PLRG

Programming Language Research Group

Towards Co-evolution of JavaScript Specification and Tools

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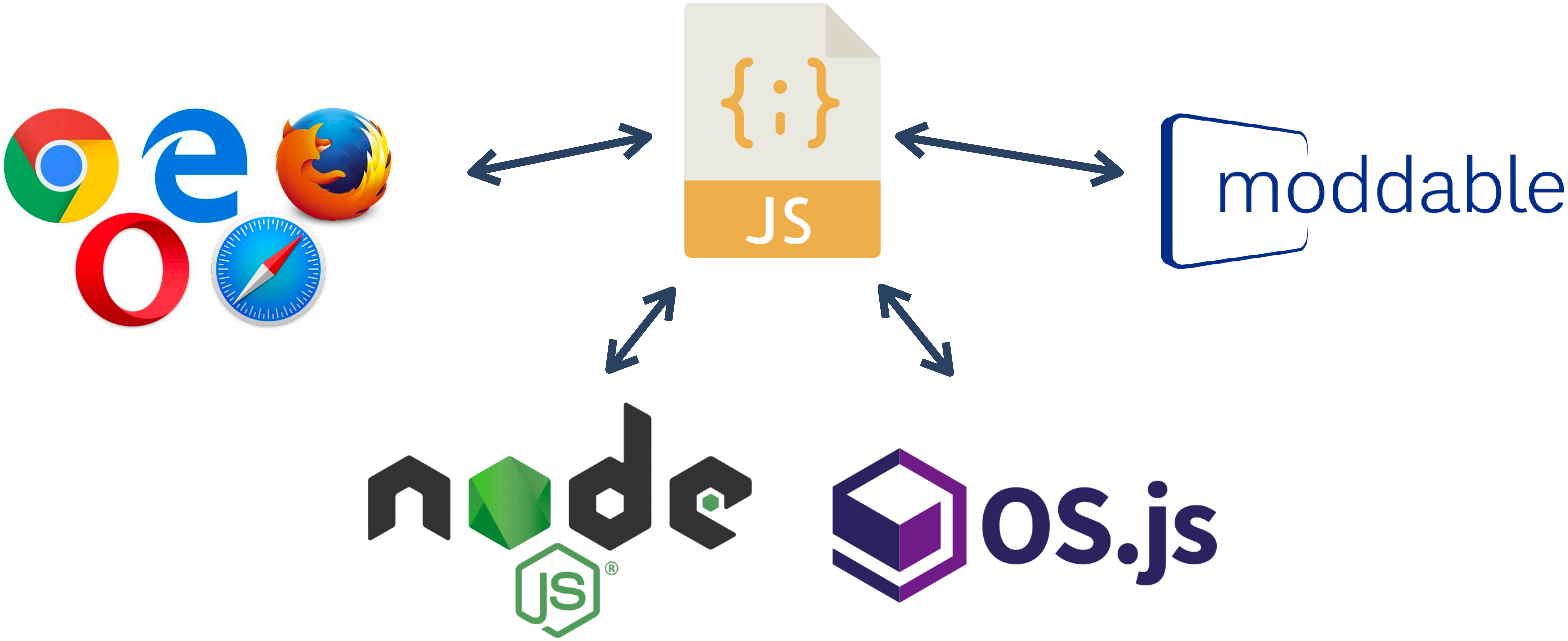
PLRG @ KAIST

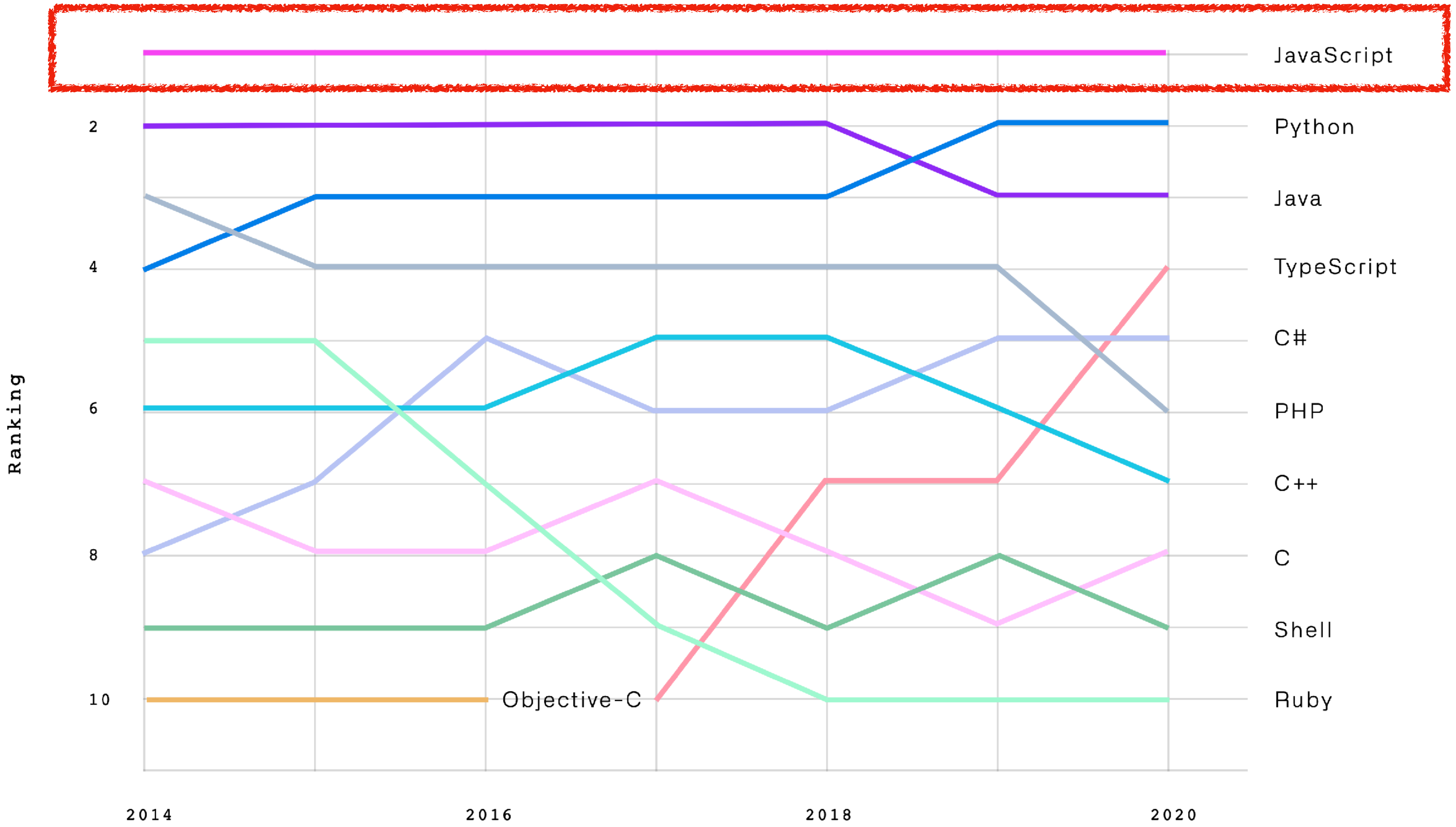
Programming Systems Laboratory Seminar

June 28, 2021

JavaScript is Everywhere



JavaScript is Dominating



https://octoverse.github.com/

JavaScript Complex Semantics

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

Always return `false`?

JavaScript Complex Semantics

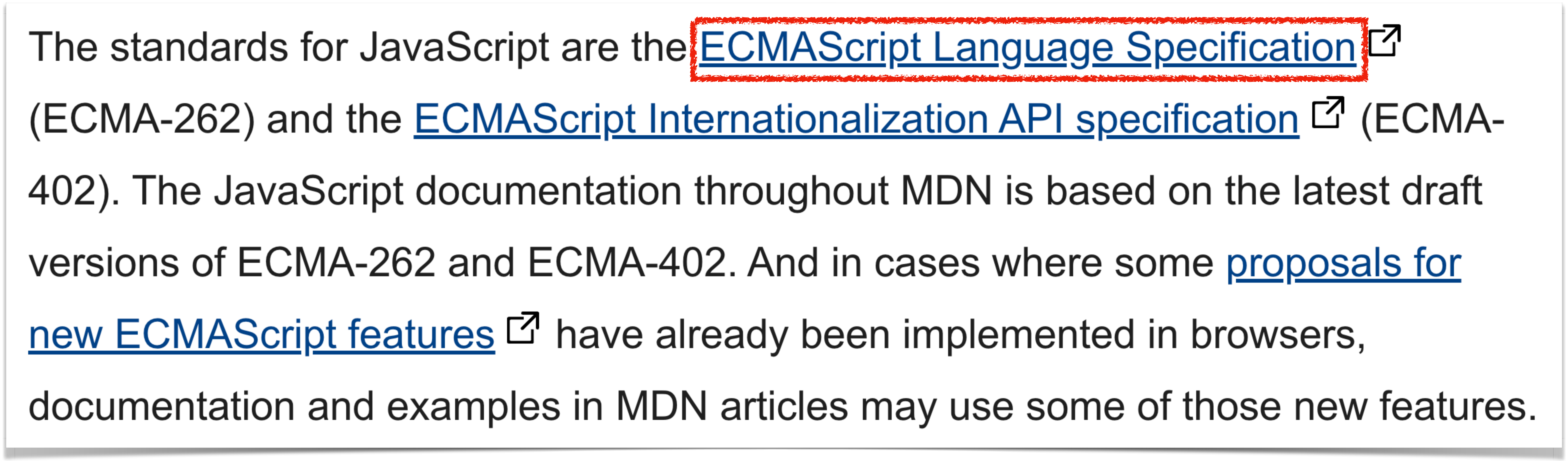
```
function f(x) { return x == !x; }
```

Always return `false`?

NO!!

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

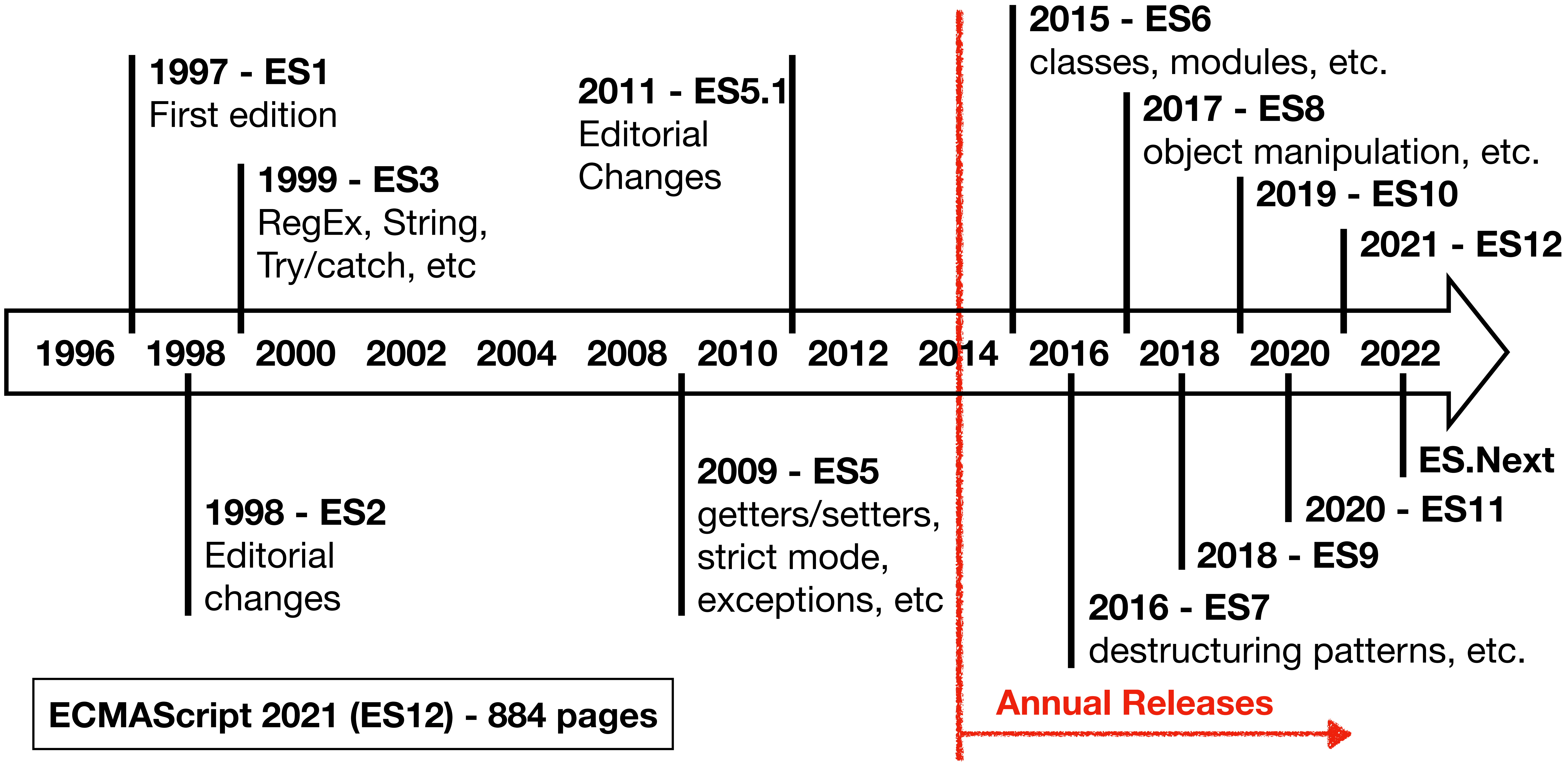
ECMAScript: JavaScript Specification



The standards for JavaScript are the ECMAScript Language Specification (ECMA-262) and the ECMAScript Internationalization API specification (ECMA-402). The JavaScript documentation throughout MDN is based on the latest draft versions of ECMA-262 and ECMA-402. And in cases where some proposals for new ECMAScript features have already been implemented in browsers, documentation and examples in MDN articles may use some of those new features.

https://developer.mozilla.org/en-US/docs/Web/JavaScript

Fast Evolving JavaScript



1996 1998 2000 2002 2004 2008 2010 2012 2014 2016 2018 2020 2022

1997 - ES1
First edition

1998 - ES2
Editorial
changes

1999 - ES3
RegEx, String,
Try/catch, etc

2009 - ES5
getters/setters,
strict mode,
exceptions, etc

2011 - ES5.1
Editorial
Changes

2015 - ES6
classes, modules, etc.

2016 - ES7
destructuring patterns, etc.

2017 - ES8
object manipulation, etc.

2018 - ES9

2019 - ES10

2020 - ES11

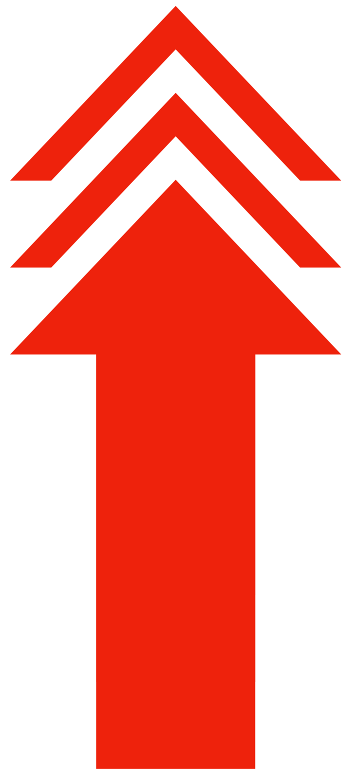
2021 - ES12

ES.Next

Annual Releases

ECMAScript 2021 (ES12) - 884 pages

JavaScript Specification and Tools

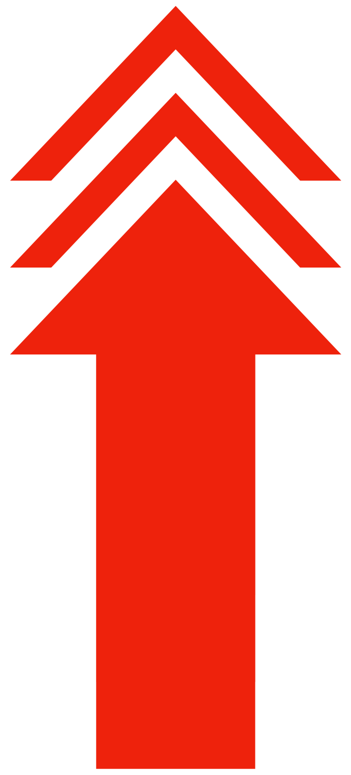


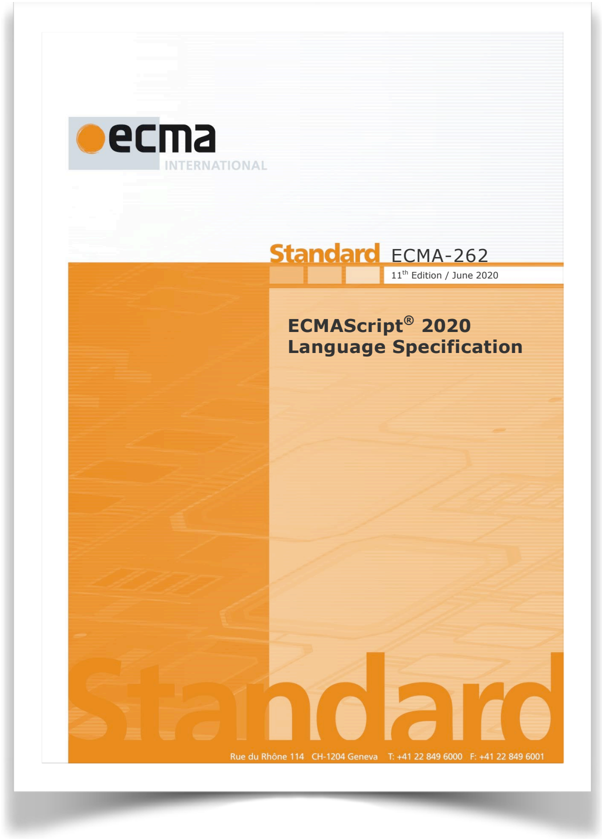
ECMAScript

Parser	Engine
Debugger	Symbolic Executor
Formal Verifier	Static Analyzer

JavaScript Tools

JavaScript Specification and Tools





ecma INTERNATIONAL

Standard ECMA-262

11th Edition / June 2020

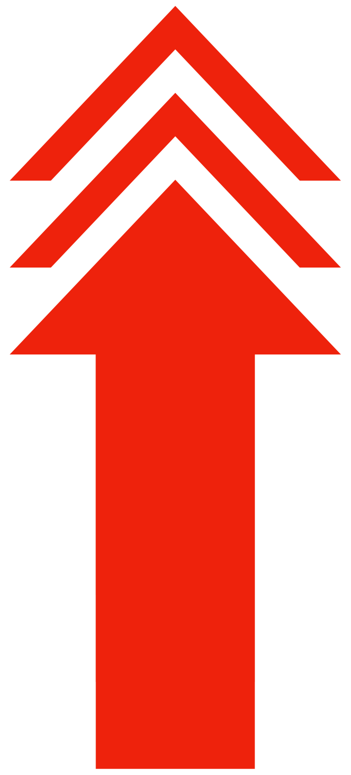
ECMAScript® 2020 Language Specification

Standard

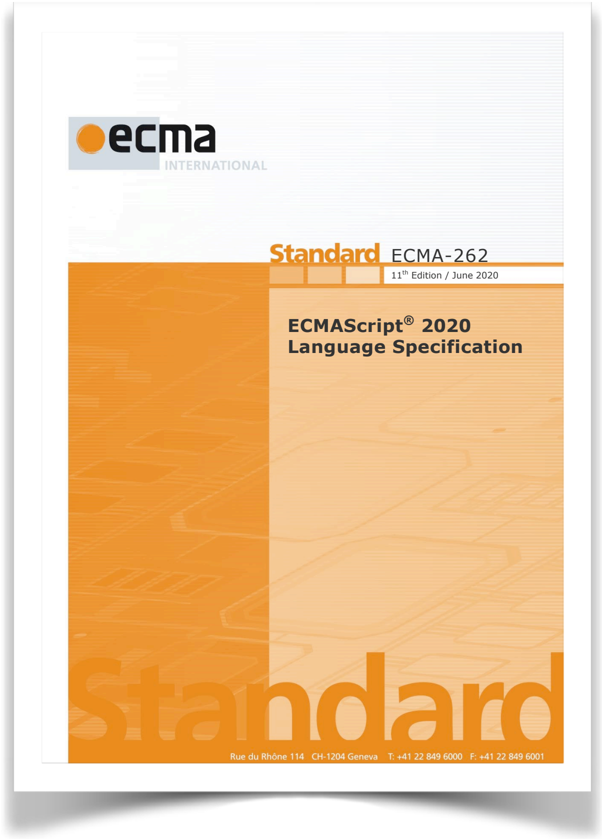
ECMAScript

Parser	Engine
Debugger	Symbolic Executor
Formal Verifier	Static Analyzer

JavaScript Tools



JavaScript Specification and Tools



ECMAScript

Conformance

Parser	Engine
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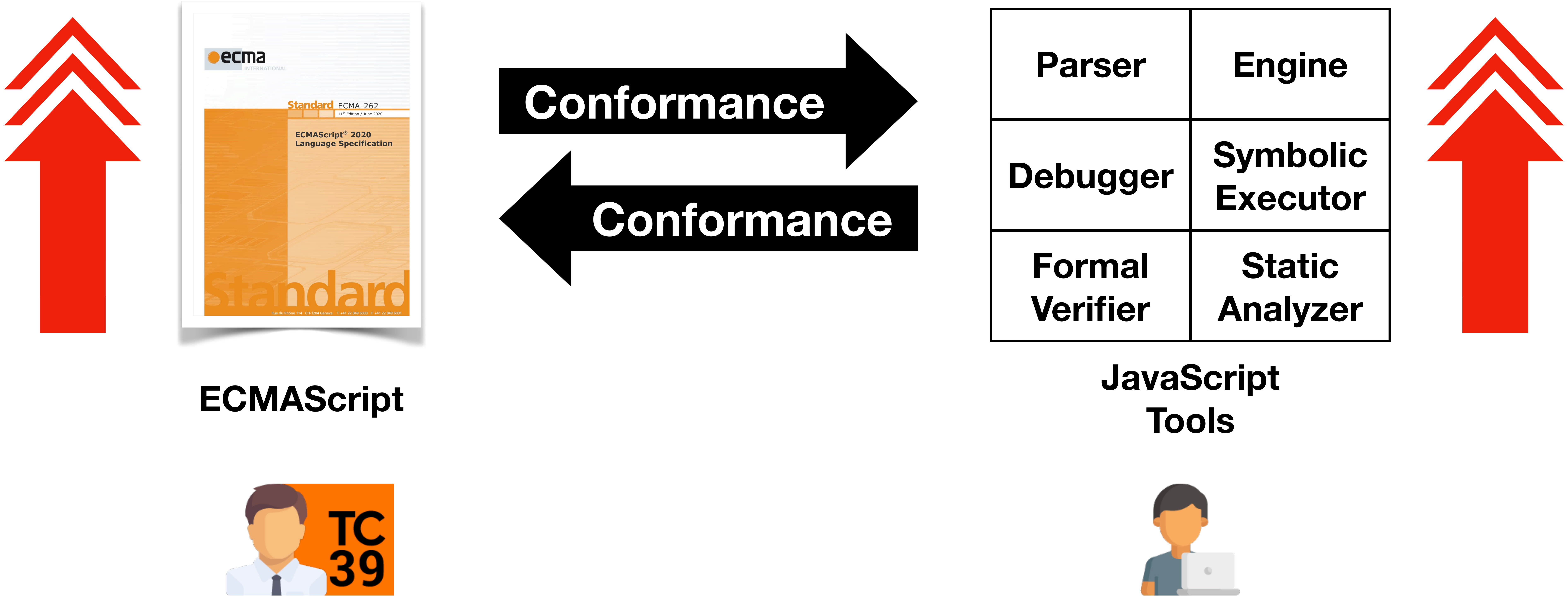
JavaScript Tools

