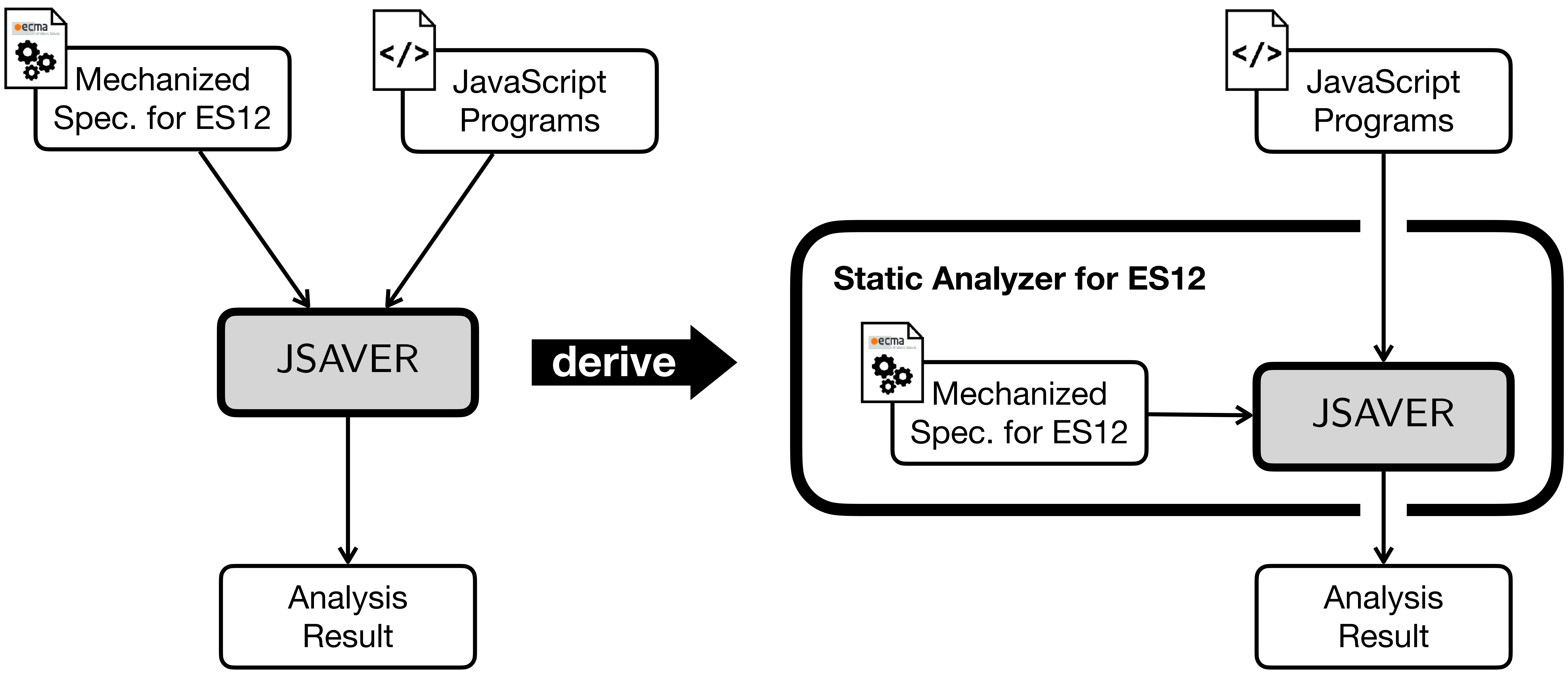
defined-language (JavaScript)	**defining-language** (IR_{ES})
flow-sensitivity	$\delta^{\text{js-flow}}(t_\bot) = \{\sigma = (\_, \_, \bar{c}, \_) \in \mathbb{S} \mid \text{ast}(\bar{c}) = t_\bot\}$
k-callsite sensitivity	$\delta^{\text{js-}k\text{-cfa}}([t_1, \cdots, t_n]) = \{\sigma = (\_, \_, \bar{c},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

JSAVER Submitted to [PLDI'22]

<u>J</u>avaScript <u>S</u>tatic <u>A</u>nalyzer via <u>E</u>CMAScript <u>R</u>epresentation