JavaScript Specification and Tools



ECMAScript

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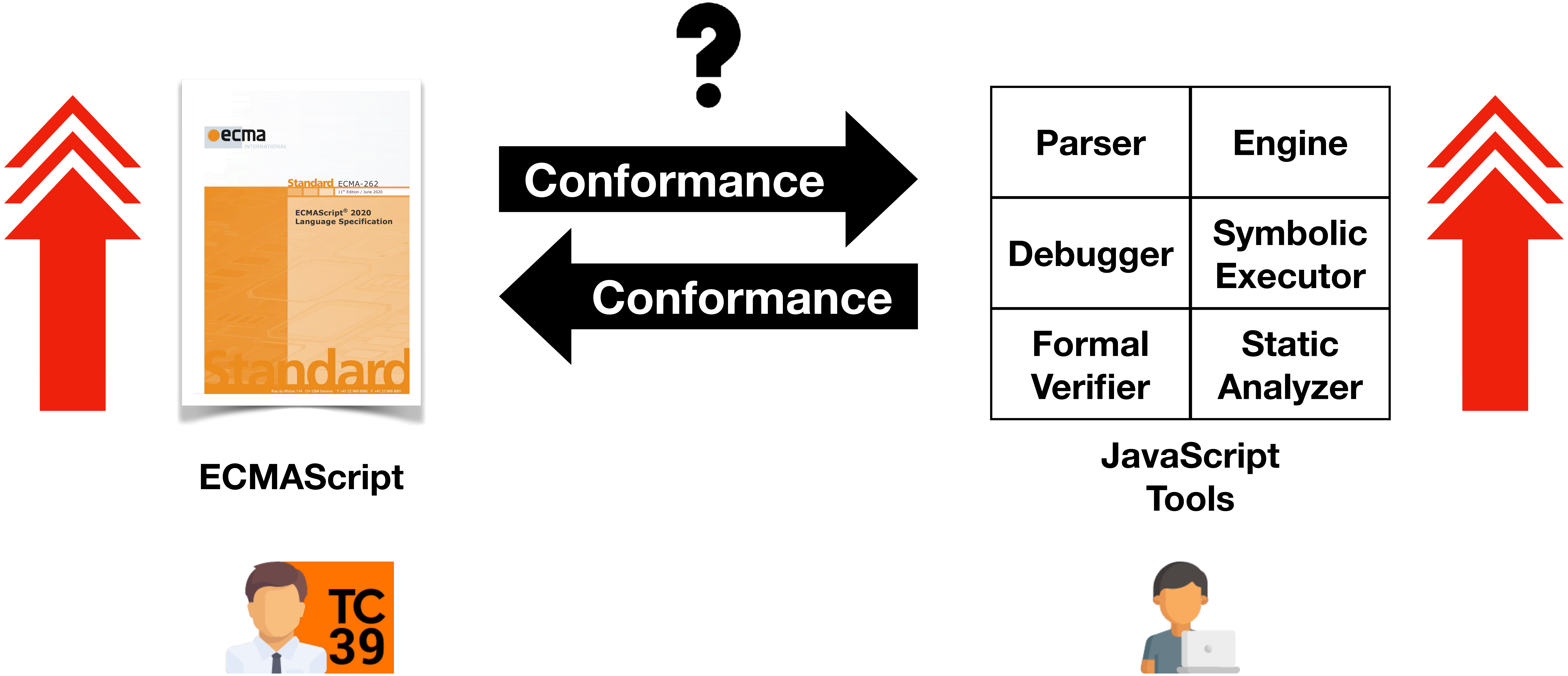
JavaScript Tools

JavaScript Specification and Tools



Conformance

Conformance

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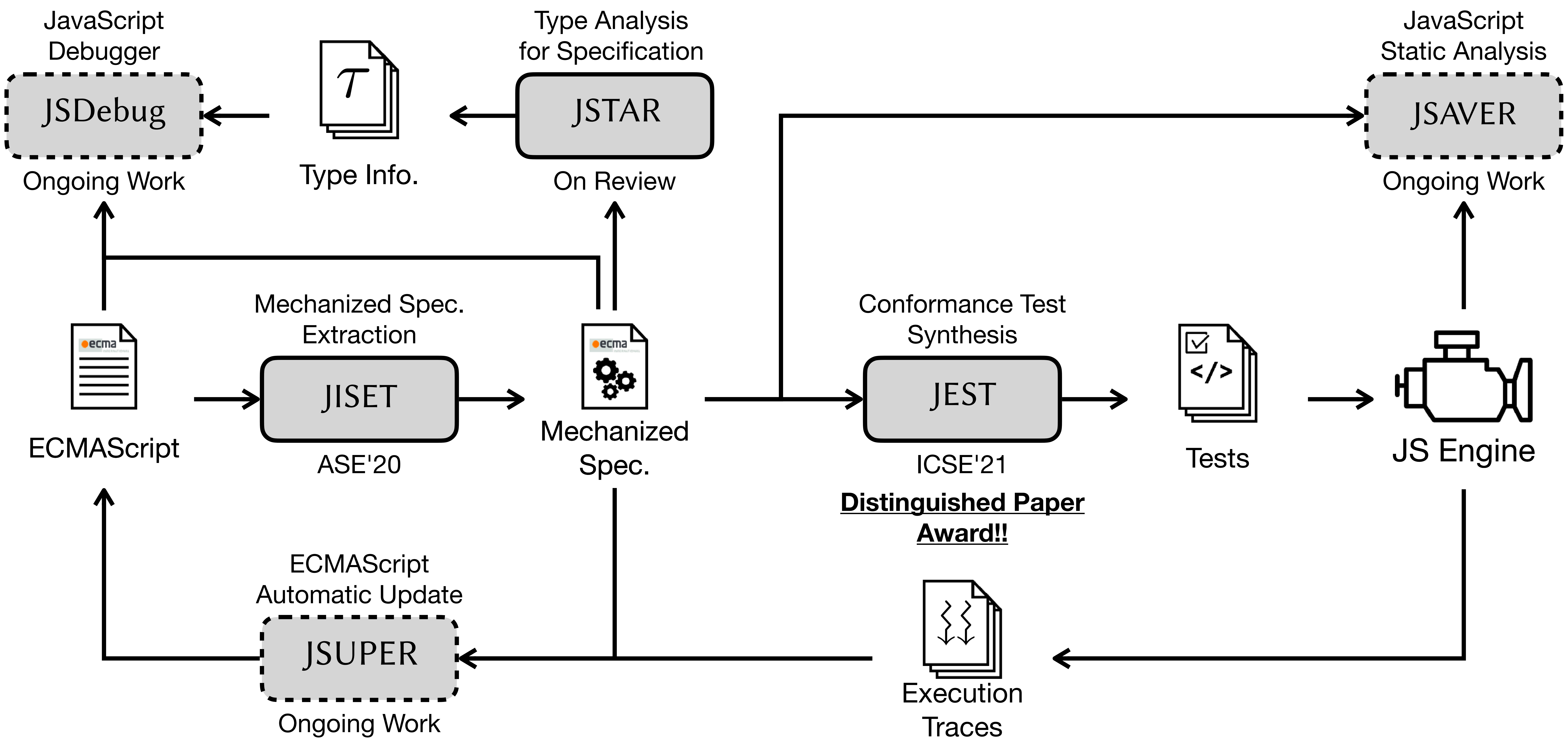
Formal Verifier	Static Analyzer

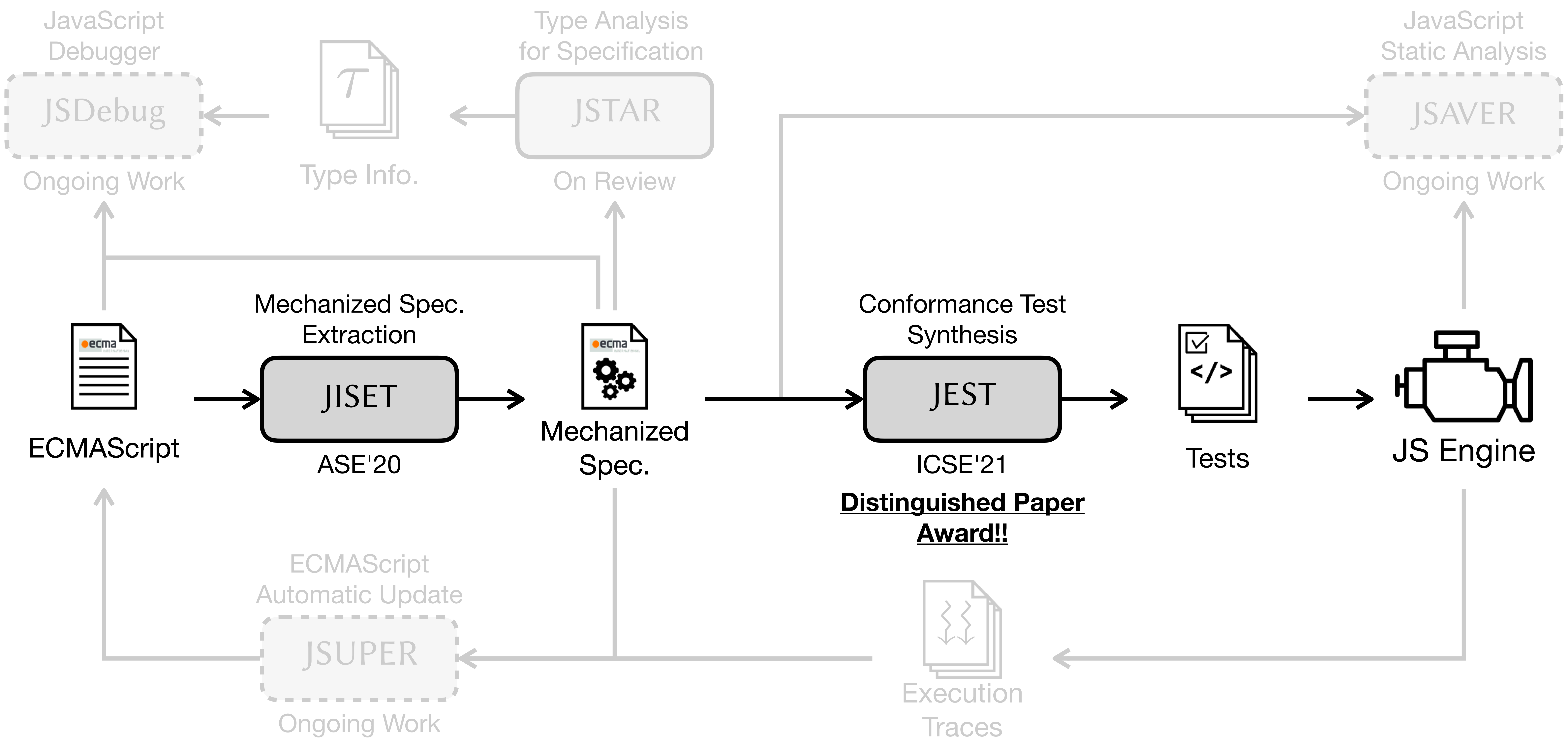
ECMAScript

JavaScript Tools

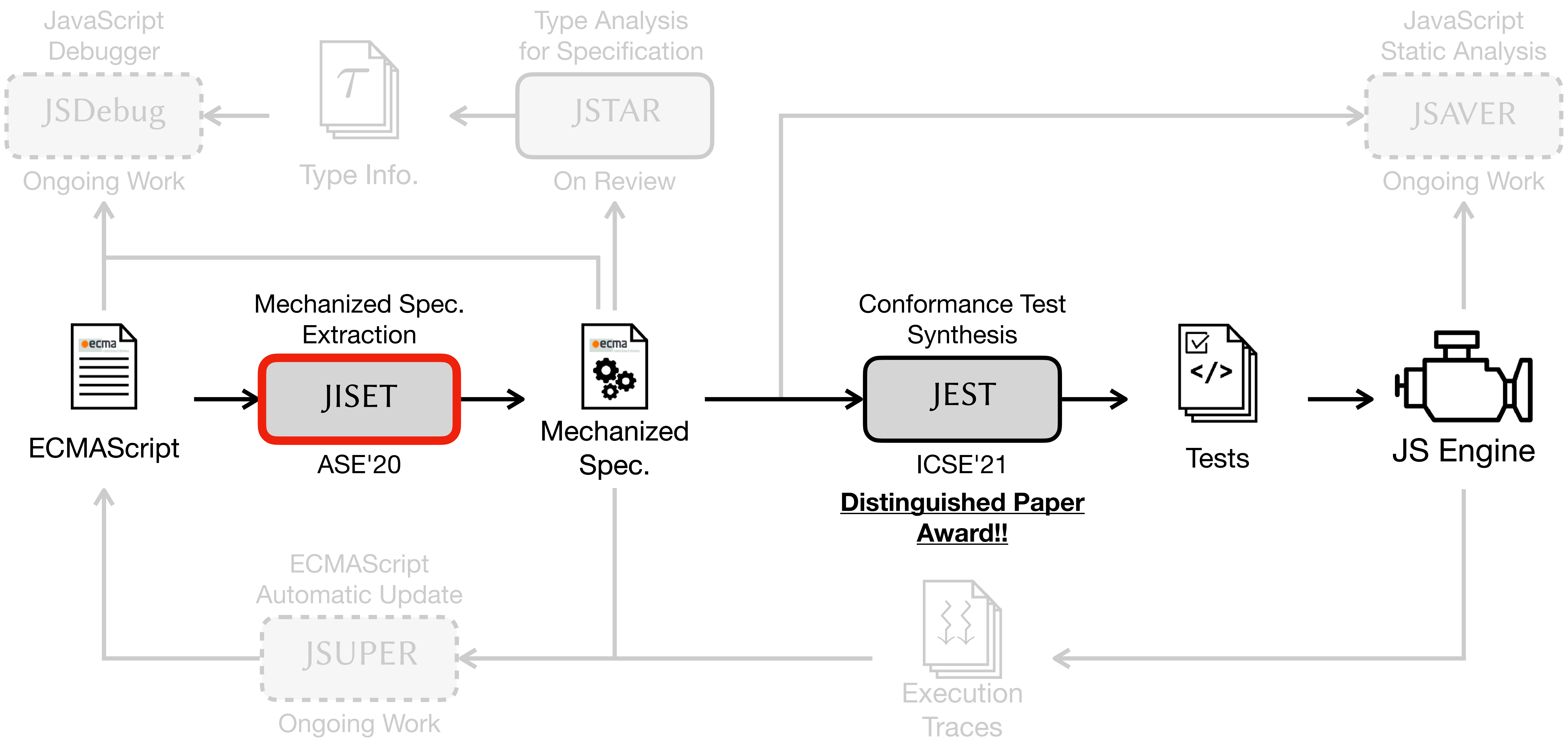
Co-evolution of JavaScript Spec. and Tools



Co-evolution of JavaScript Spec. and Tools

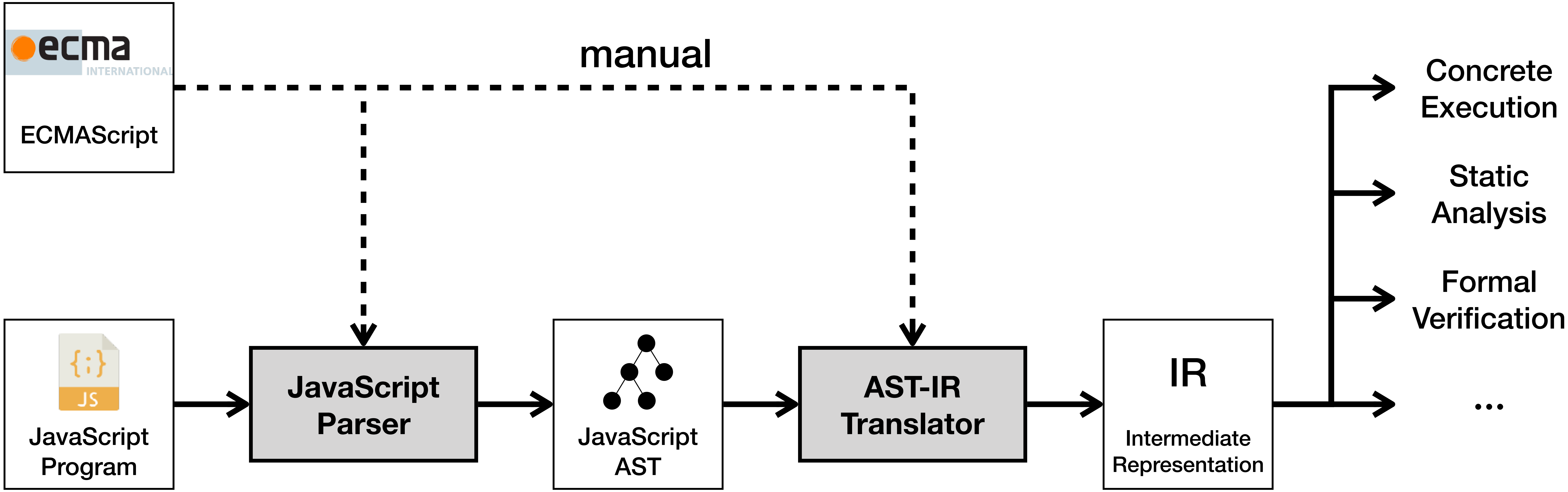


Co-evolution of JavaScript Spec. and Tools

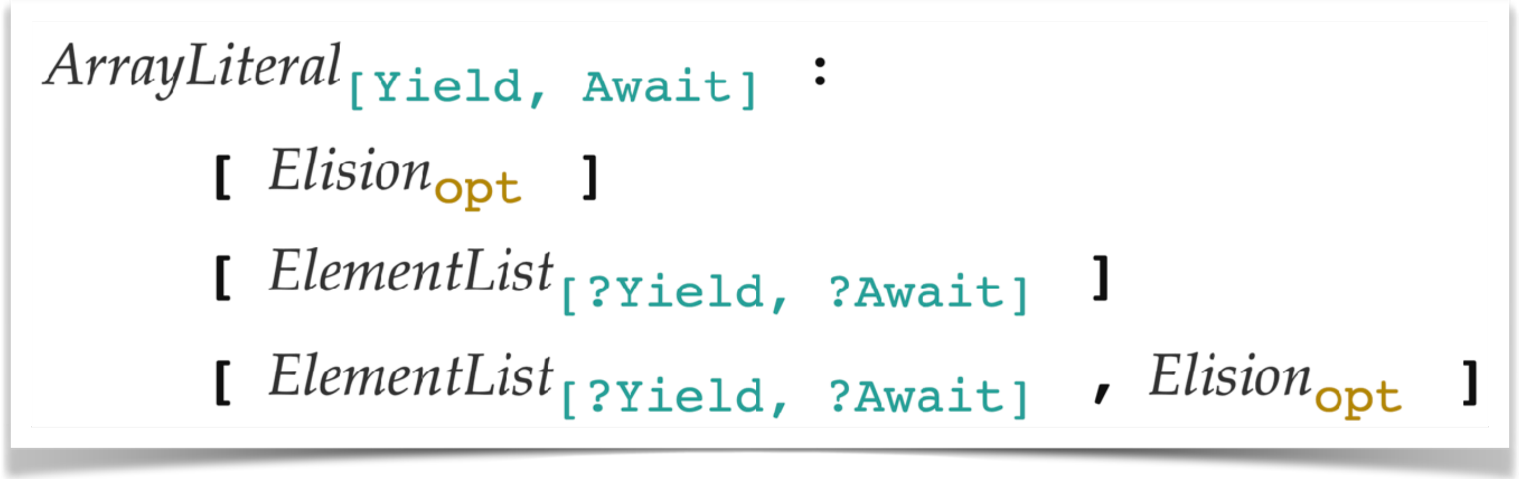


JISET: JavaScript IR-based Semantics Extraction Toolchain [ASE'20]

IR-based Semantics Extraction



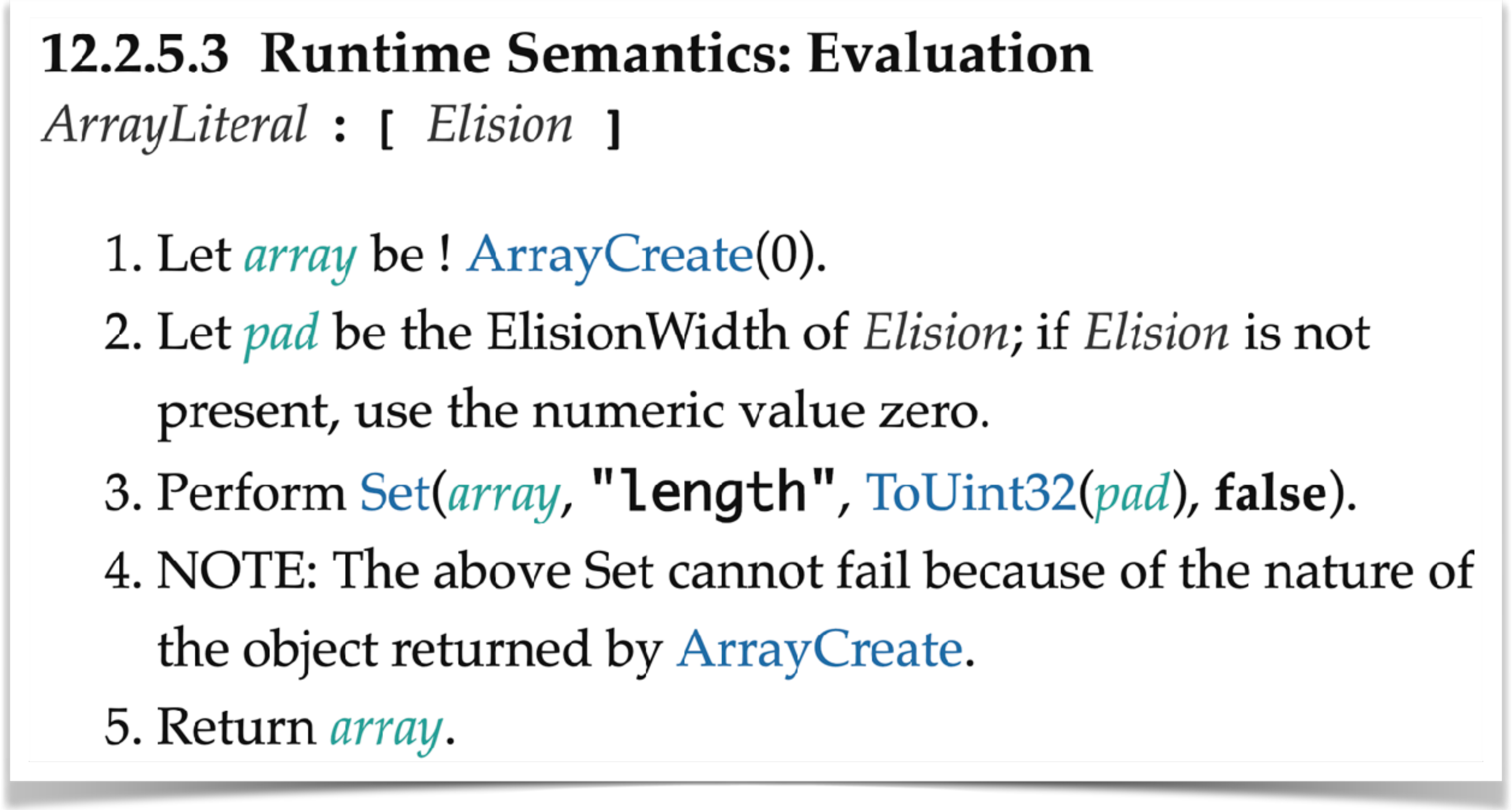
IR-based Semantics Extraction



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

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

The production of *ArrayLiteral* in ES10

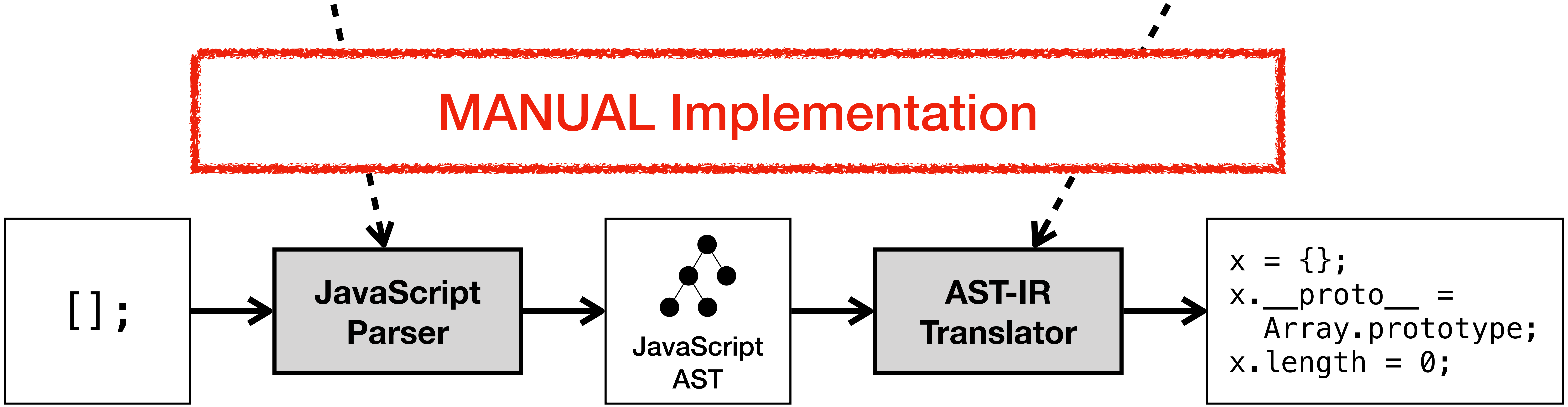


12.2.5.3 Runtime Semantics: Evaluation

ArrayLiteral **: [** *Elision* **]**

1. Let *array* be ! ArrayCreate(0).
2. Let *pad* be the ElisionWidth of *Elision*; if *Elision* is not present, use the numeric value zero.
3. Perform Set(*array*, `"length"`, ToUint32(*pad*), **false**).
4. NOTE: The above Set cannot fail because of the nature of the object returned by ArrayCreate.
5. Return *array*.

The Evaluation algorithm for the first alternative of *ArrayLiteral* in ES10



MANUAL Implementation

`[];`

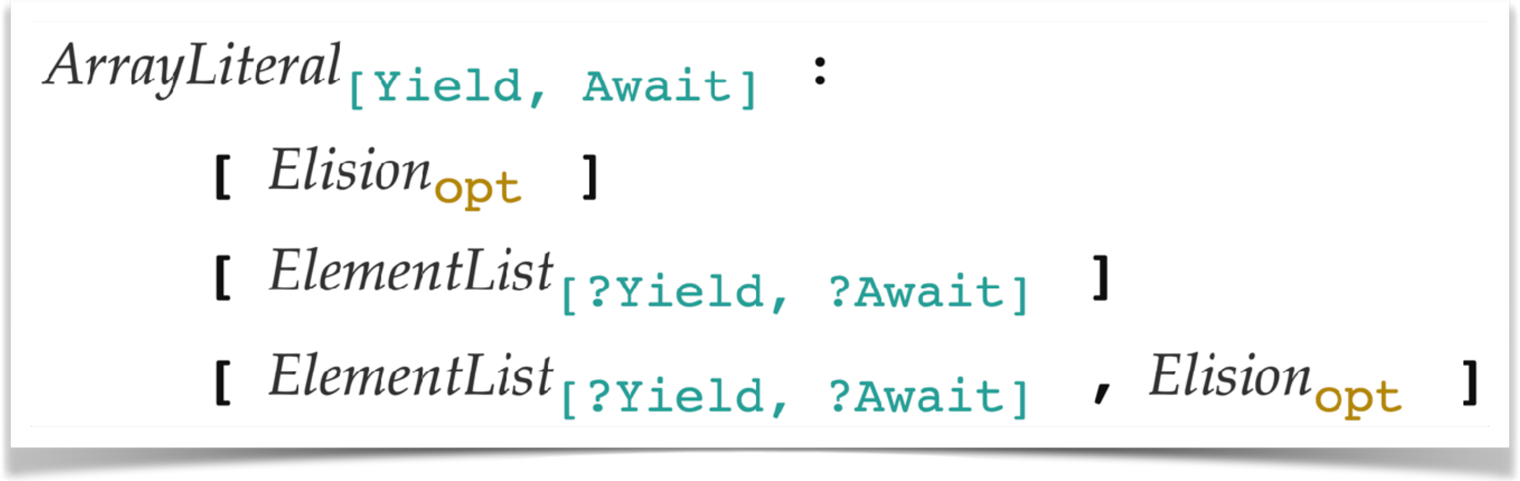
JavaScript Parser

JavaScript AST

AST-IR Translator

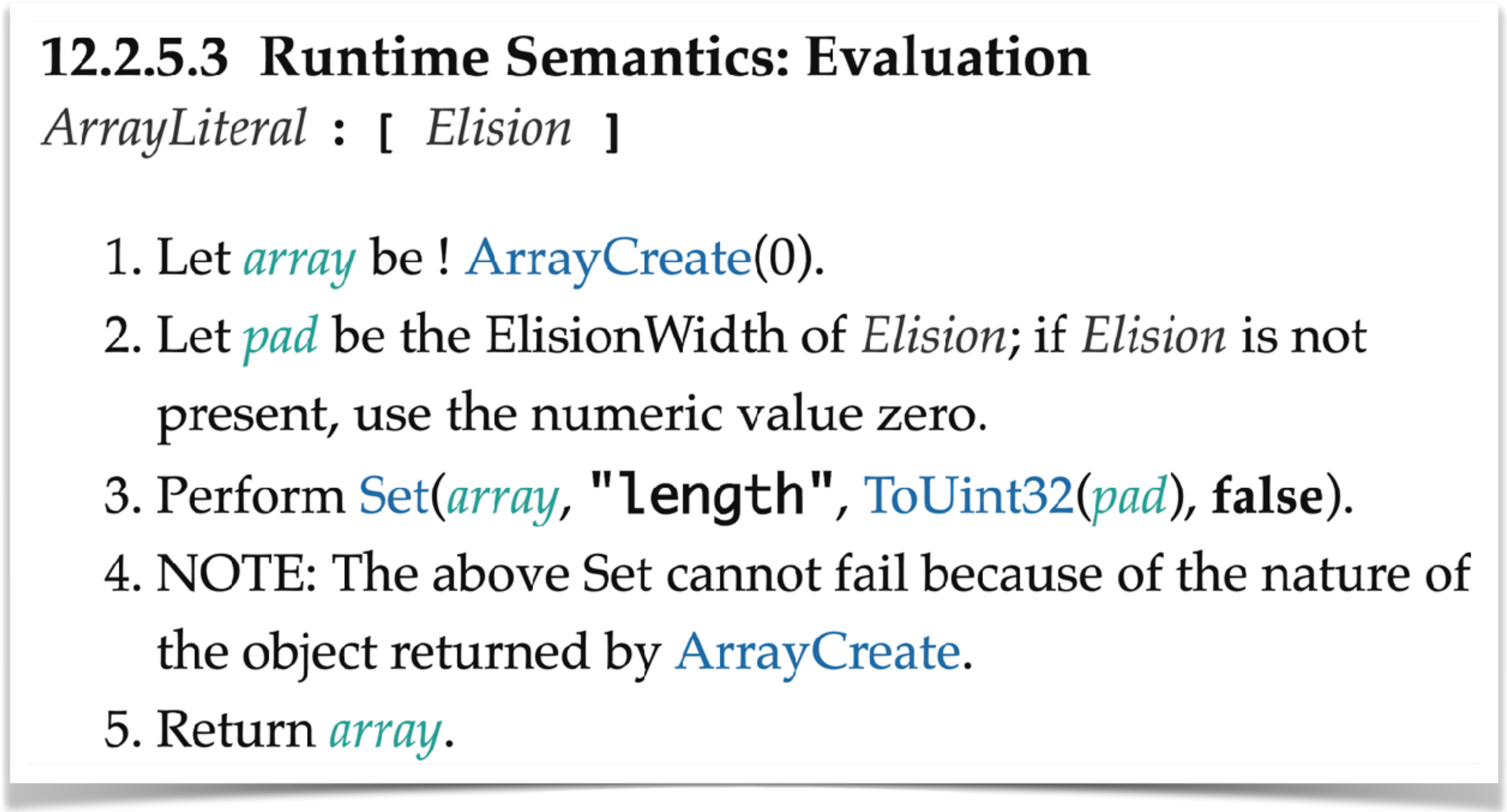
```
x = {};
x.__proto__ =
  Array.prototype;
x.length = 0;
```

Our Approach



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

The production of *ArrayLiteral* in ES10



12.2.5.3 Runtime Semantics: Evaluation

ArrayLiteral : [*Elision*]

1. Let *array* be ! ArrayCreate(0).
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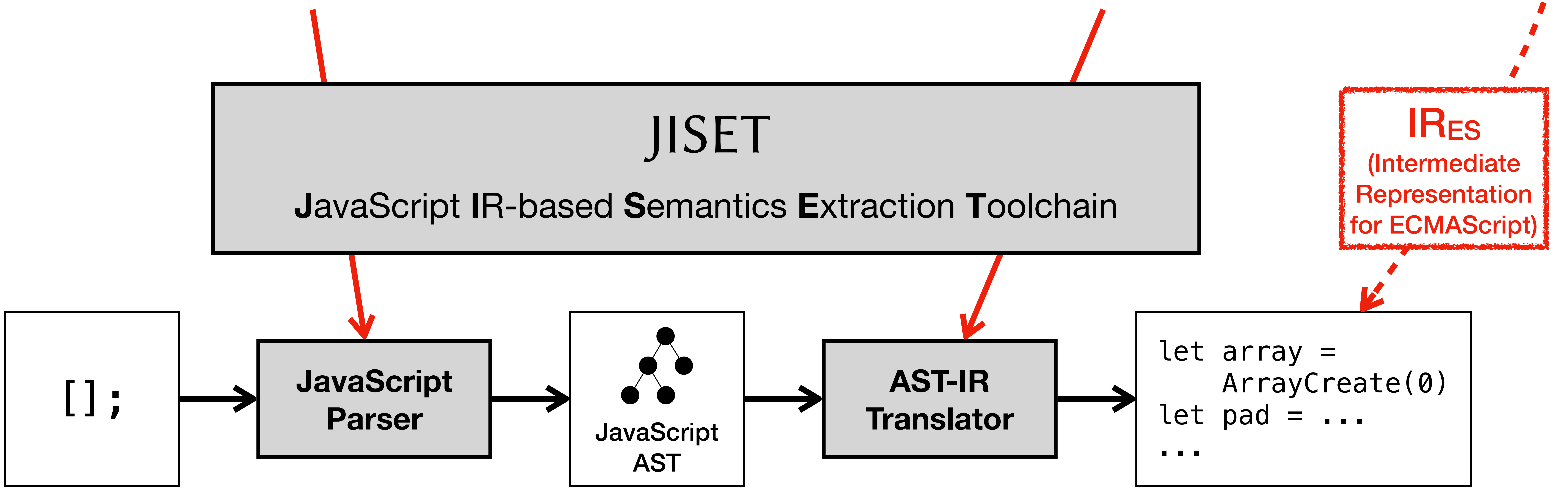
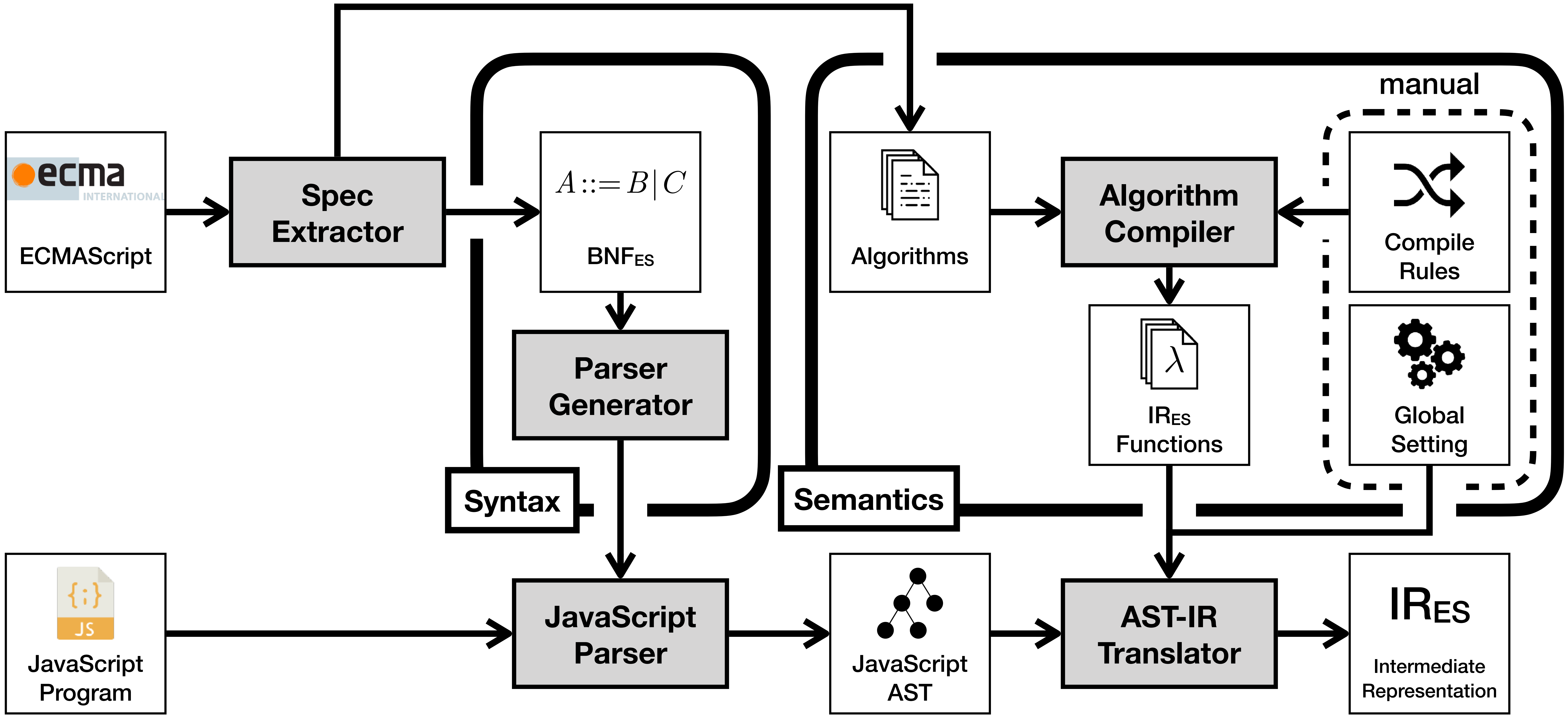
The Evaluation **algorithm for the first alternative of** *ArrayLiteral* **in ES10**

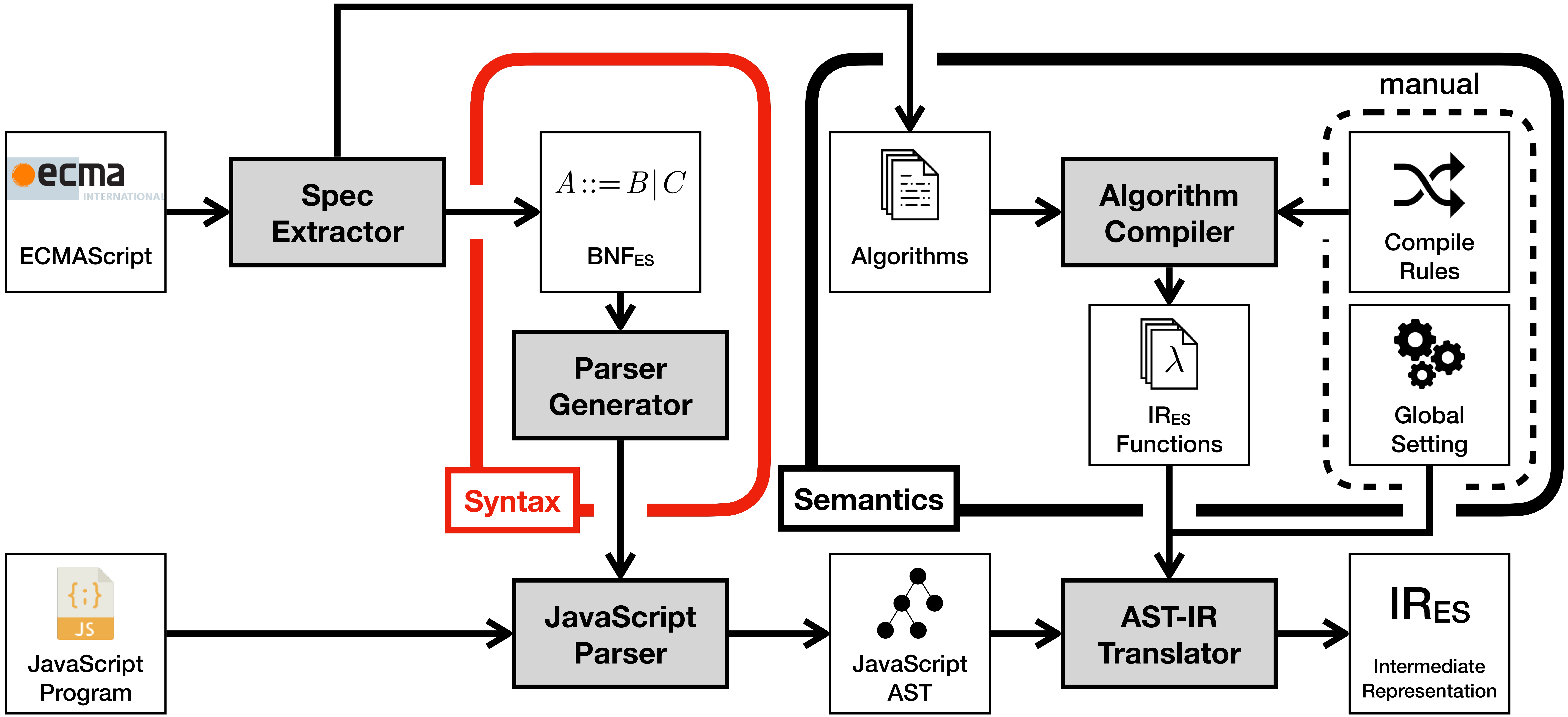

JISET
JavaScript IR-based Semantics Extraction Toolchain
IRES
(Intermediate Representation for ECMAScript)
[];
JavaScript Parser
JavaScript AST
AST-IR Translator

```
let array =
    ArrayCreate(0)
let pad = ...
...
```