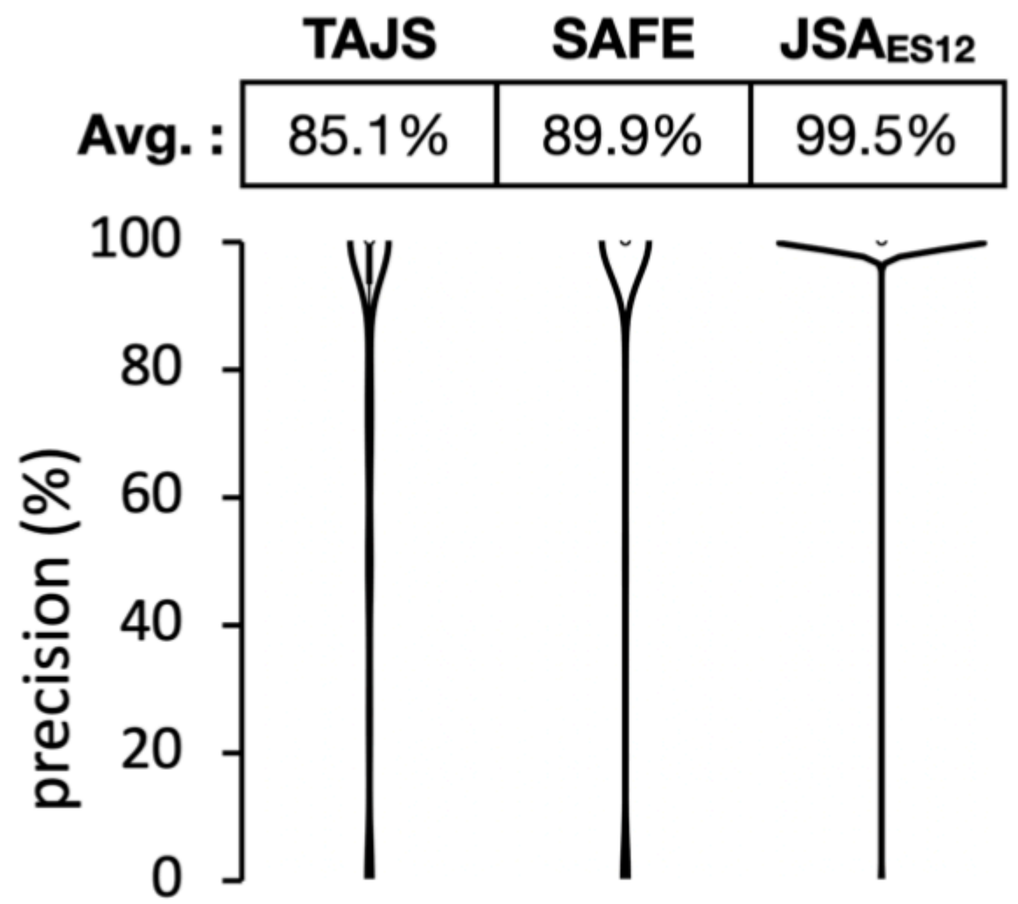


JSAVER - Static Analyzer Derivation

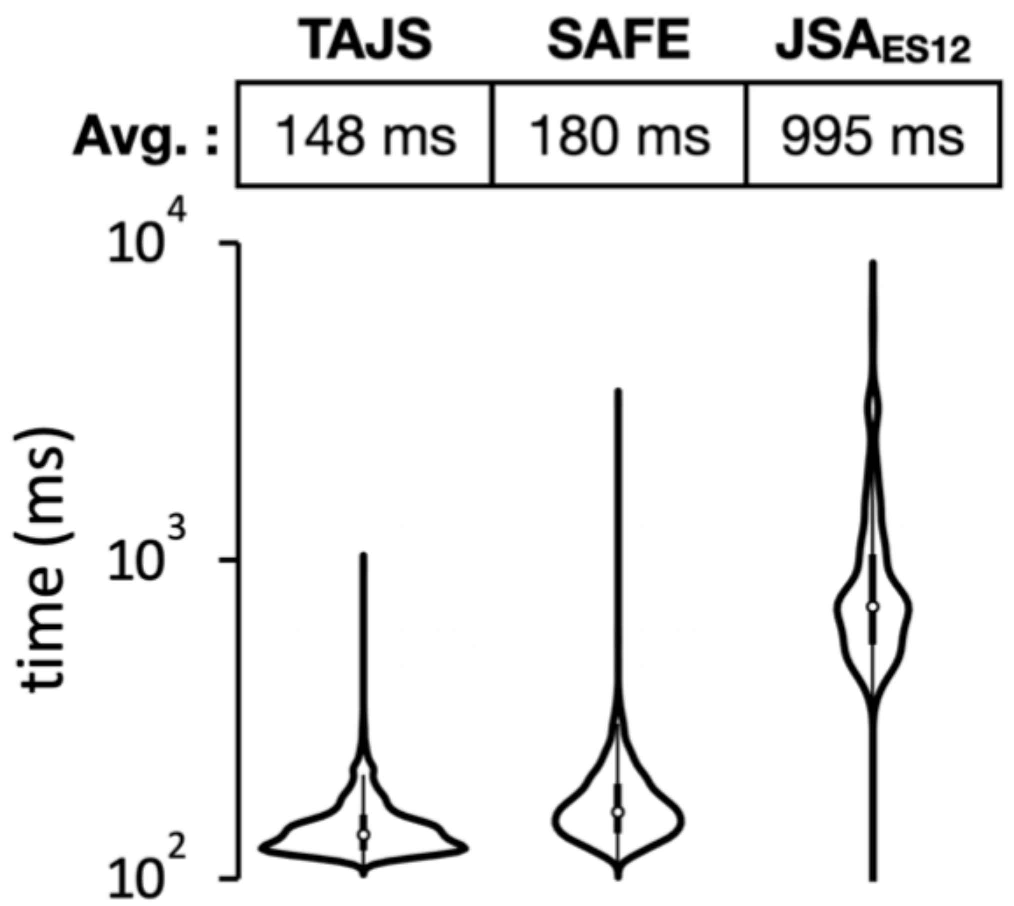


JSAVER - Evaluation