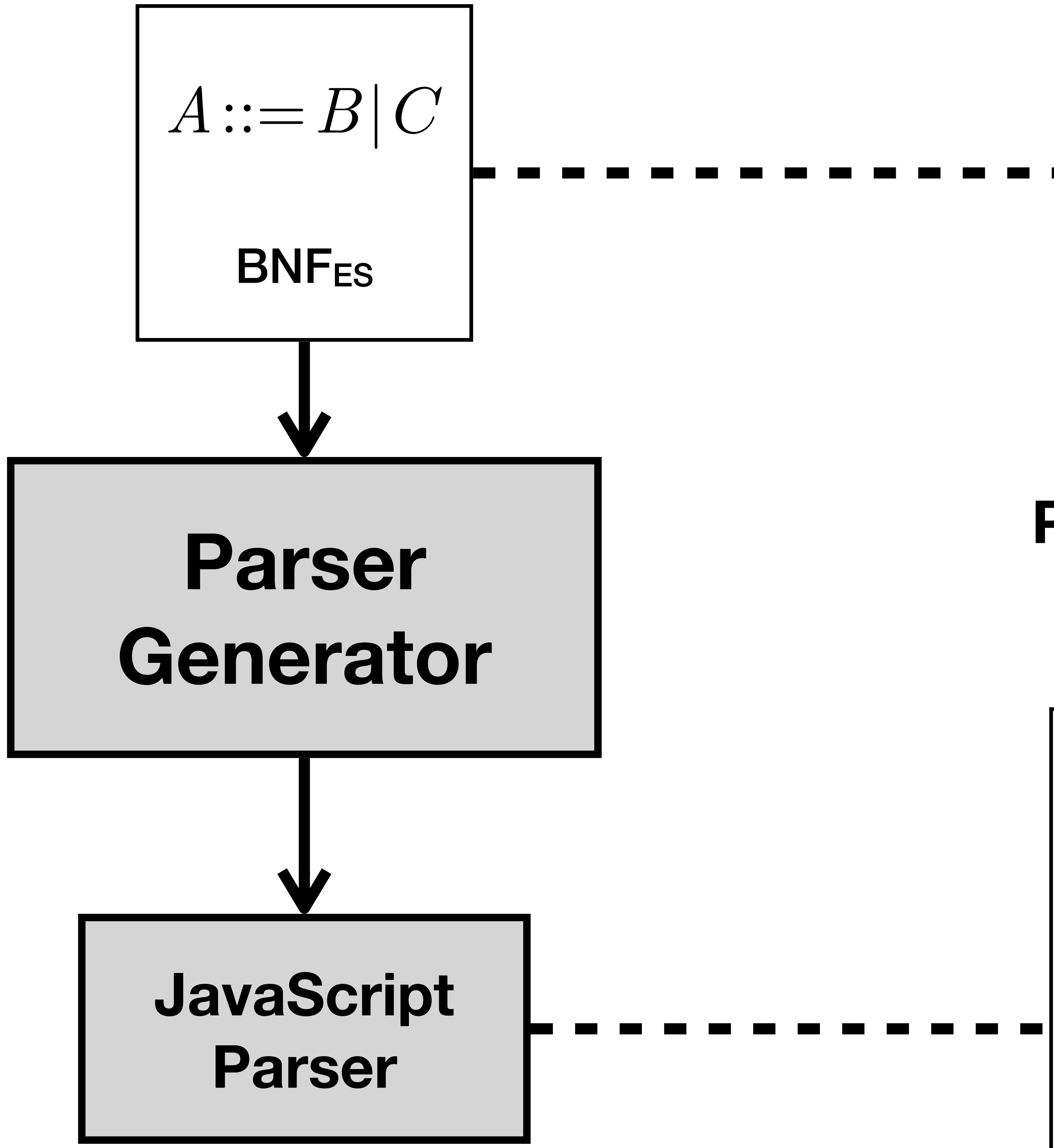
Overall Structure of JISET

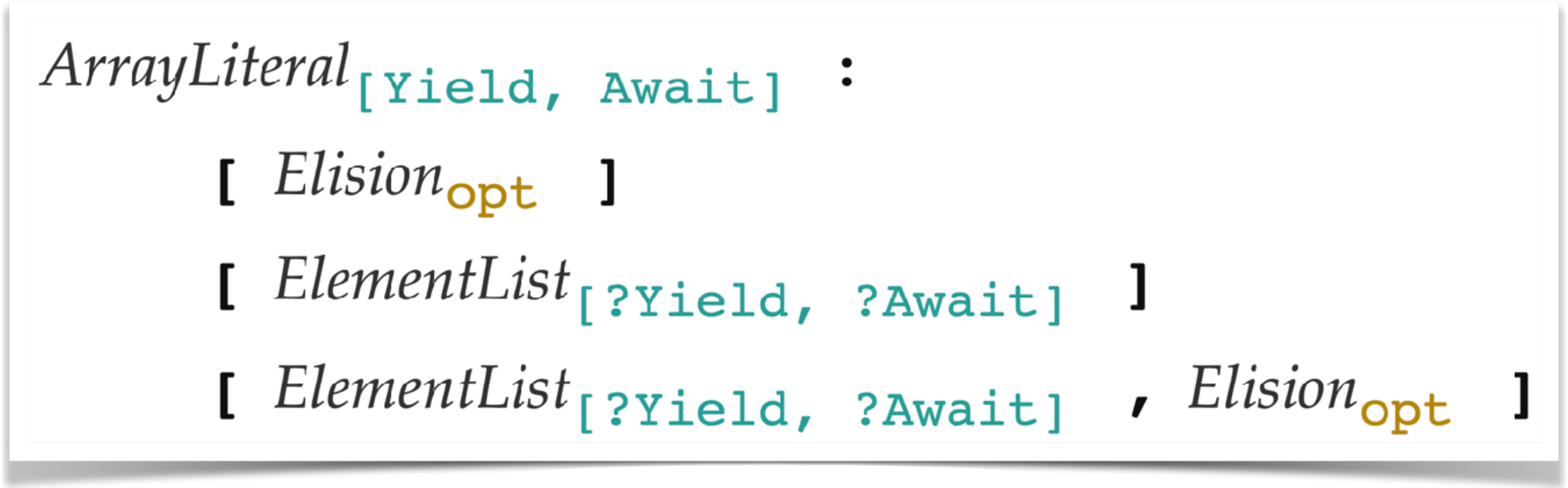


Overall Structure of JISET



Syntax - Parser Synthesis




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

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

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

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

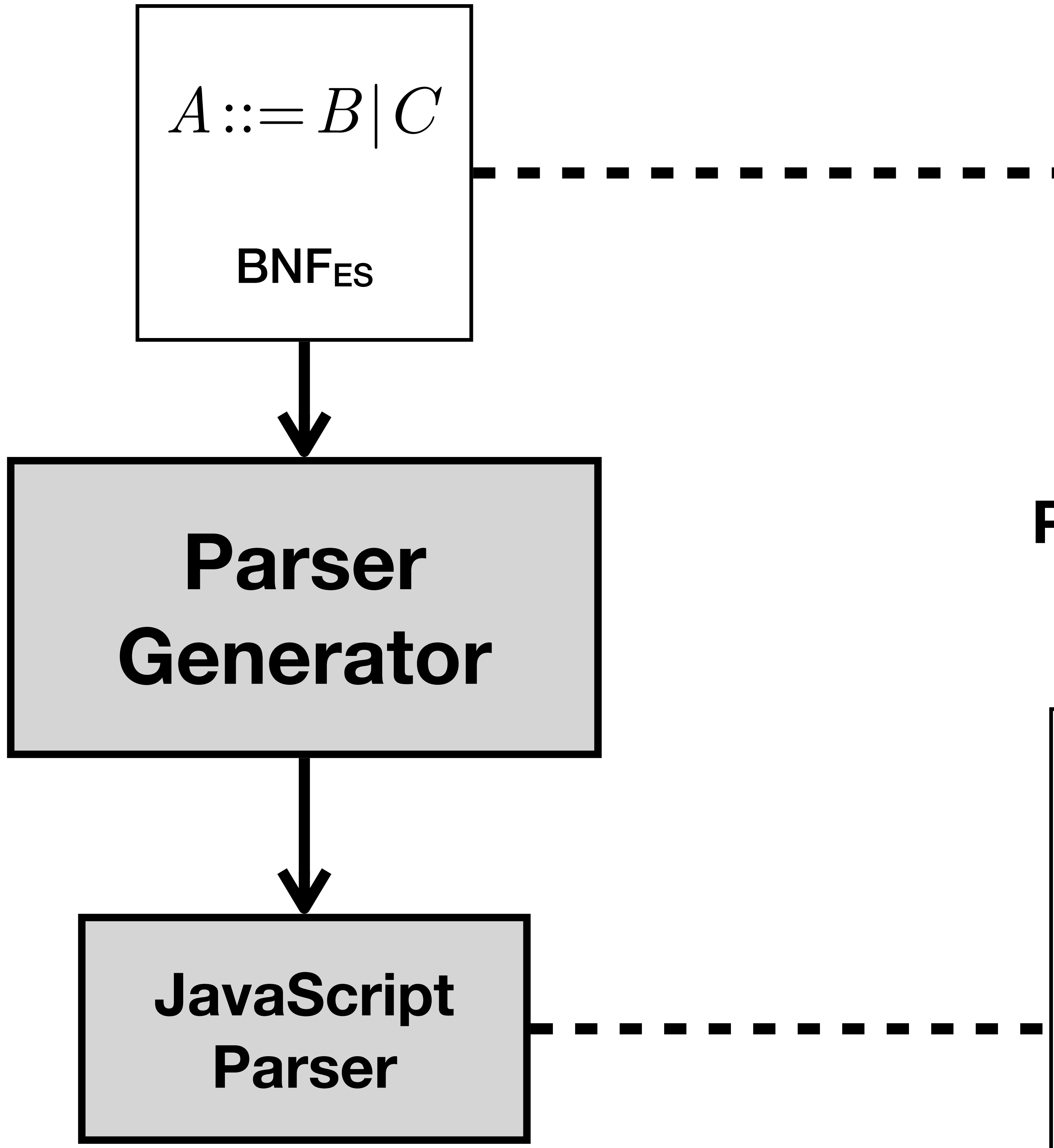
The production of *ArrayLiteral* in ES10

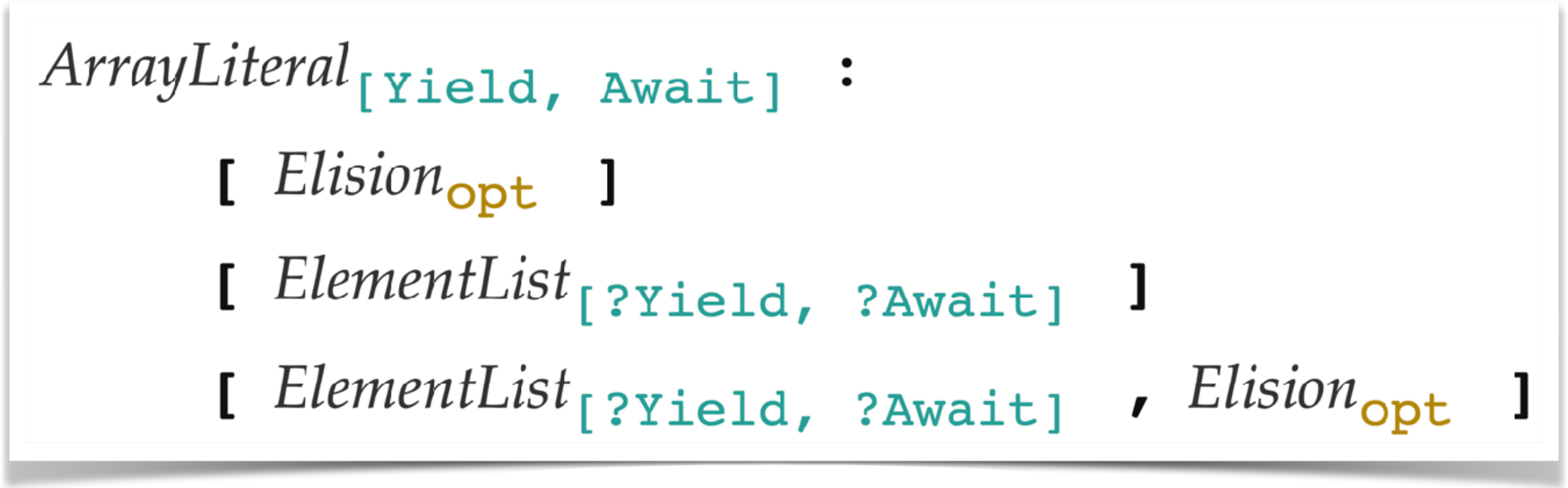
Parsing Expression Grammar (PEG)

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

The generated parser for *ArrayLiteral* in ES10

Syntax - Parser Synthesis





$ArrayLiteral_{[\mathtt{Yield,\ Await}]}$:

[$Elision_{\mathtt{opt}}$]

[$ElementList_{[\mathtt{?Yield,\ ?Await}]}$]

[$ElementList_{[\mathtt{?Yield,\ ?Await}]}$, $Elision_{\mathtt{opt}}$]

The production of *ArrayLiteral* in ES10

Parsing Expression Grammar (PEG) + **Lookahead Parsing**

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

The generated parser for *ArrayLiteral* in ES10

Syntax - Lookahead Parsing

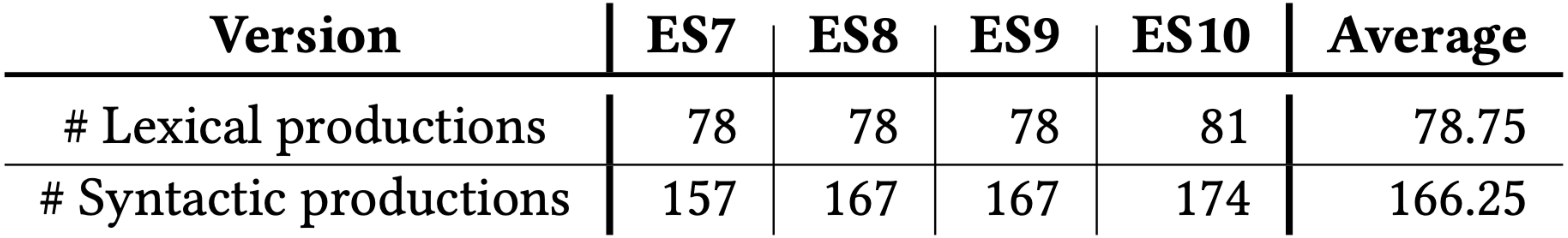
$$\begin{aligned}
\mathbf{first}_\alpha(s_1 \cdots s_n) &= \mathbf{first}_s(s_1) \mathrel{:+} \mathbf{first}_s(s_2 \cdots s_n) \\
&\quad \text{where } x \mathrel{:+} y = \begin{cases} x \cup y & \text{if } \circ \in x \\ x & \text{otherwise} \end{cases} \\
\mathbf{first}_s(\epsilon) &= \{\circ\} \\
\mathbf{first}_s(\mathsf{a})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

Algorithm for first tokens of BNF$_{\text{ES}}$

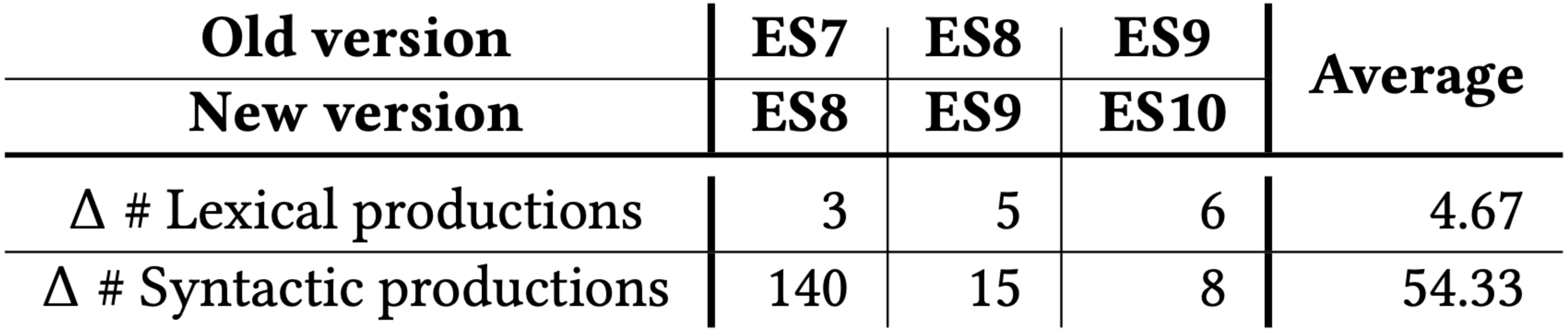
Algorithm for lookahead parsing

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

Syntax - Evaluation



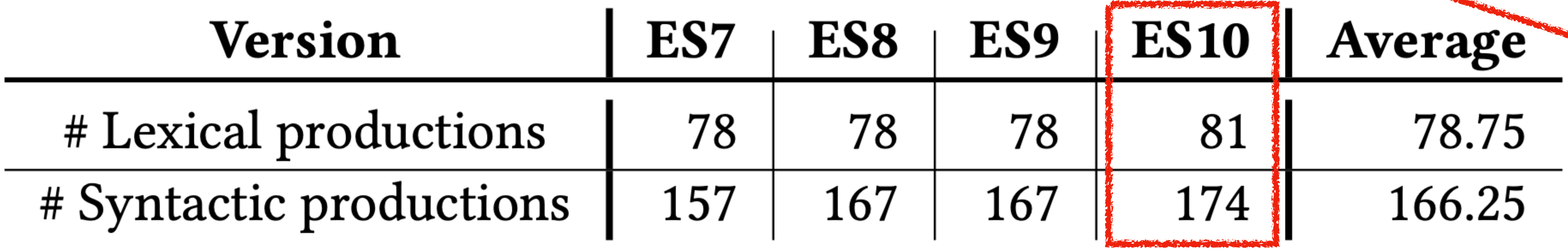
Version	ES7	ES8	ES9	ES10	Average
# Lexical productions	78	78	78	81	78.75
# Syntactic productions	157	167	167	174	166.25



Old version	ES7	ES8	ES9	Average
New version	ES8	ES9	ES10	
Δ # Lexical productions	3	5	6	4.67
Δ # Syntactic productions	140	15	8	54.33

Syntax - Evaluation

All Success!!



Version	ES7	ES8	ES9	ES10	Average
# Lexical productions	78	78	78	81	78.75
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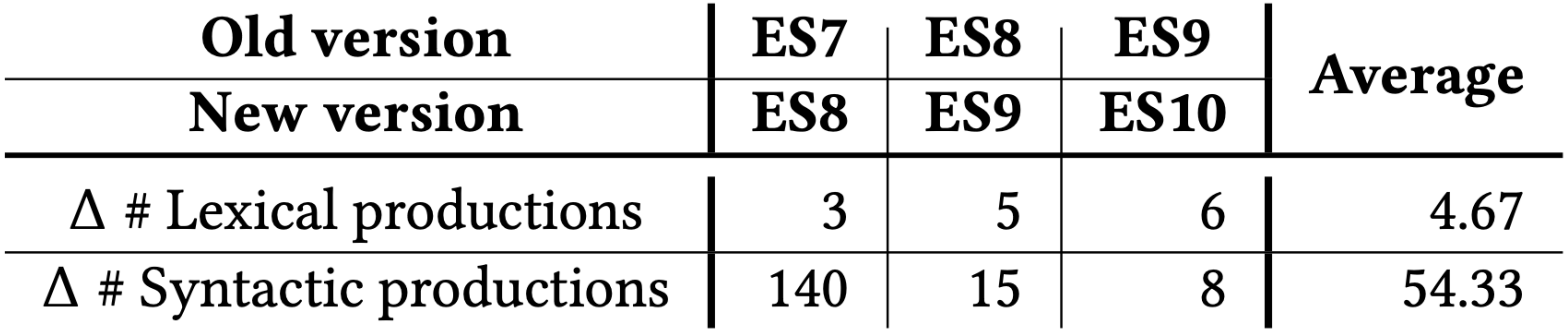
Pass all parsing tests in Test262



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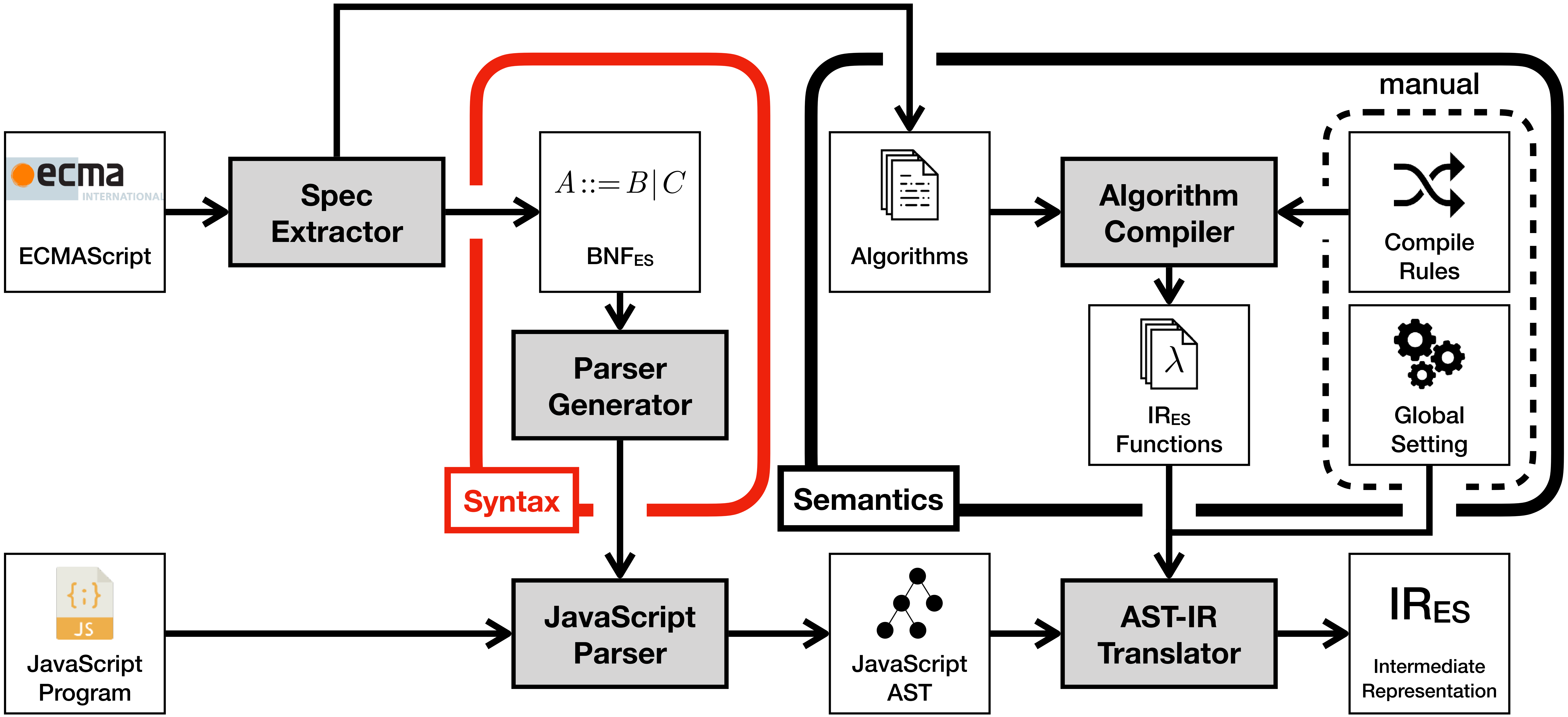

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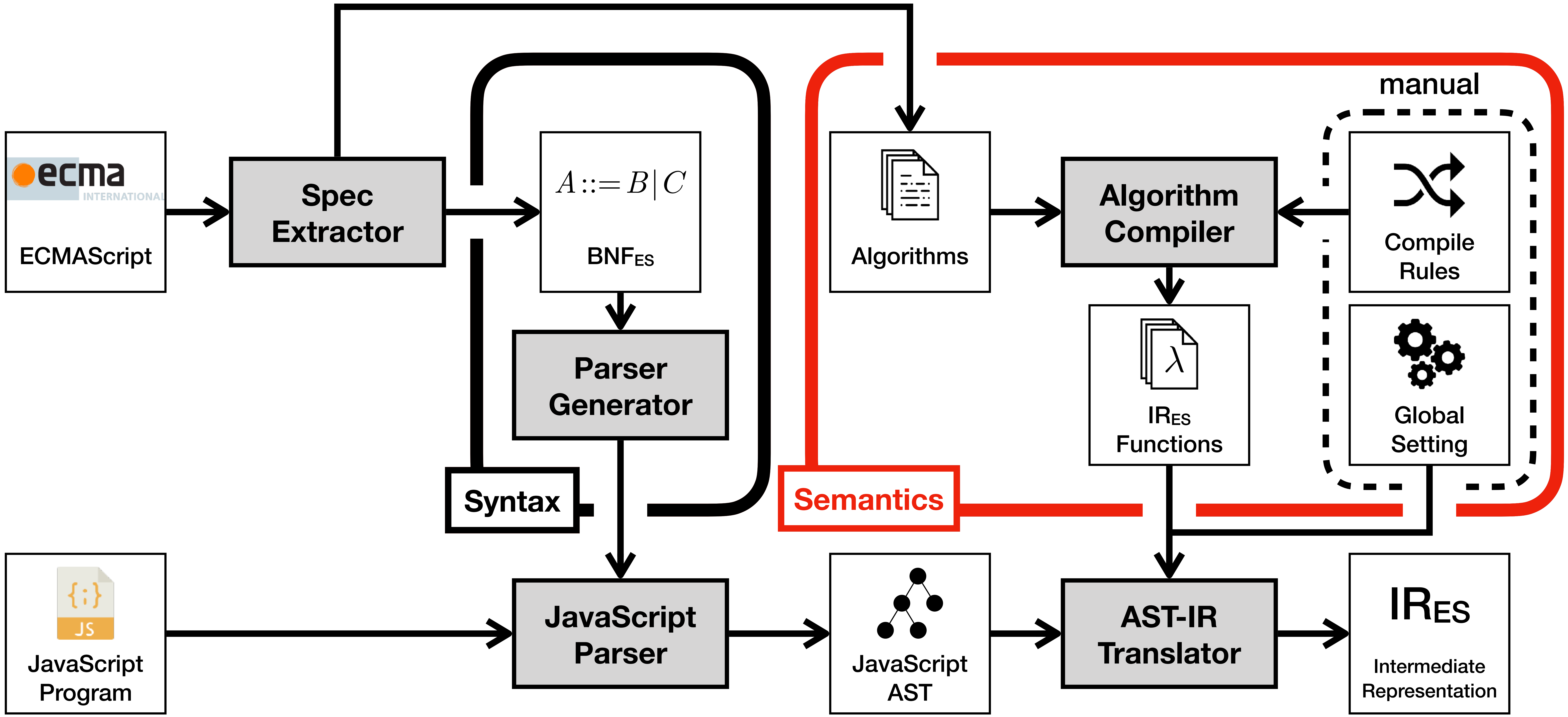
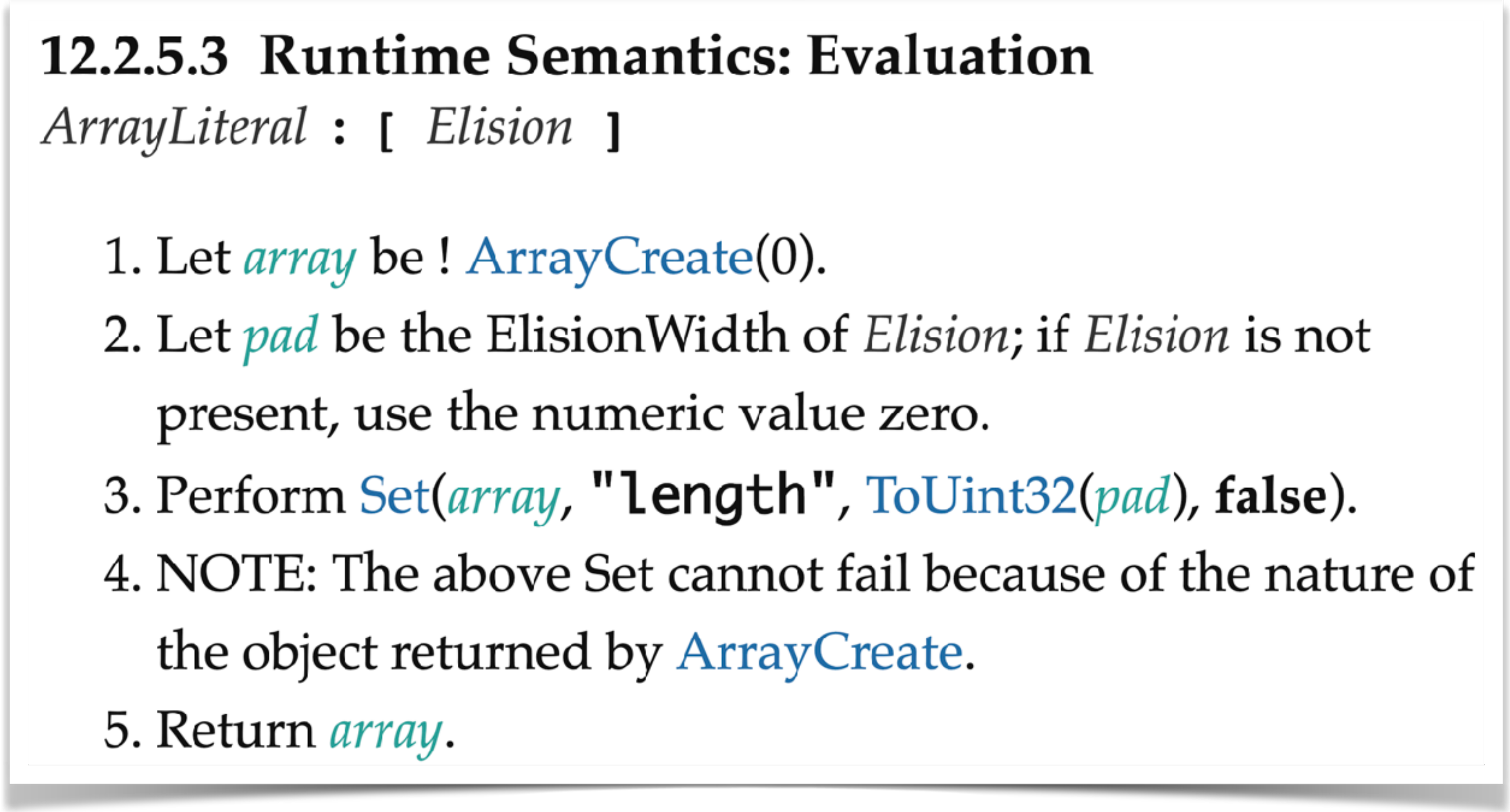


Semantics - Algorithm Compilation



12.2.5.3 Runtime Semantics: Evaluation

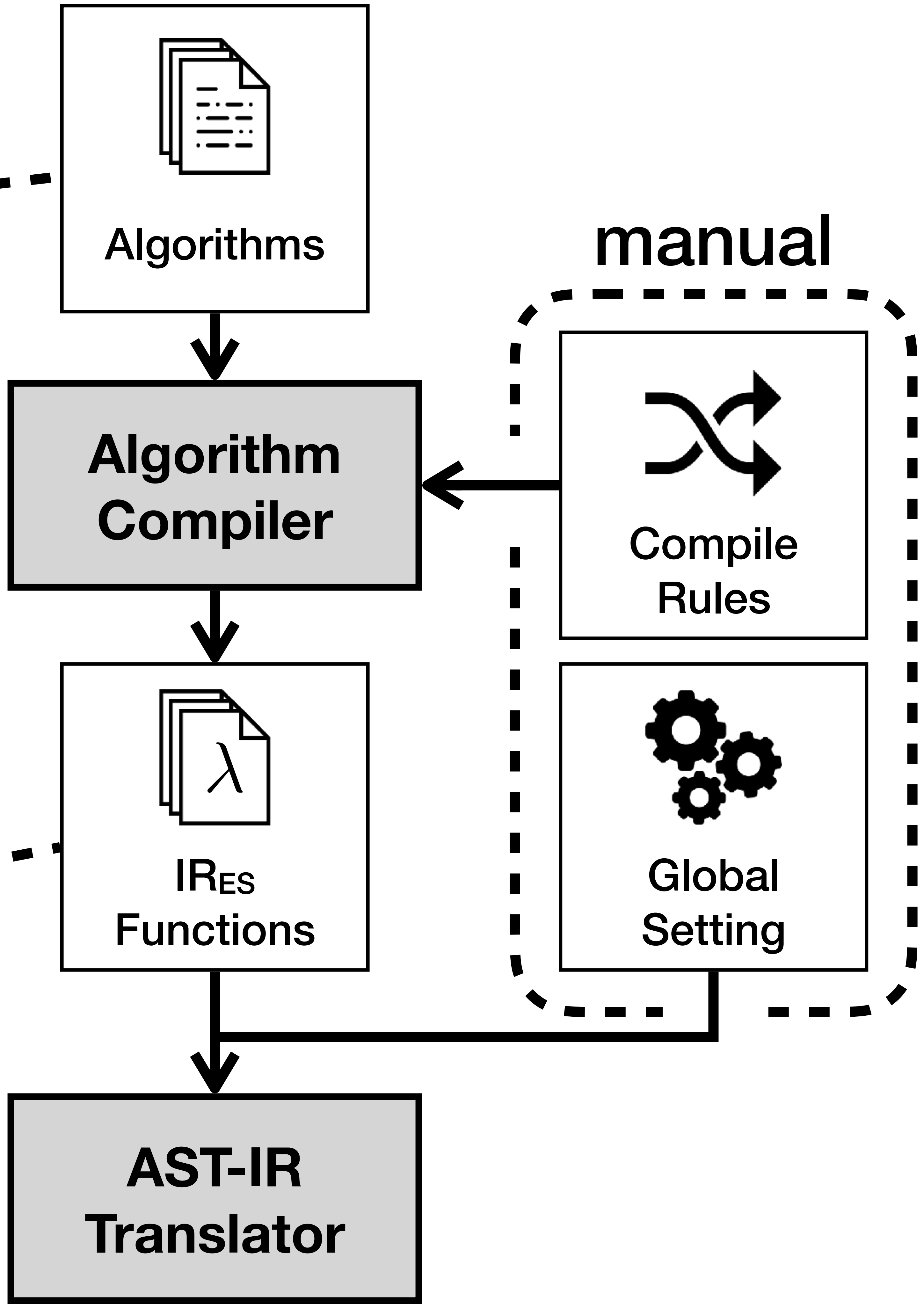
ArrayLiteral **:** **[** *Elision* **]**

1. Let *array* be ! ArrayCreate(0).
2. Let *pad* be the ElisionWidth of *Elision*; if *Elision* is not present, use the numeric value zero.
3. Perform Set(*array*, `"length"`, ToUint32(*pad*), **false**).
4. NOTE: The above Set cannot fail because of the nature of the object returned by ArrayCreate.
5. Return *array*.

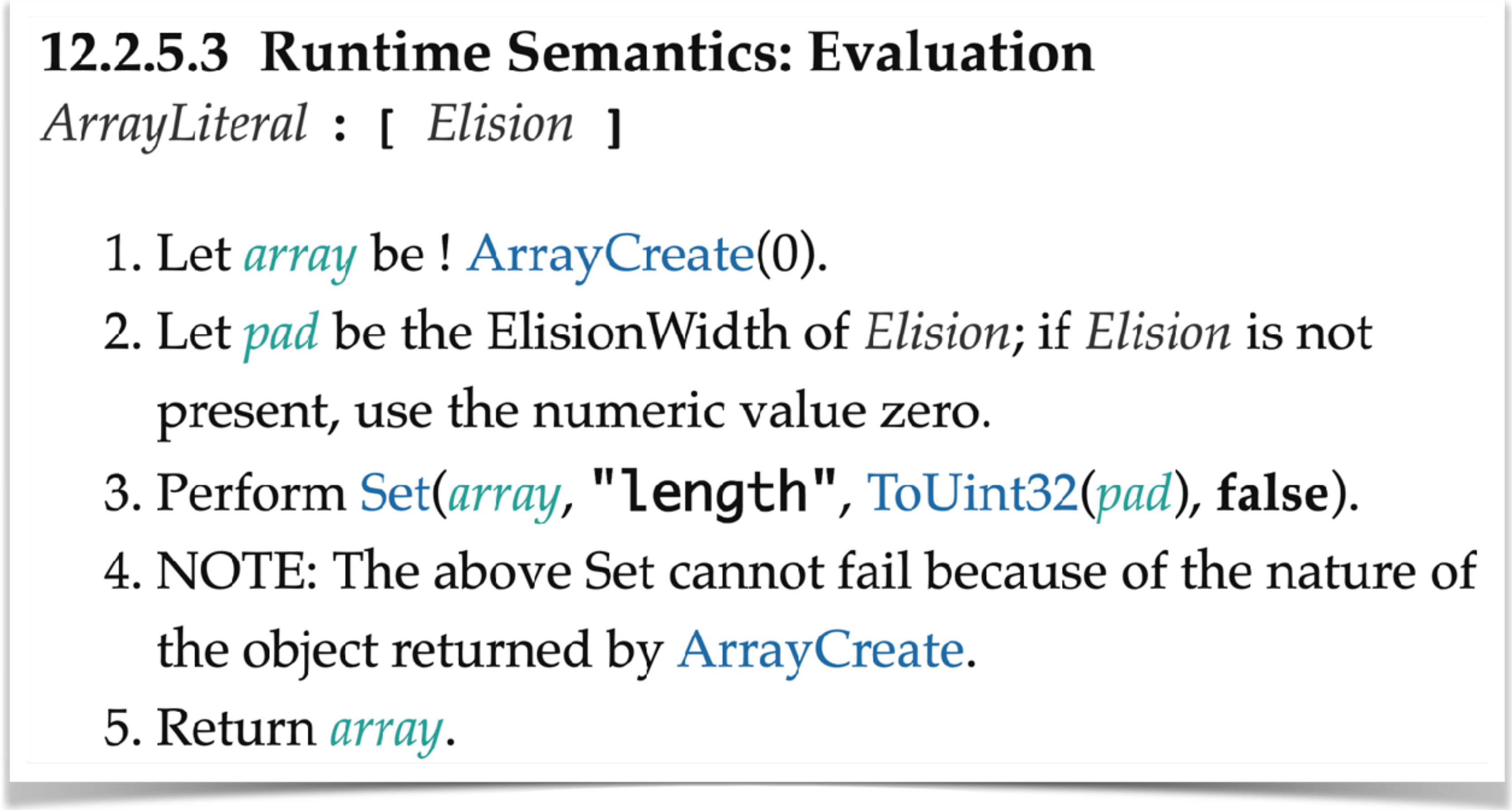
The Evaluation **algorithm for the first alternative of** *ArrayLiteral* **in ES10**

```
"ArrayLiteral0.Evaluation" (Elision) => {
  let array = ! (ArrayCreate 0)
  if (= Elision absent) let pad = 0
  else let pad = Elision.ElisionWidth
  (Set array "length" (ToUint32 pad) false)
  return array
}
```

The IR$_{ES}$ function of the first alternative of *ArrayLiteral* **in ES10**



Semantics - Algorithm Compilation



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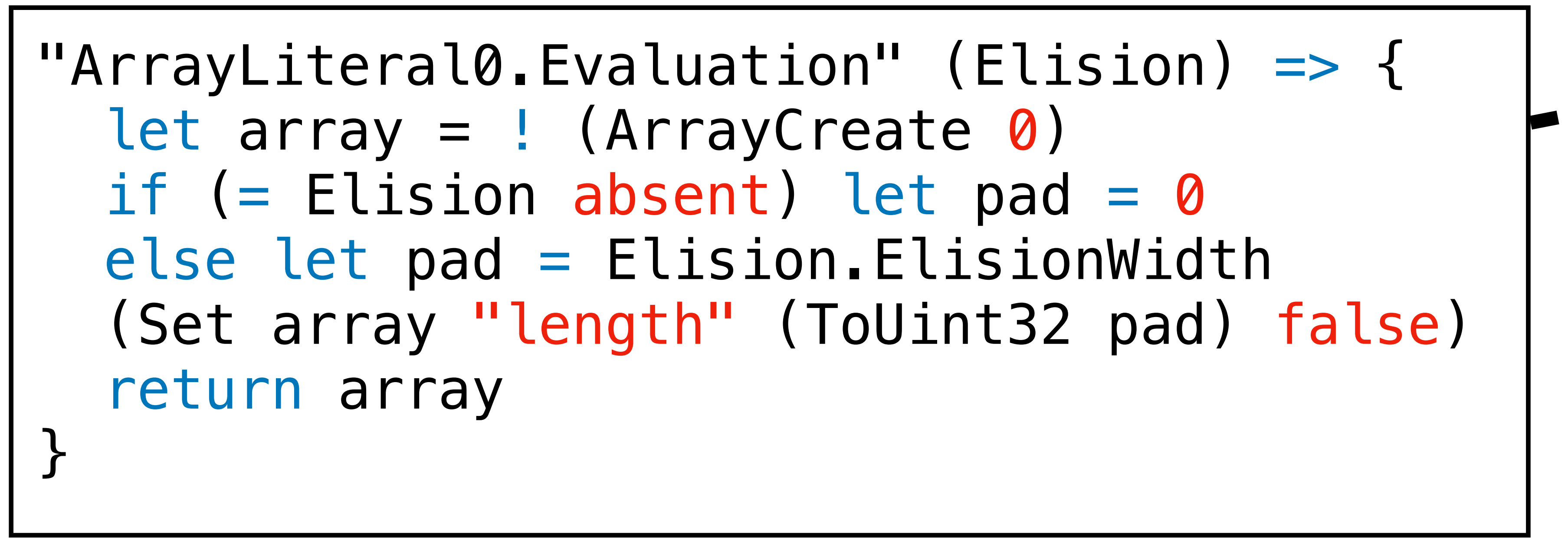

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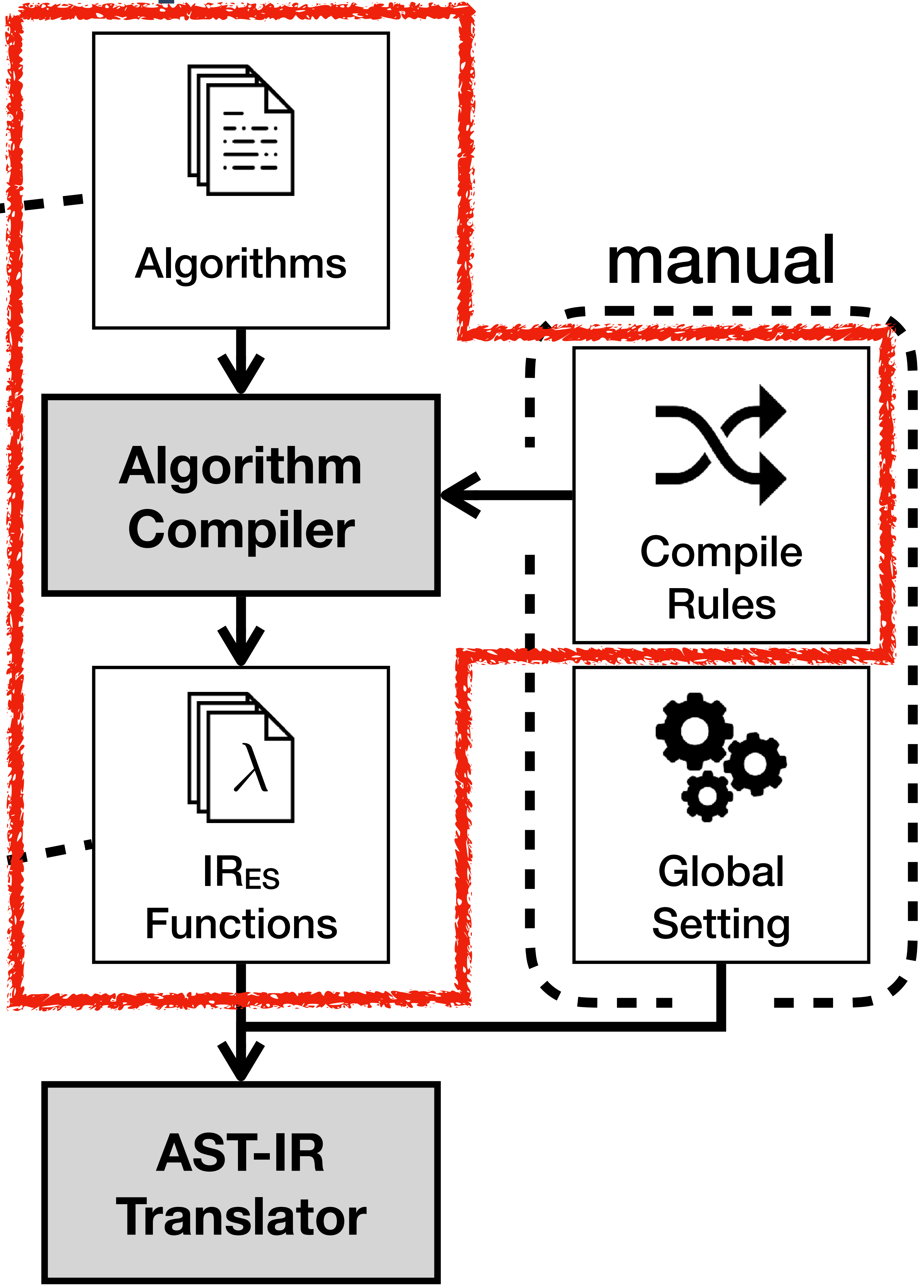

Parsing rules   Conversion Rules

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

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

Simplified compile rules

Let *array* be ! ArrayCreate (0) .

Parsing rules Conversion Rules

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S = // statements
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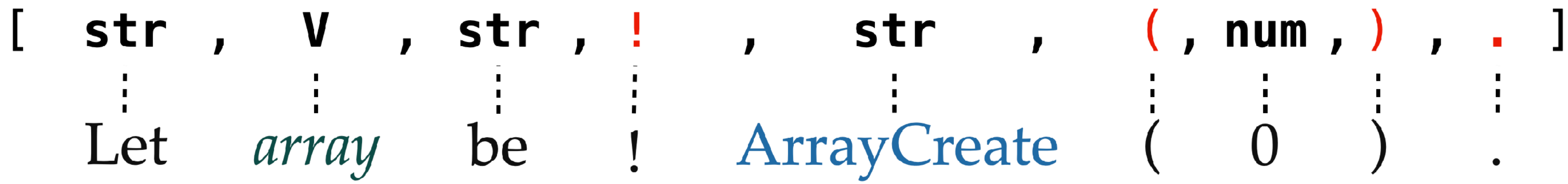
Simplified compile rules



[str , V , str , ! , str , (, num ,) , .]

Let *array* be ! ArrayCreate (0) .