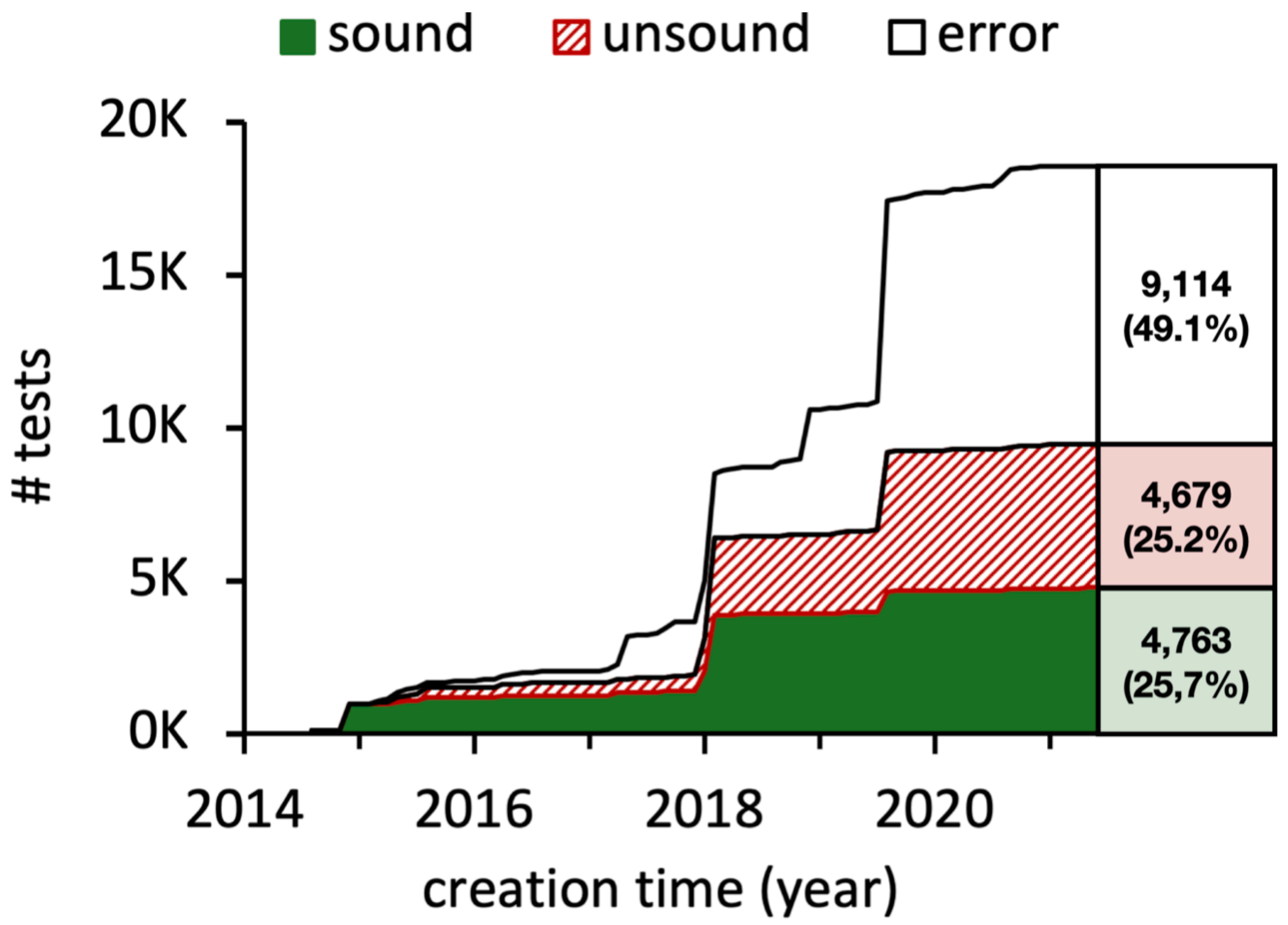
- **Soundness / Precision / Performance**
  - 18,556 applicable tests in Test262
  - 3,903 tests analyzable by all the three analyzers