Parsing rules Conversion Rules

```
S = // statements
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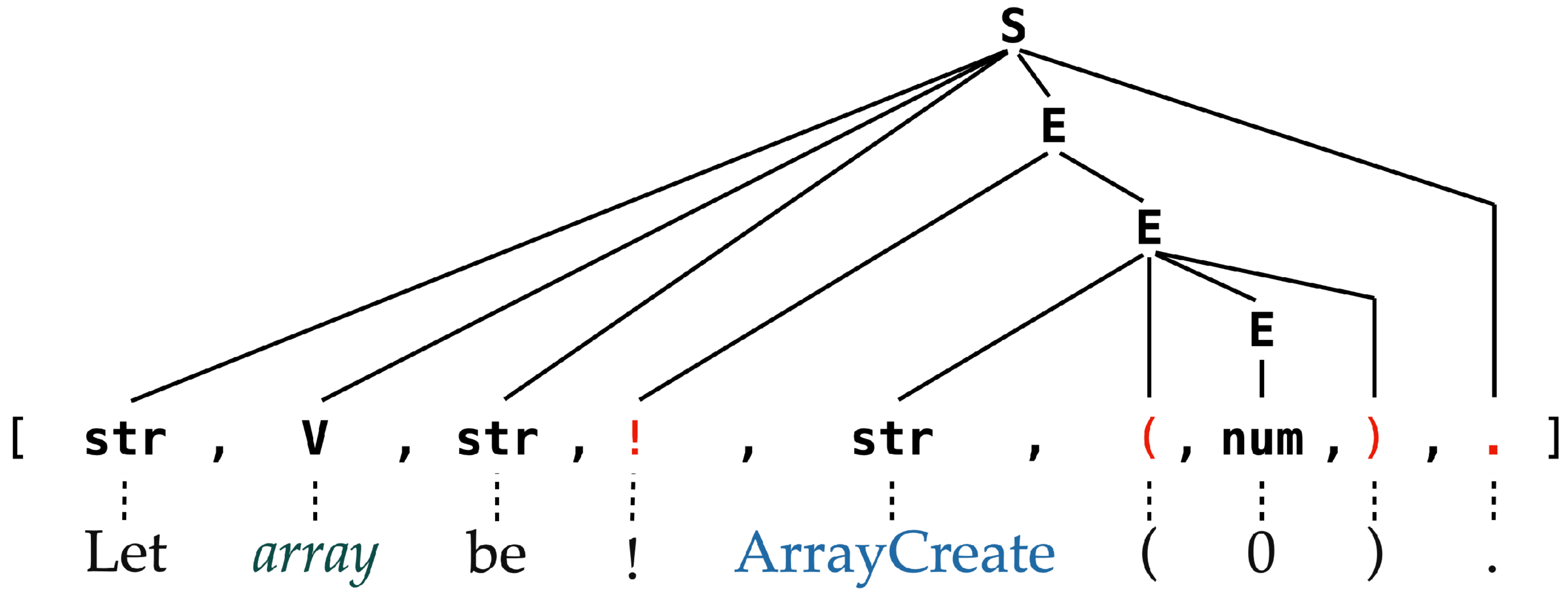

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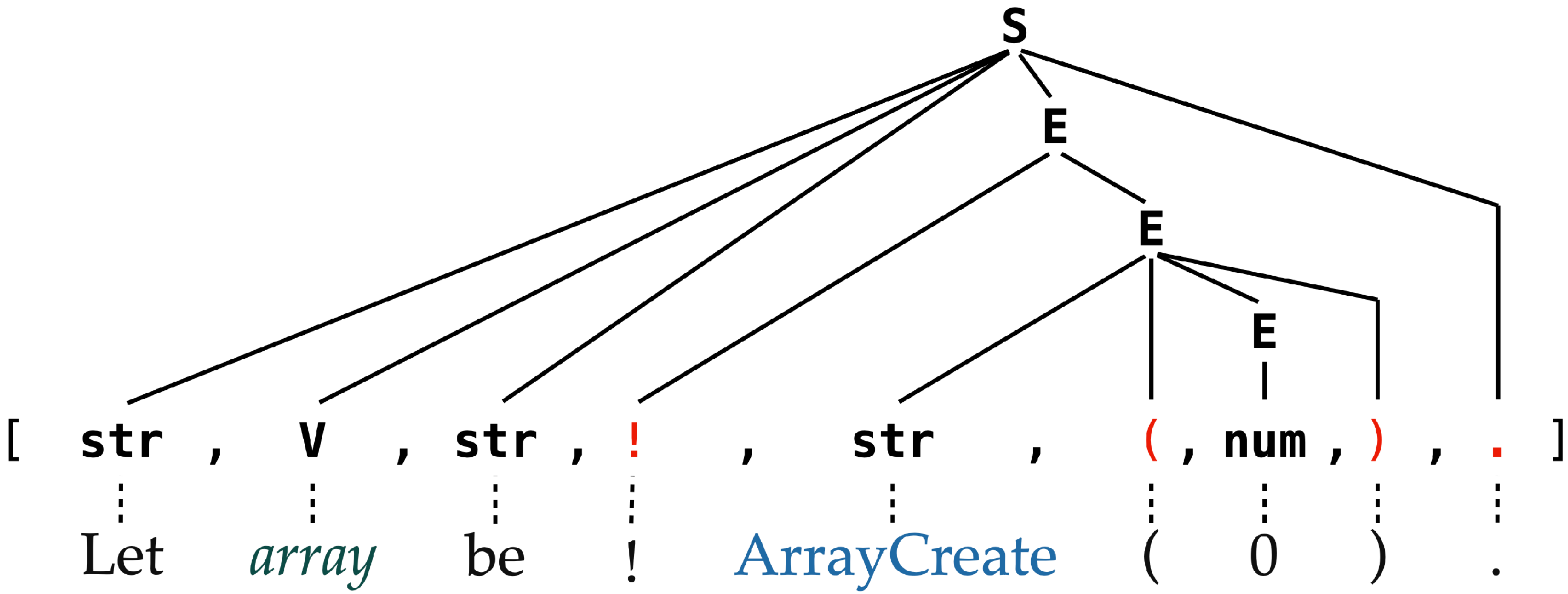
```

Simplified compile rules



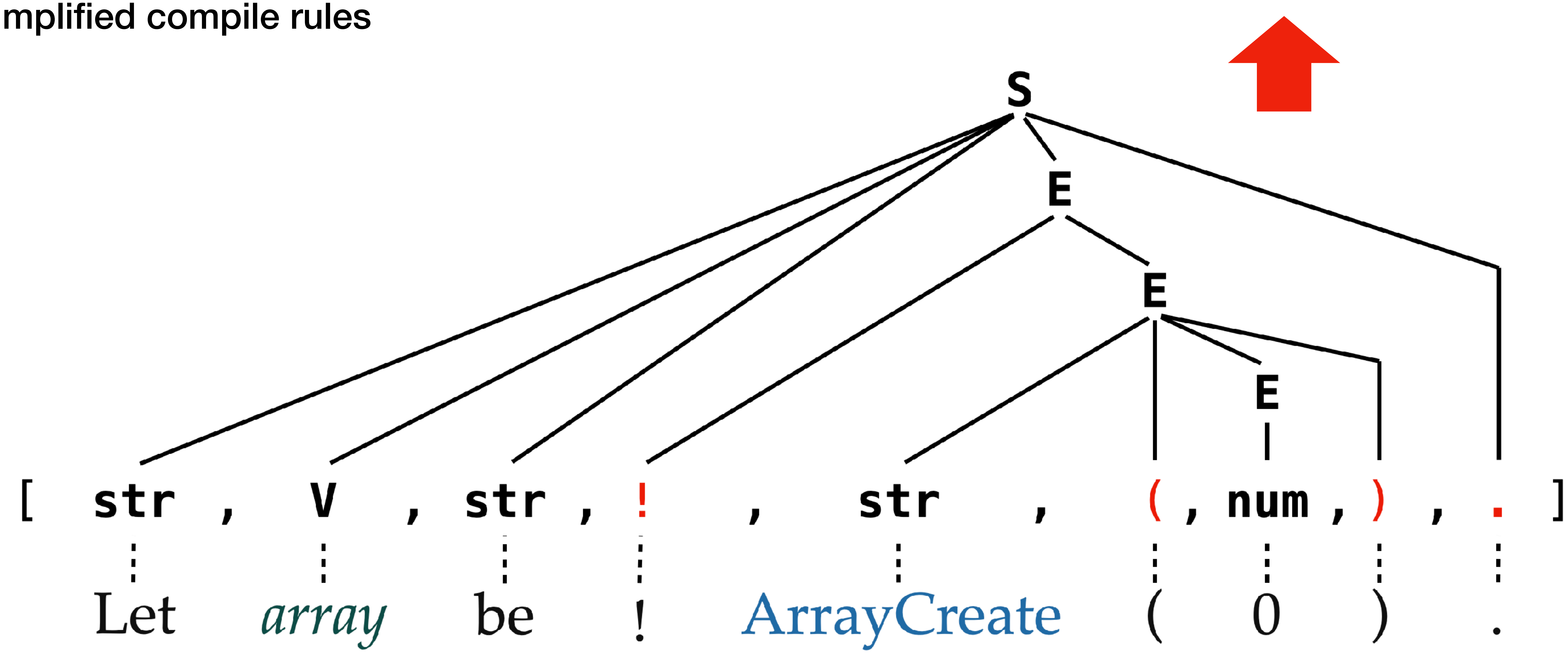
Parsing rules   Conversion Rules

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

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

Simplified compile rules

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



Parsing rules   Conversion Rules

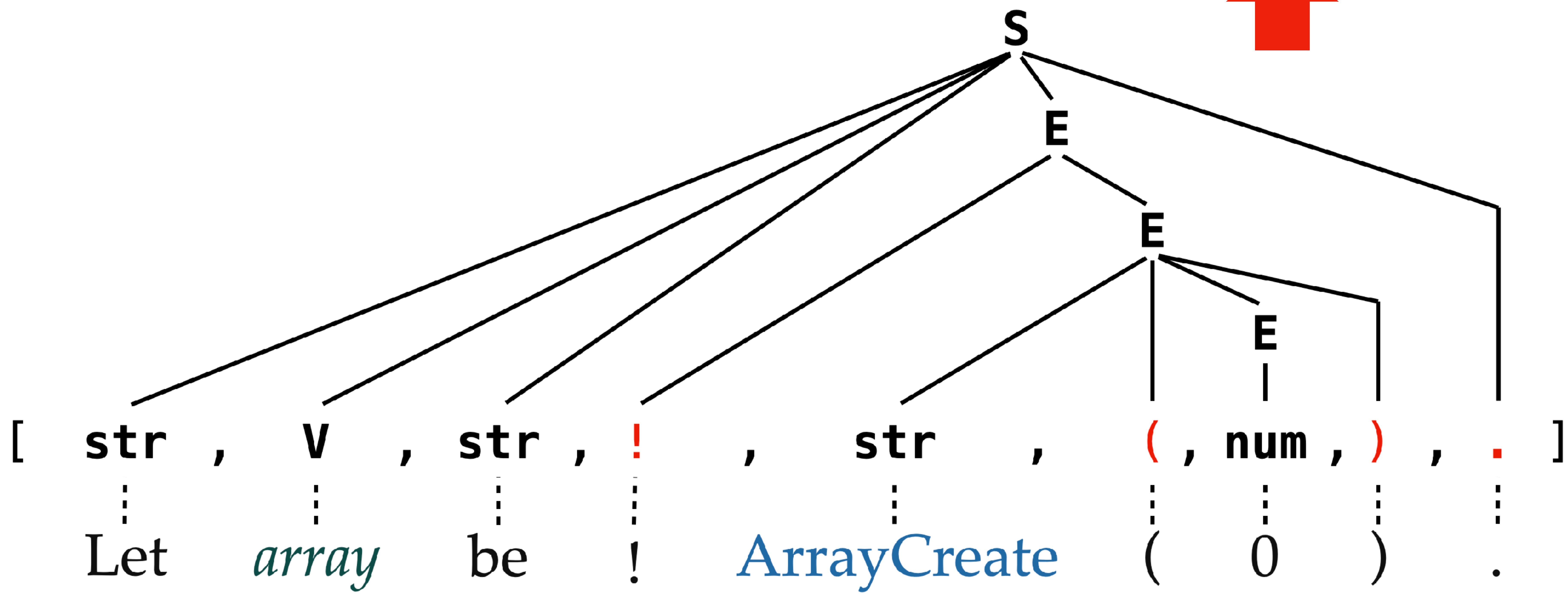
```
S = // statements
  Let ~ V ~ be ~ E ~ .  ^^ ILet

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

Simplified compile rules

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

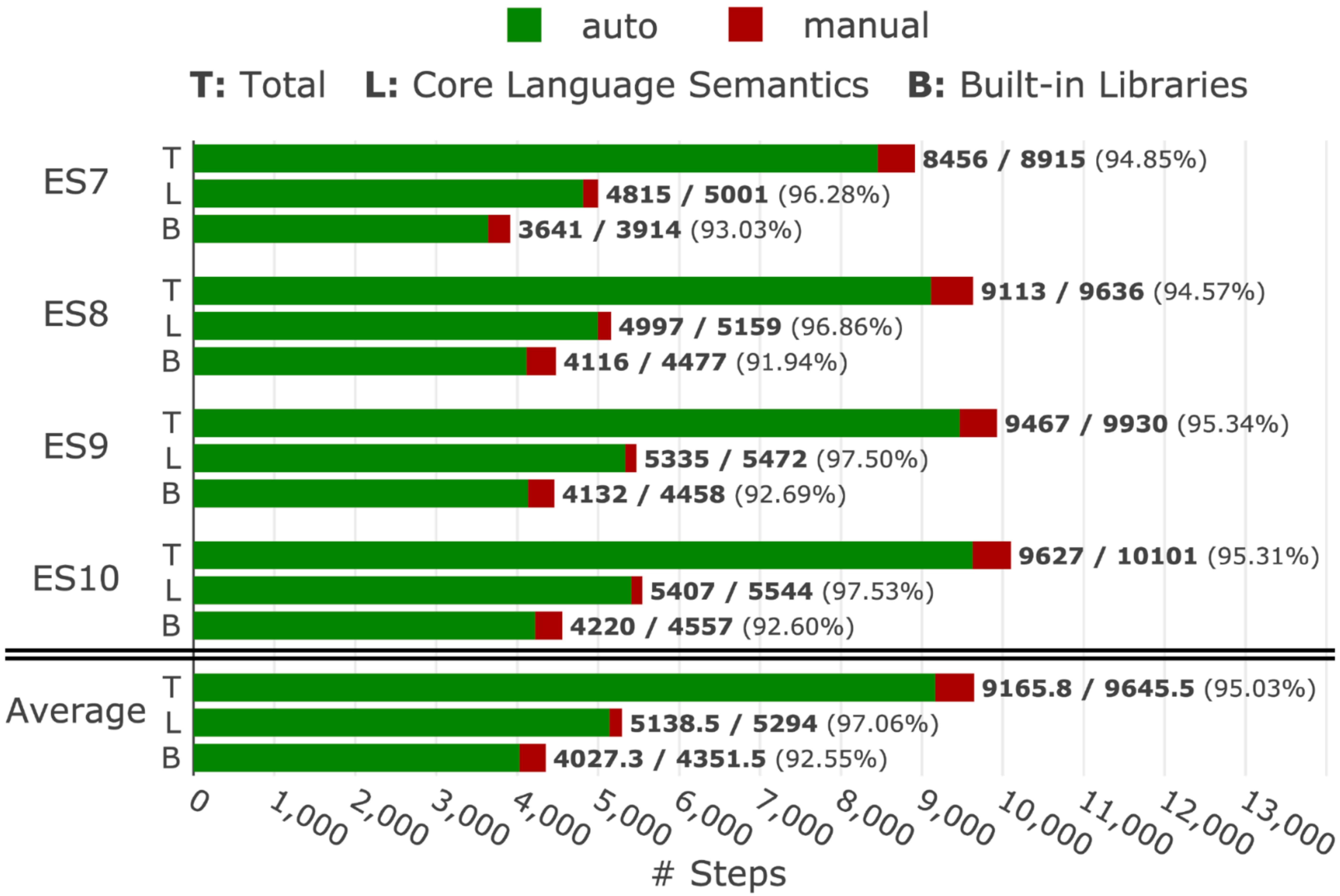
```
ILet(array, EAbruptCheck(
  ECall("ArrayCreate", 0)))
```


S
E
E
E
[str , V , str , ! , str , (, num ,) , .]
Let array be ! ArrayCreate (0) .

Semantics - Evaluation

The number of compile rules

Name	# Rules
Statment	21
Expression	27
Condition	16
Value	11
Type	34
Reference	9
Total	118



Semantics - Evaluation

≈ 95% Compiled

The number of compile rules

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Statment	21
Expression	27
Condition	16
Value	11
Type	34
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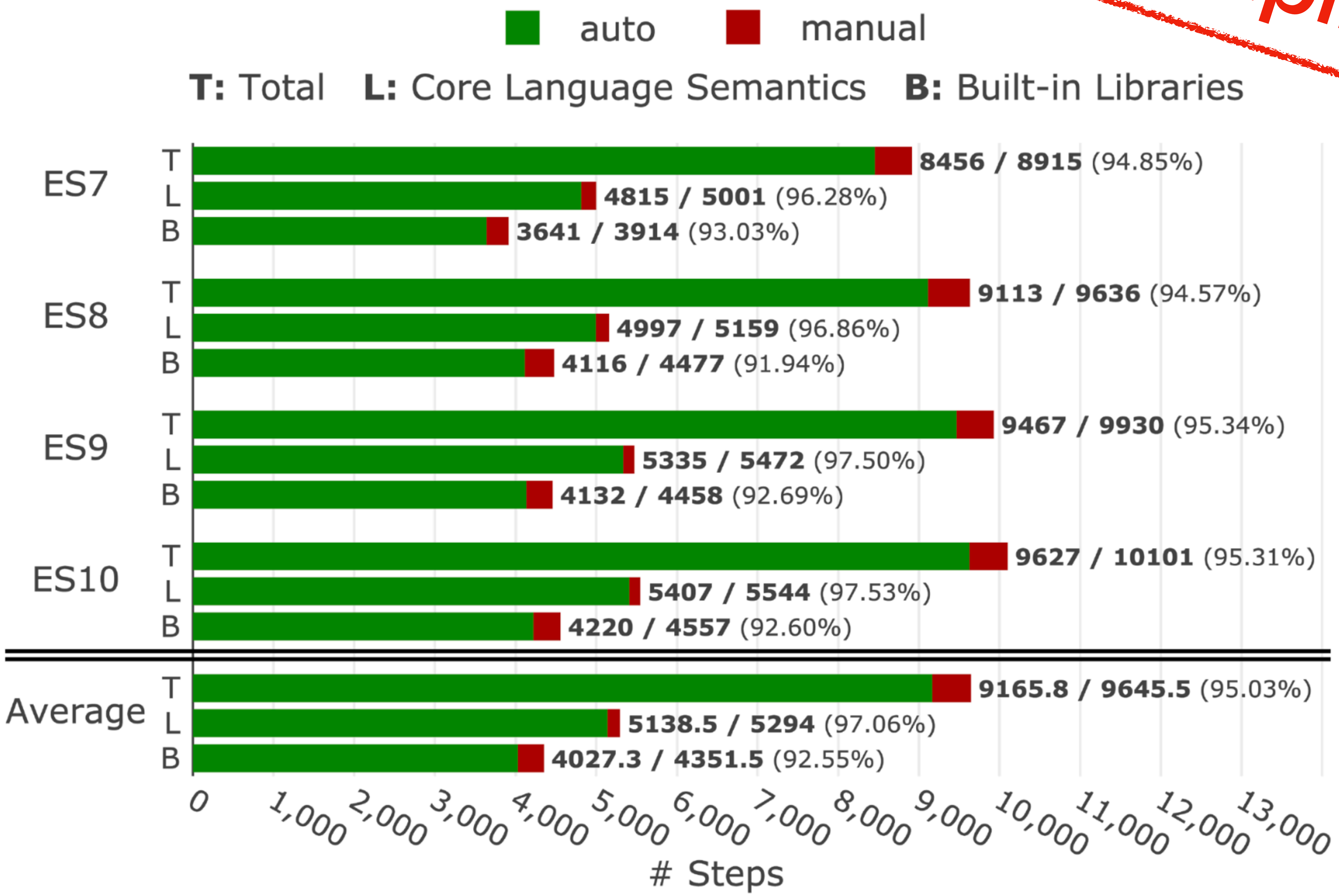
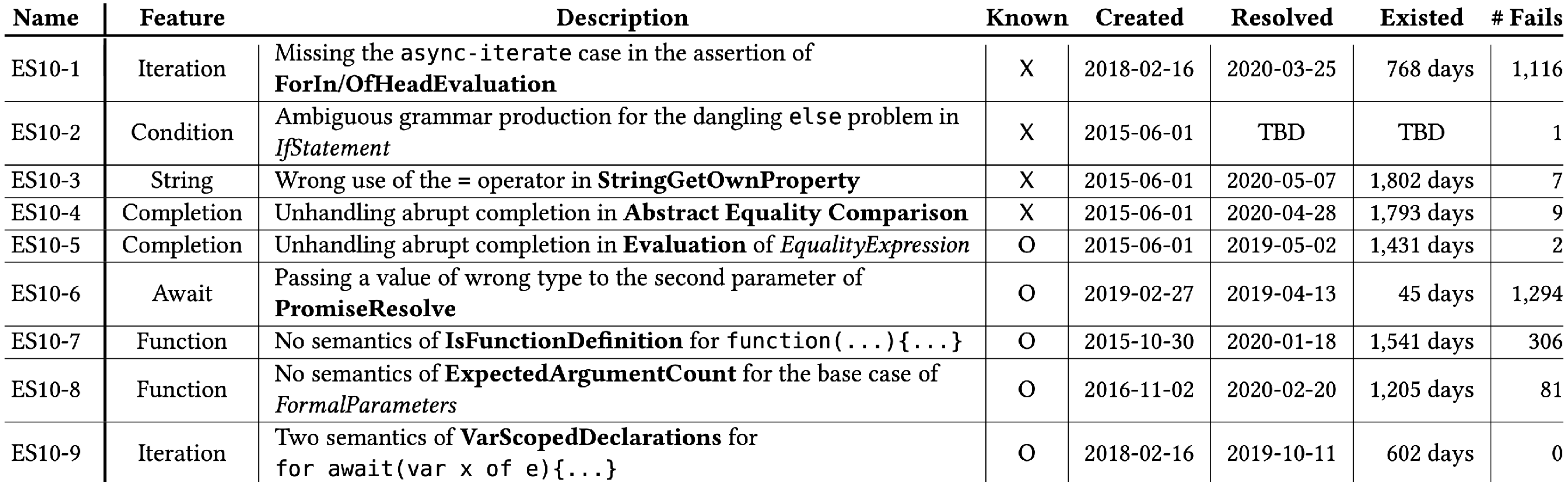


Semantics - Evaluation

- **Test262** - Official ECMAScript test suite

16,355 / 18,064 (90.54%)



Name	Feature	Description	Known	Created	Resolved	Existed	# Fails
ES10-1	Iteration	Missing the `async-iterate` case in the assertion of **ForIn/OfHeadEvaluation**	X	2018-02-16	2020-03-25	768 days	1,116
ES10-2	Condition	Ambiguous grammar production for the dangling `else` problem in *IfStatement*	X	2015-06-01	TBD	TBD	1
ES10-3	String	Wrong use of the = operator in **StringGetOwnProperty**	X	2015-06-01	2020-05-07	1,802 days	7
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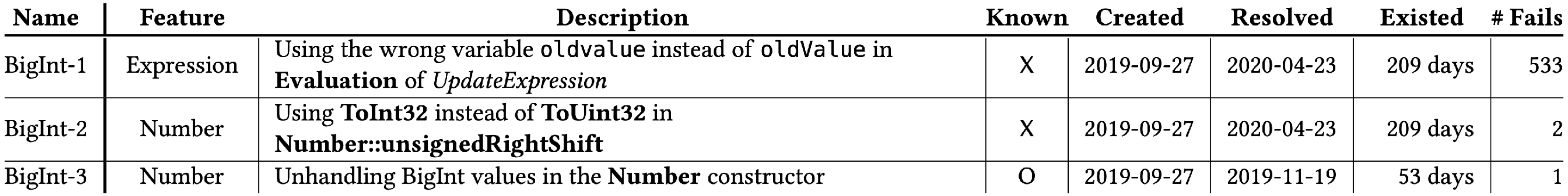
ES10-5	Completion	Unhandling abrupt completion in **Evaluation** of *EqualityExpression*	O	2015-06-01	2019-05-02	1,431 days	2
ES10-6	Await	Passing a value of wrong type to the second parameter of **PromiseResolve**	O	2019-02-27	2019-04-13	45 days	1,294
ES10-7	Function	No semantics of **IsFunctionDefinition** for `function(...){...}`	O	2015-10-30	2020-01-18	1,541 days	306
ES10-8	Function	No semantics of **ExpectedArgumentCount** for the base case of *FormalParameters*	O	2016-11-02	2020-02-20	1,205 days	81
ES10-9	Iteration	Two semantics of **VarScopedDeclarations** for `for await(var x of e){...}`	O	2018-02-16	2019-10-11	602 days	0

292 / 303 (96.37%)



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Semantics - Evaluation