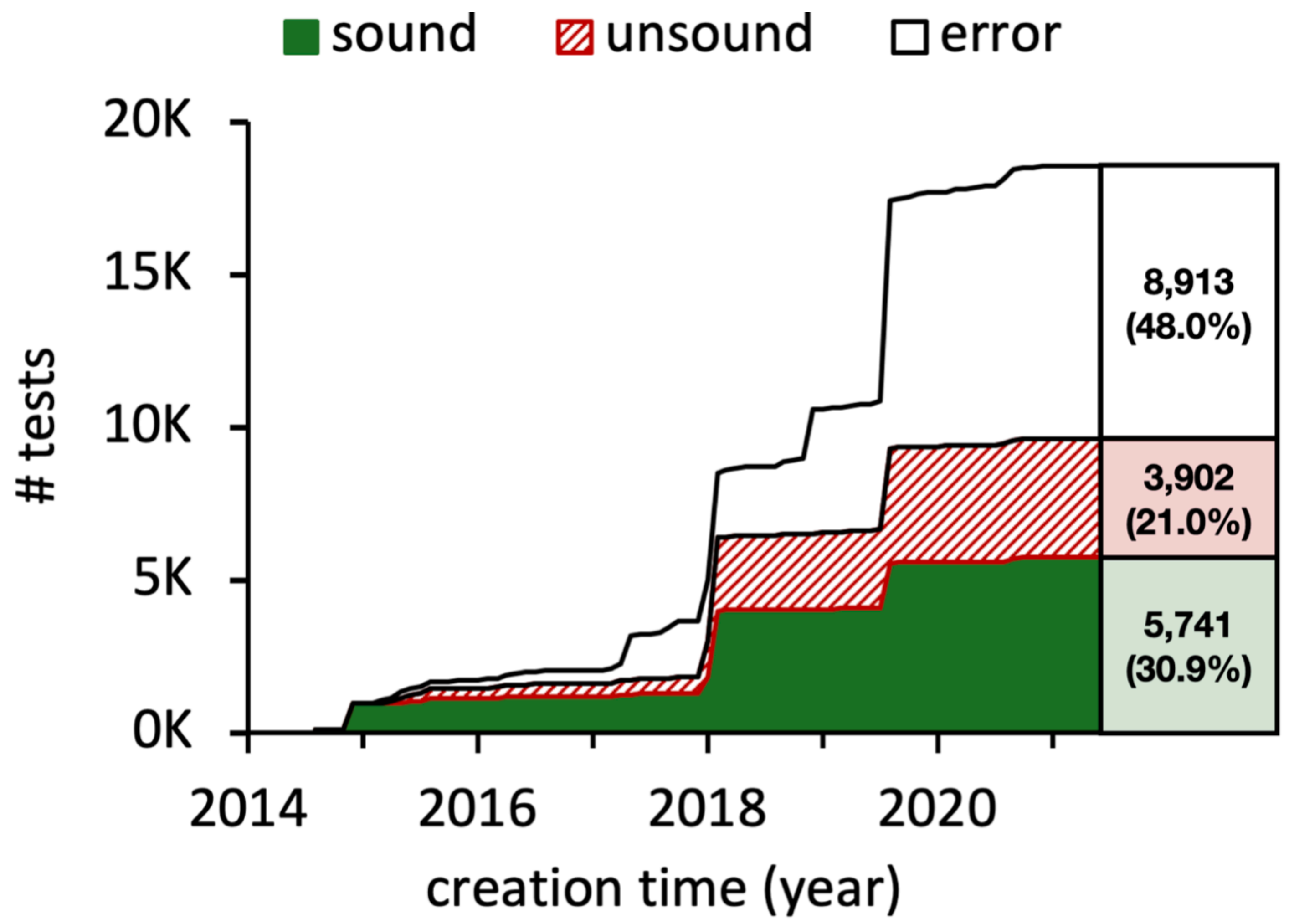
(a) The analysis precision



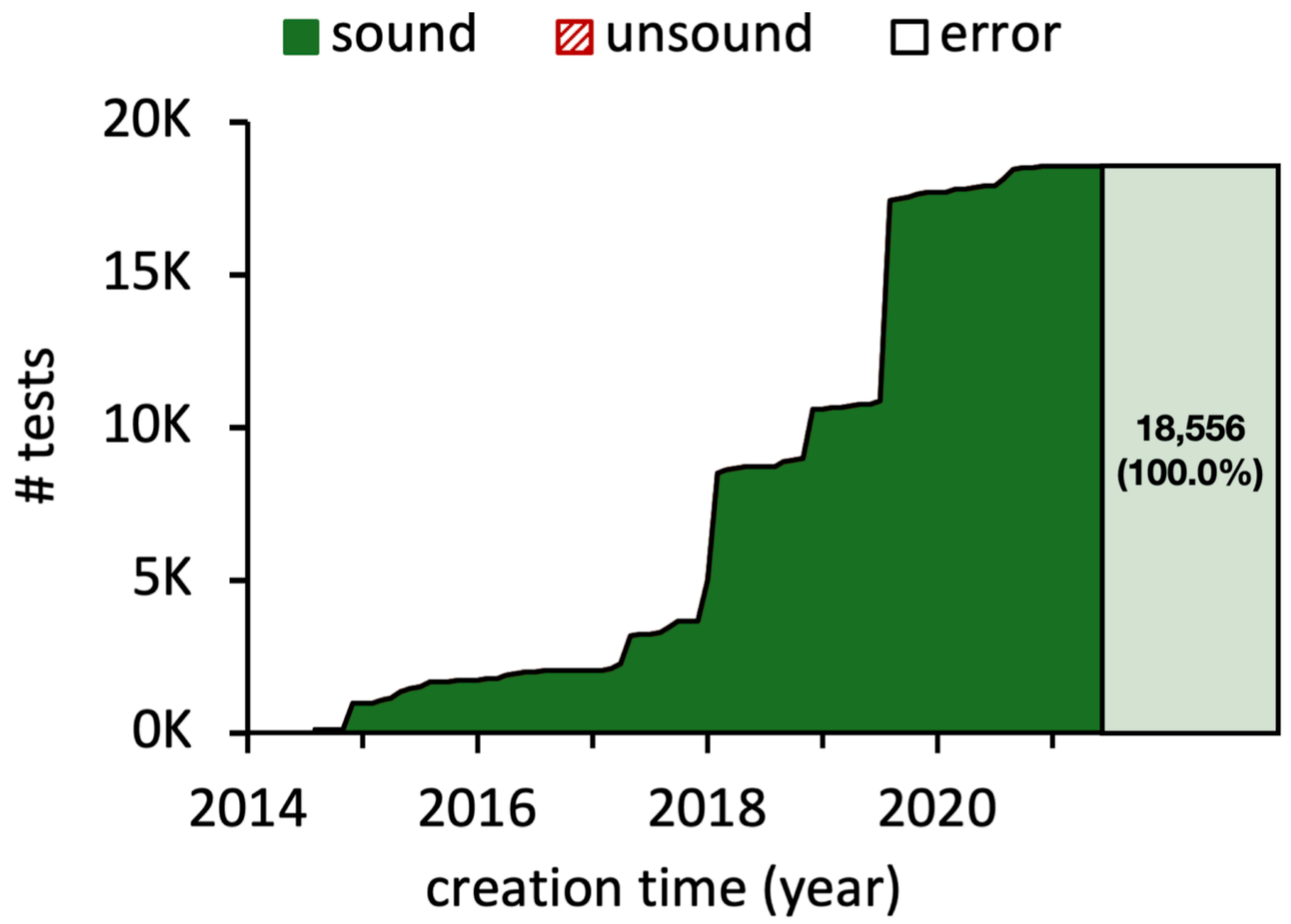
(b) The analysis performance



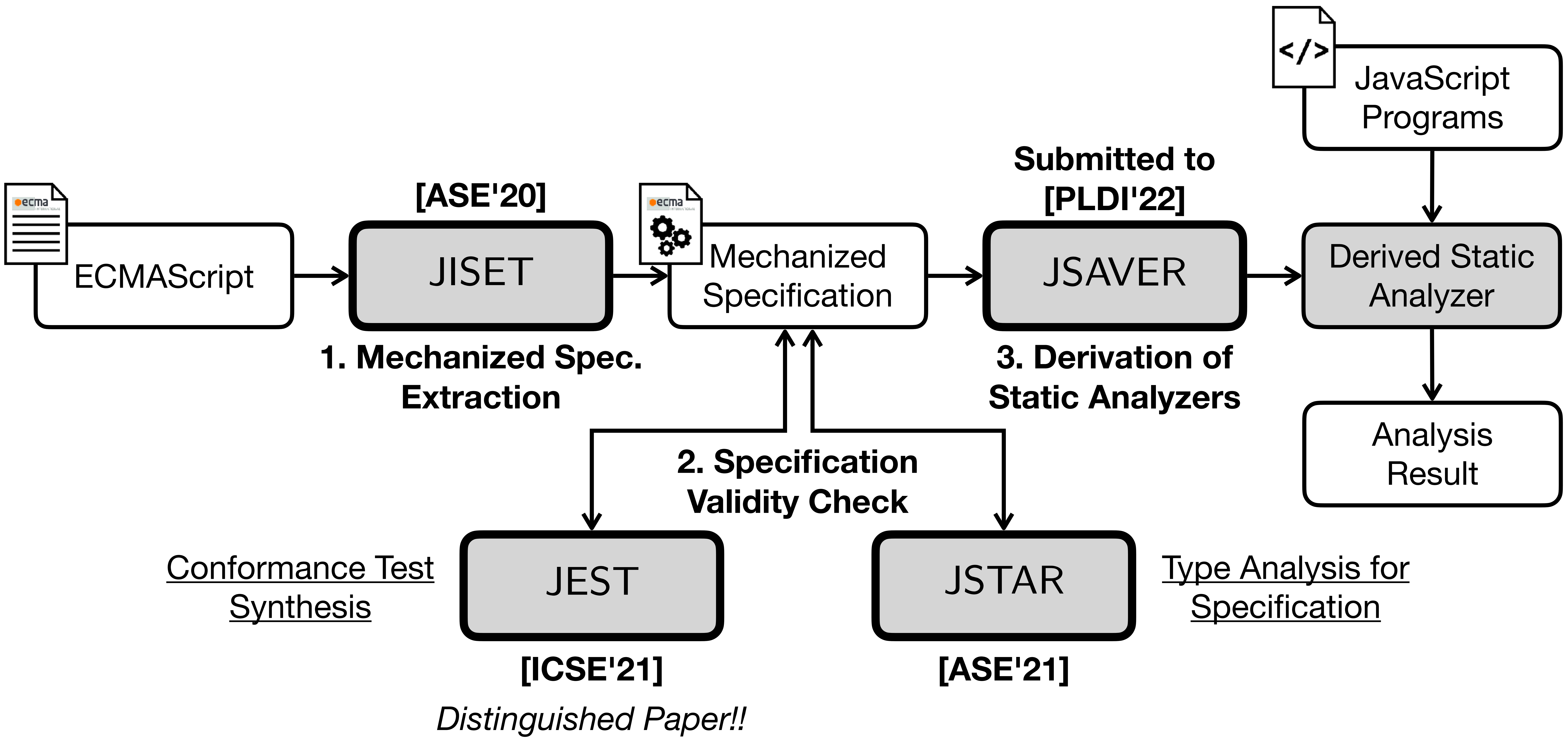
(a) Analysis results of TAJS



(b) Analysis results of SAFE



(c) Analysis results of JSA_{ES12}



ECMAScript
[ASE'20]
JISET
1. Mechanized Spec. Extraction
Mechanized Specification
Submitted to [PLDI'22]
JSAVER
3. Derivation of Static Analyzers
JavaScript Programs
Derived Static Analyzer
Analysis Result
2. Specification Validity Check
Conformance Test Synthesis
JEST
[ICSE'21]
Distinguished Paper!!
JSTAR
[ASE'21]
Type Analysis for Specification