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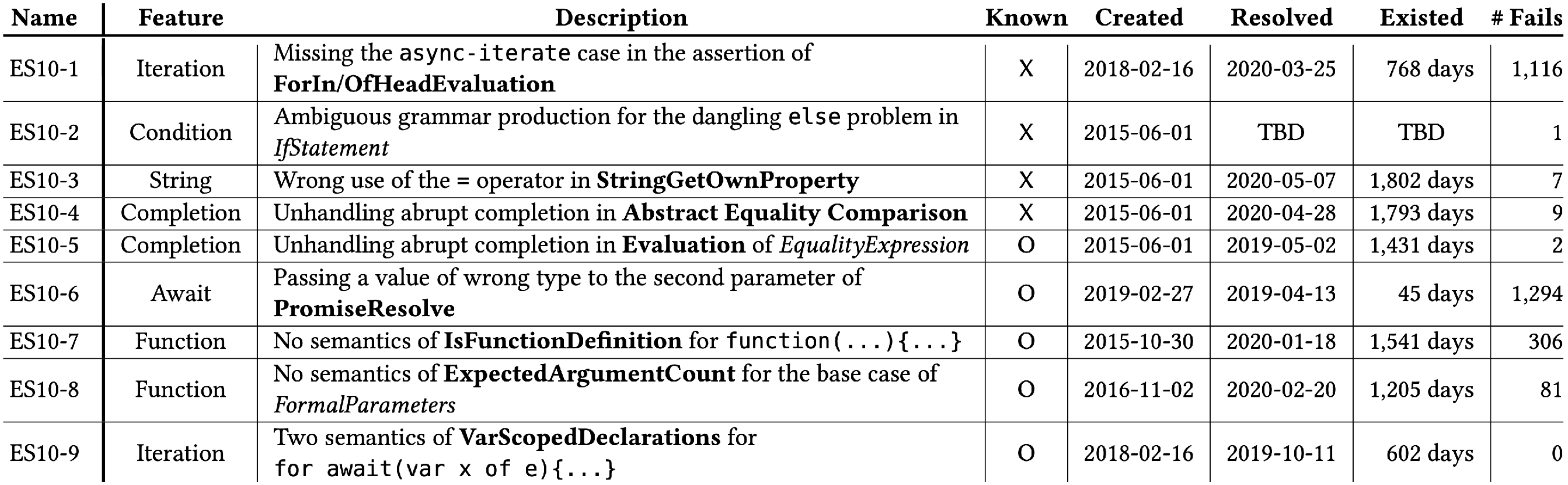
16,355 / 18,064 (90.54%)

9 bugs in ES10

18,064 / 18,064 (100.00%)



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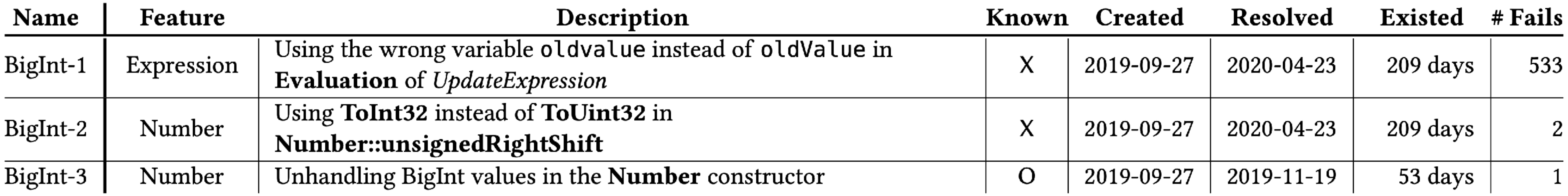

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Semantics - Evaluation

- **Test262** - Official ECMAScript test suite

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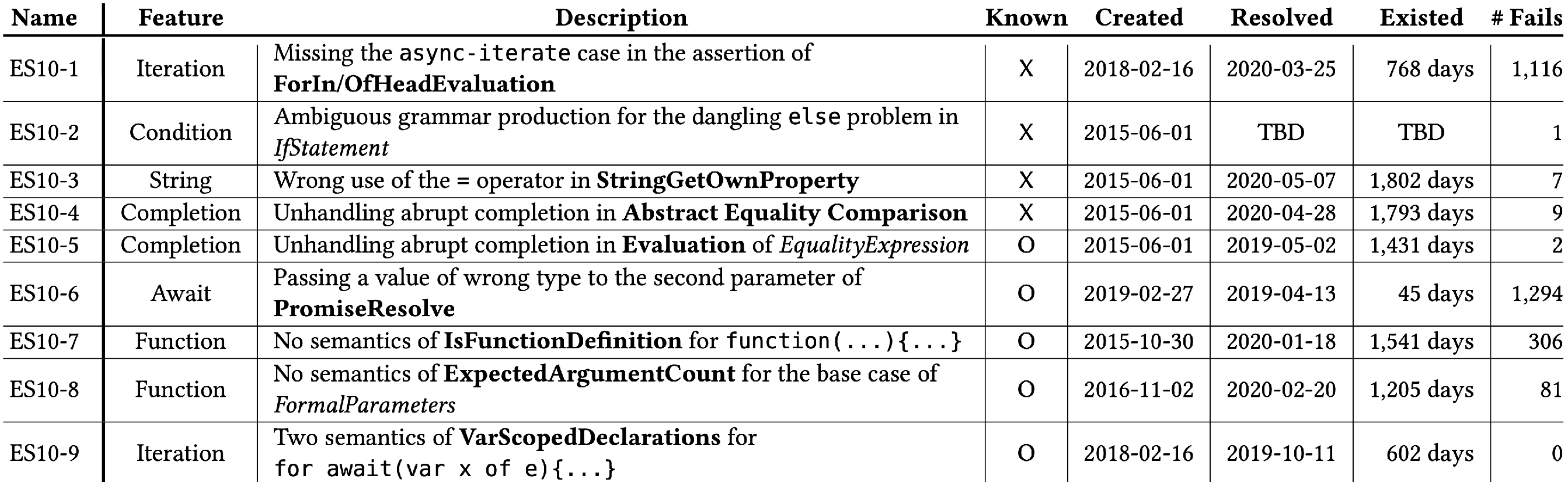

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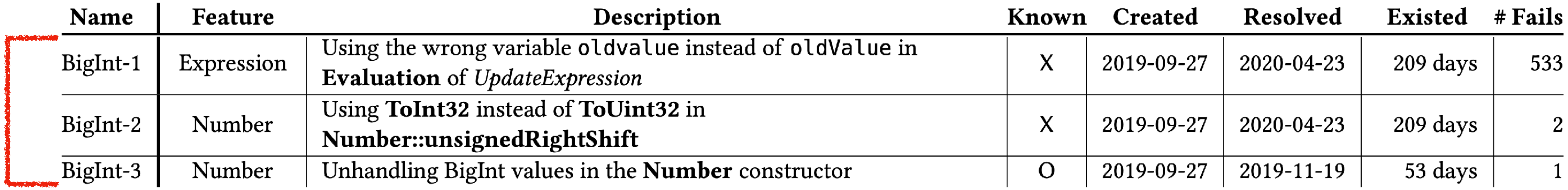
292 / 303 (96.37%)

3 bugs in ES.Next

303 / 303 (100.00%)



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Semantics - Evaluation

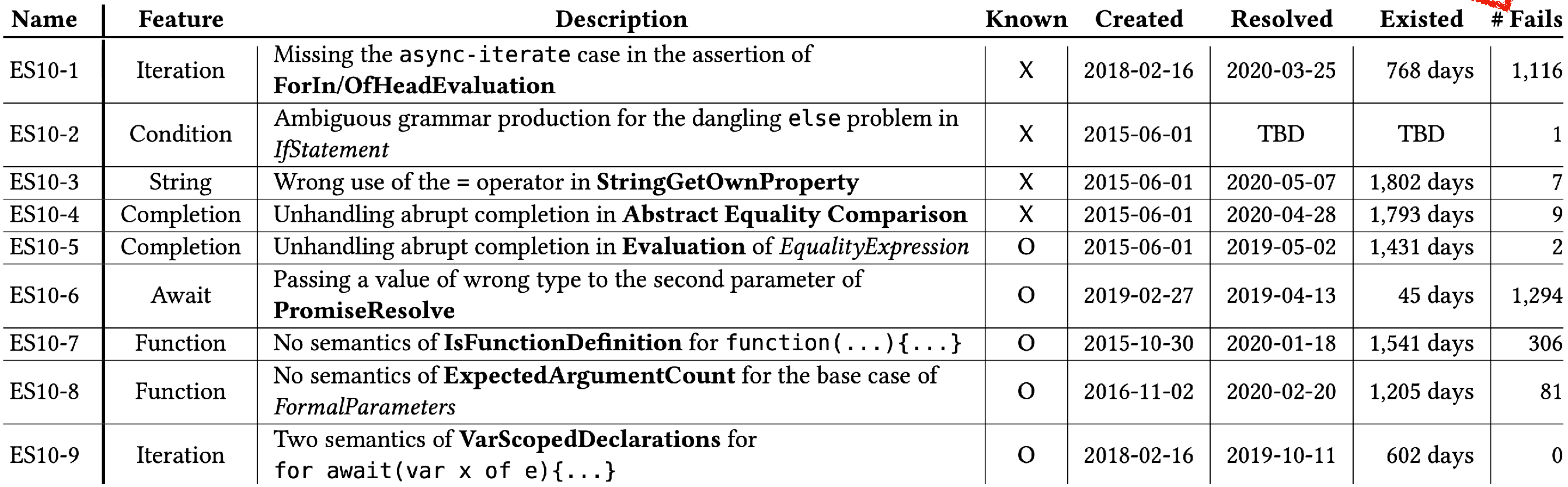
All Tests Passed

- **Test262** - Official ECMAScript test suite

16,355 / 18,064 (90.54%)

9 bugs in ES10

18,064 / 18,064 (100.00%)



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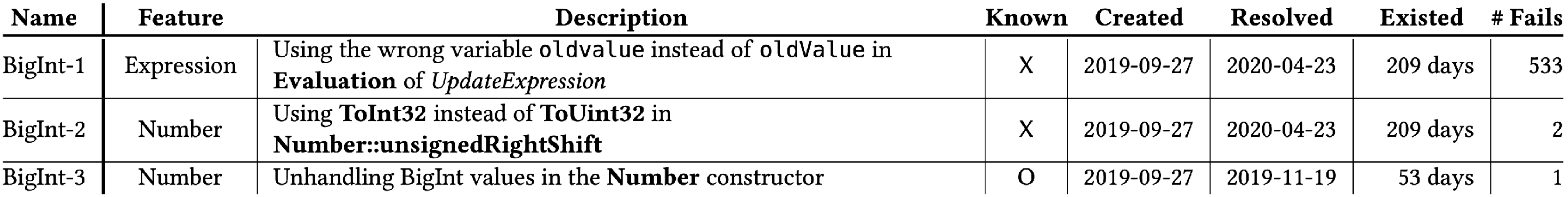

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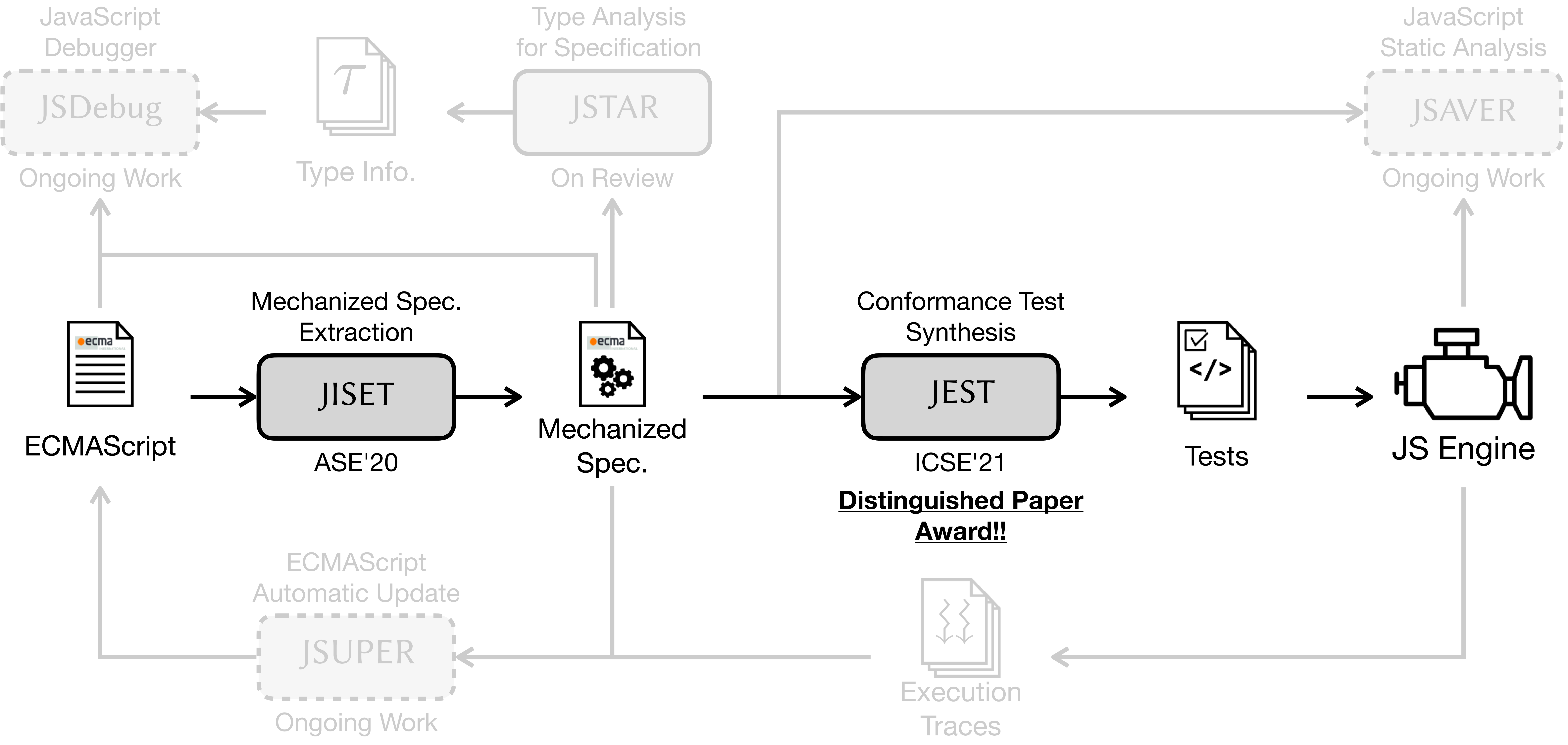
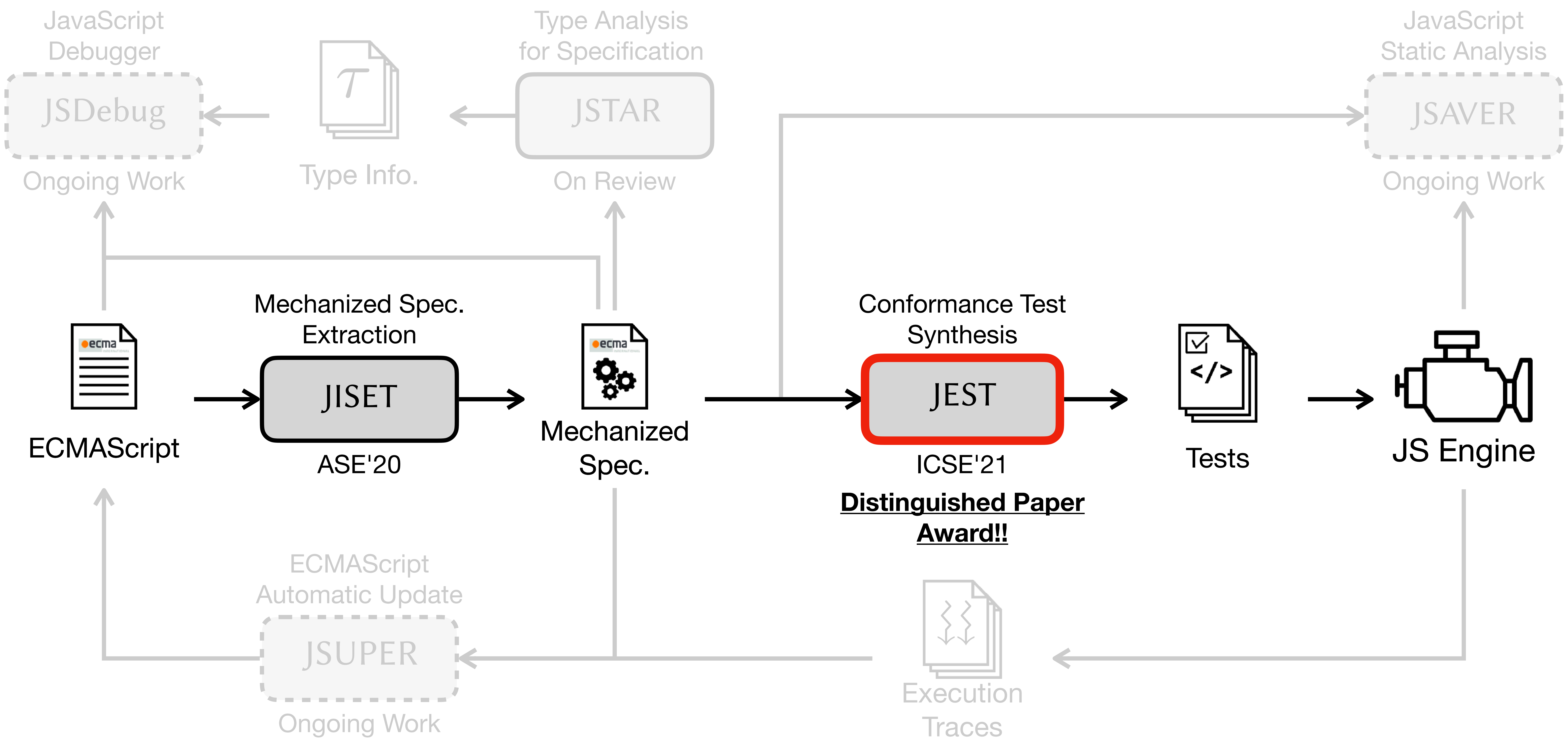
Co-evolution of JavaScript Spec. and Tools

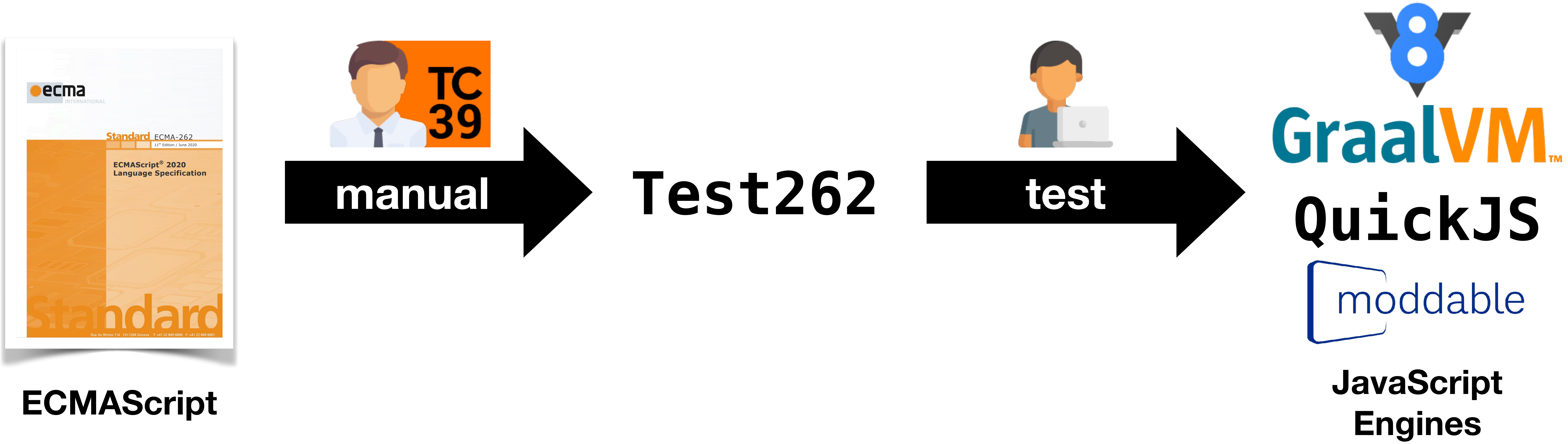


Co-evolution of JavaScript Spec. and Tools



JEST: JavaScript Engine and Specification Tester [ICSE'21]

Test262: JavaScript Conformance Tests



ECMAScript

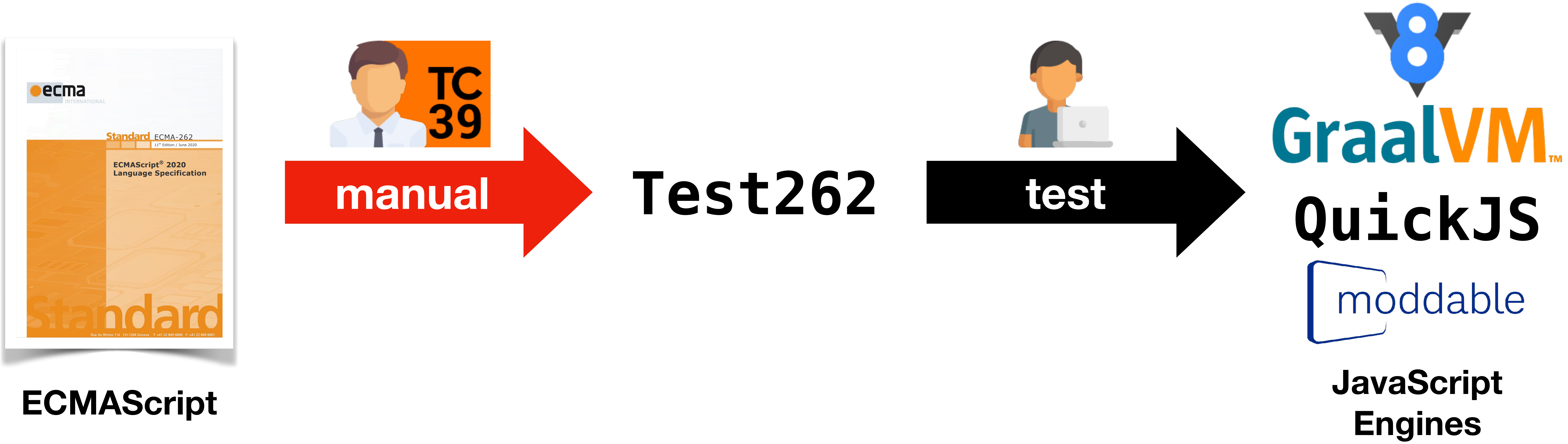
manual

Test262

test

JavaScript Engines

Test262: JavaScript Conformance Tests



ECMAScript

manual

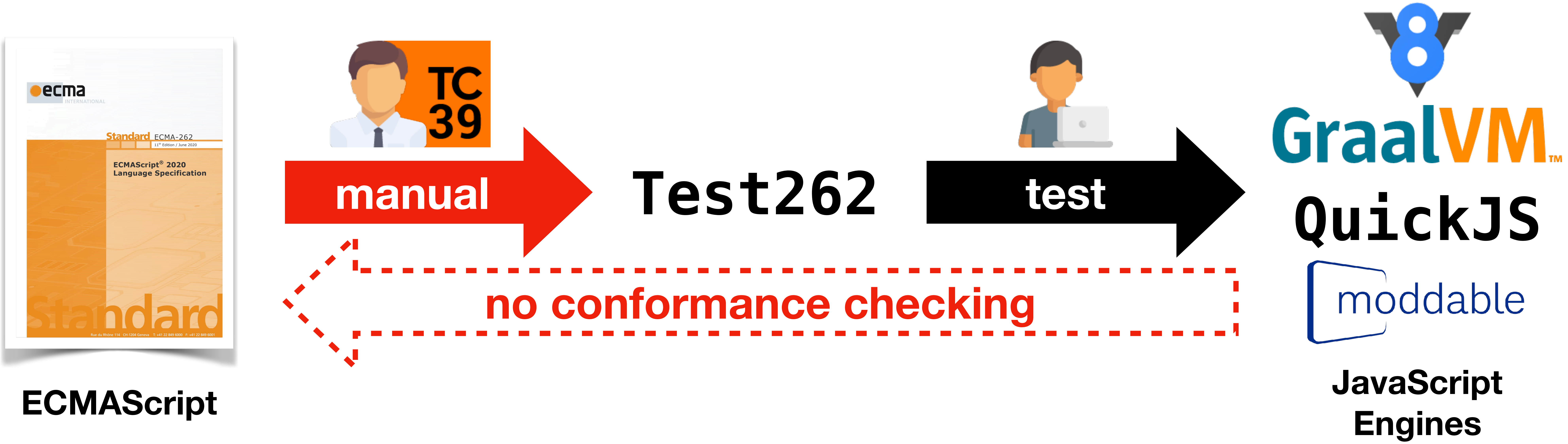
Test262

test

QuickJS

JavaScript Engines

Test262: JavaScript Conformance Tests



ECMAScript

manual

Test262

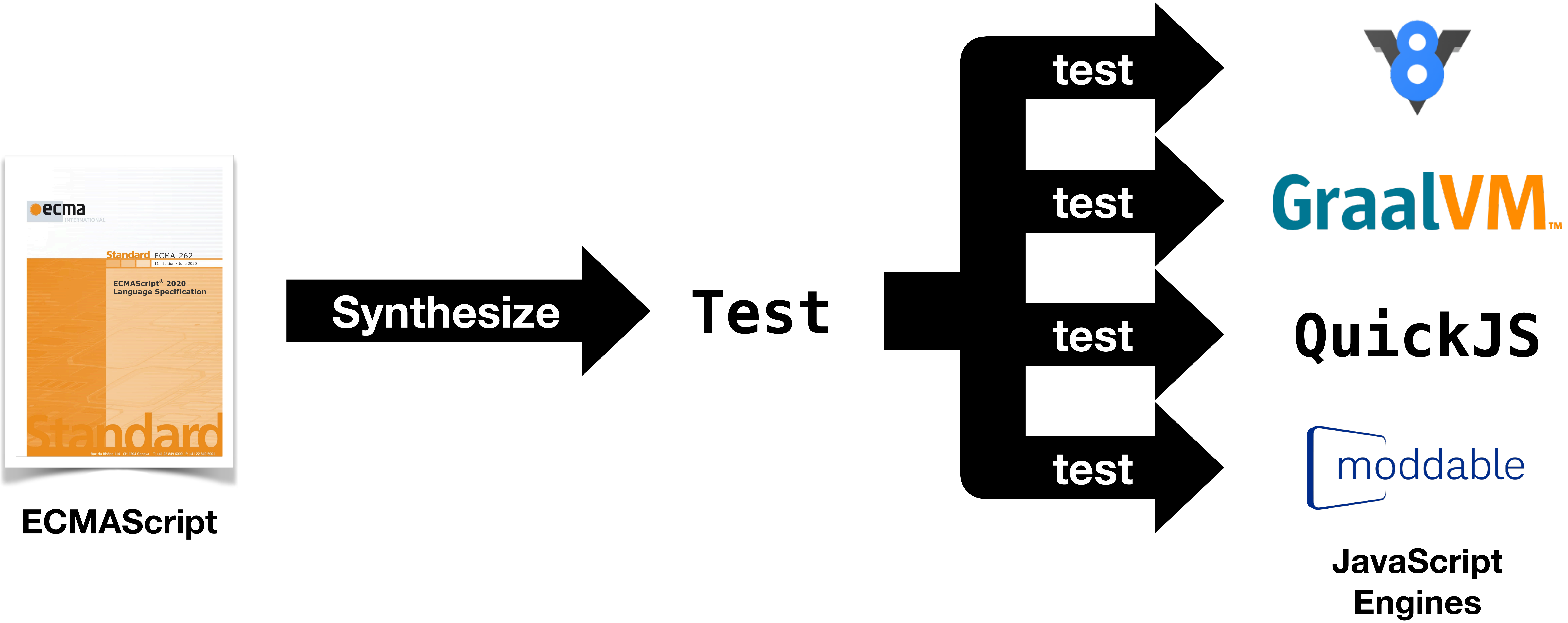
test

no conformance checking

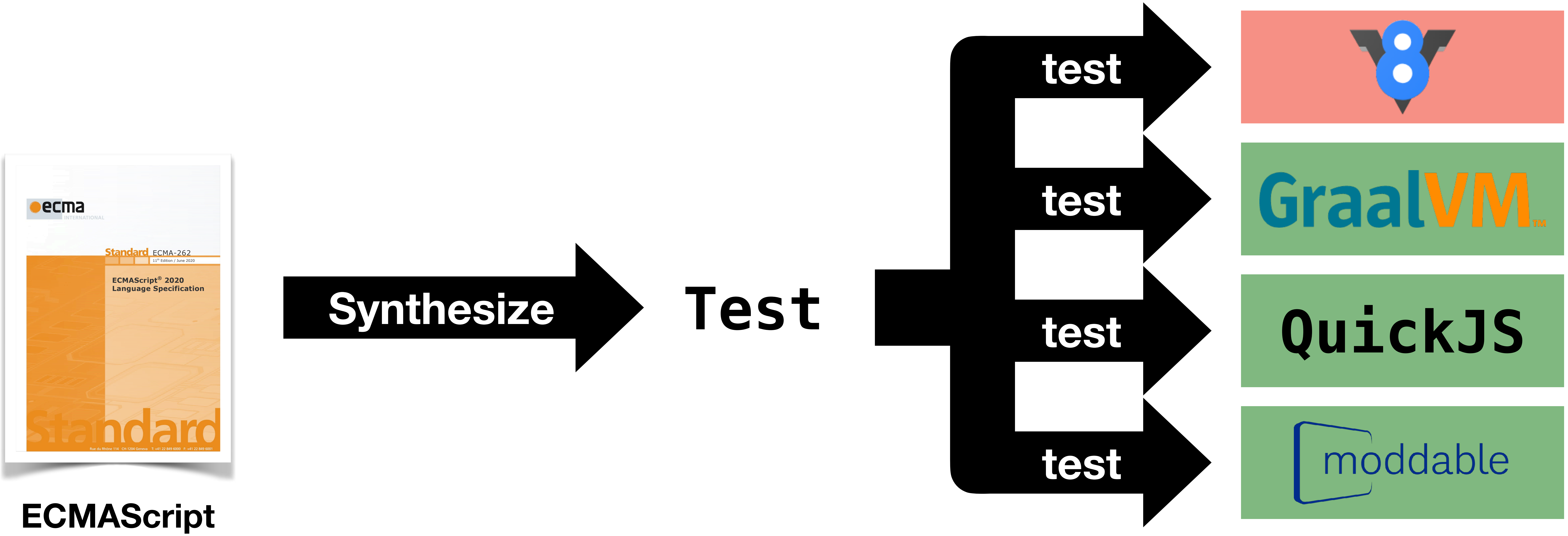
QuickJS

JavaScript Engines

N+1-version Differential Testing



N+1-version Differential Testing



ECMAScript

Synthesize

Test

test

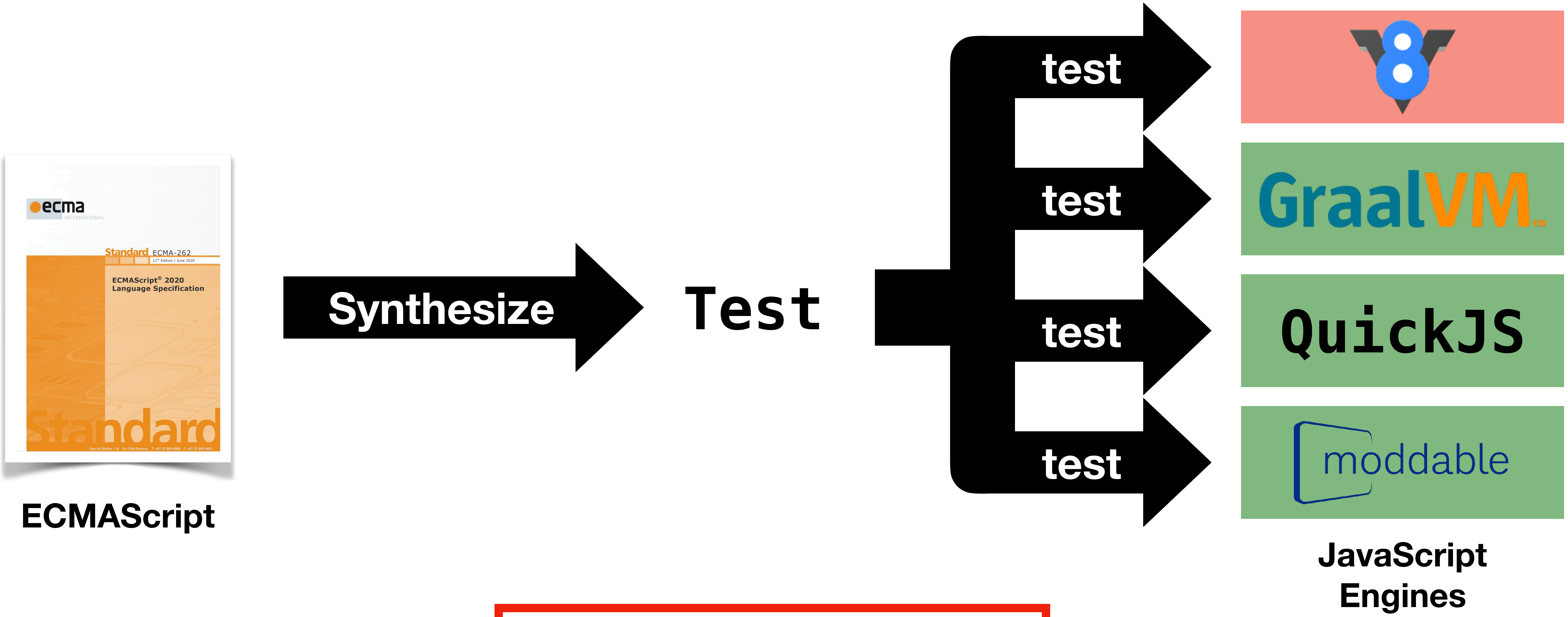
test

test

test

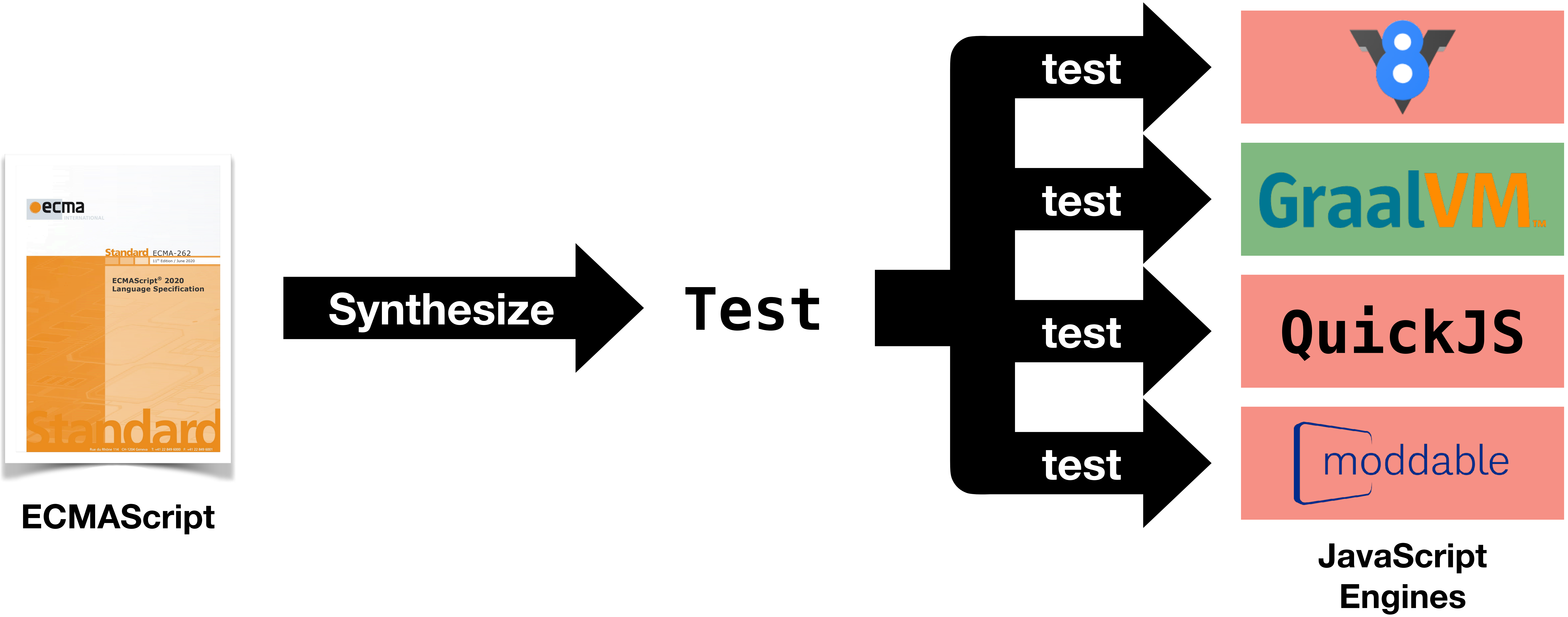
JavaScript Engines

N+1-version Differential Testing



An engine bug in

N+1-version Differential Testing



ECMAScript

Synthesize

Test

test

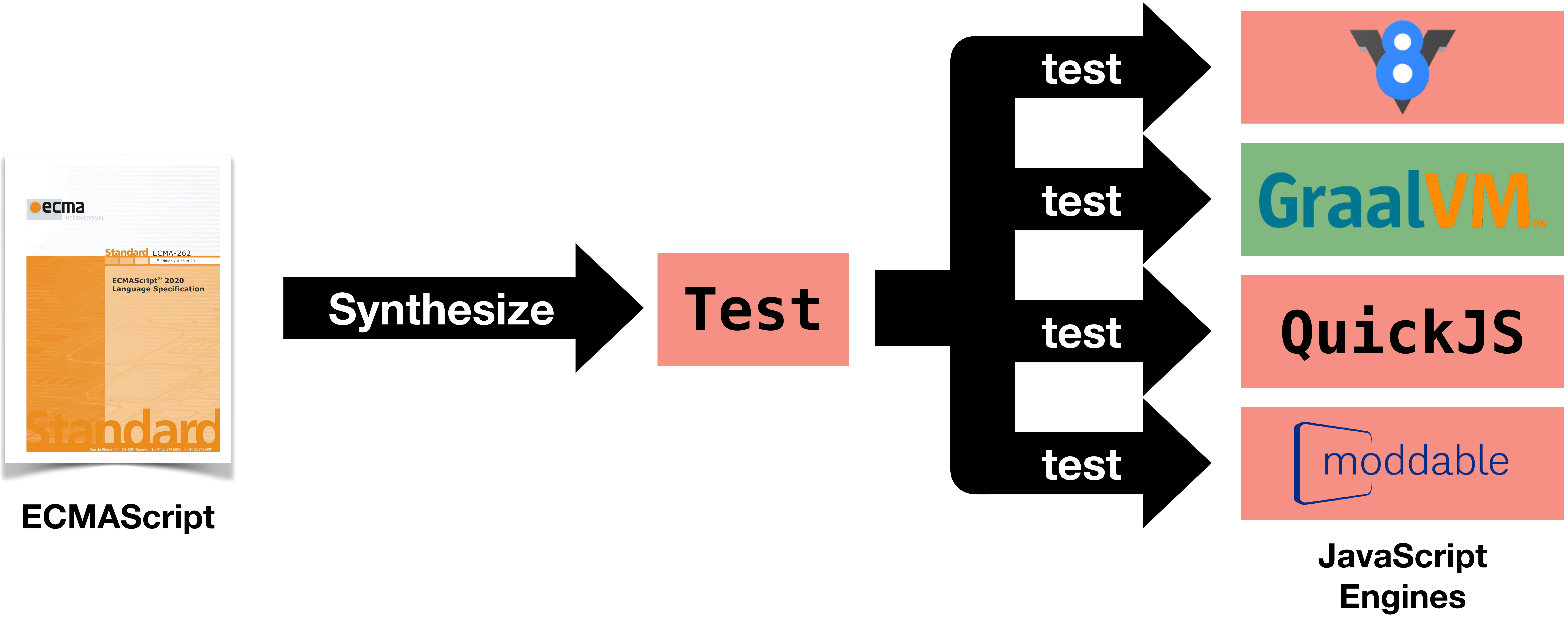
test

test

test

JavaScript Engines

N+1-version Differential Testing



ECMAScript

Synthesize

Test

test

test

test

test

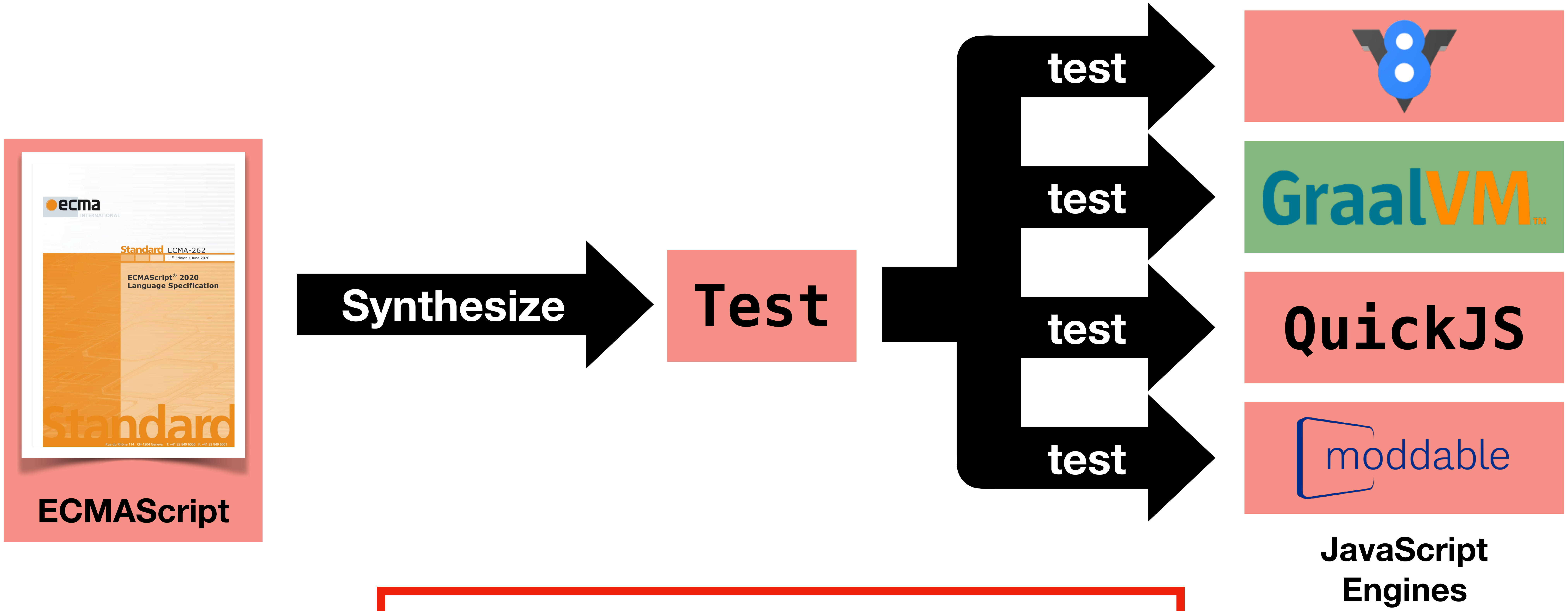
GraalVM

QuickJS

moddable

JavaScript Engines

N+1-version Differential Testing



ECMAScript

Synthesize

Test

test

test

test

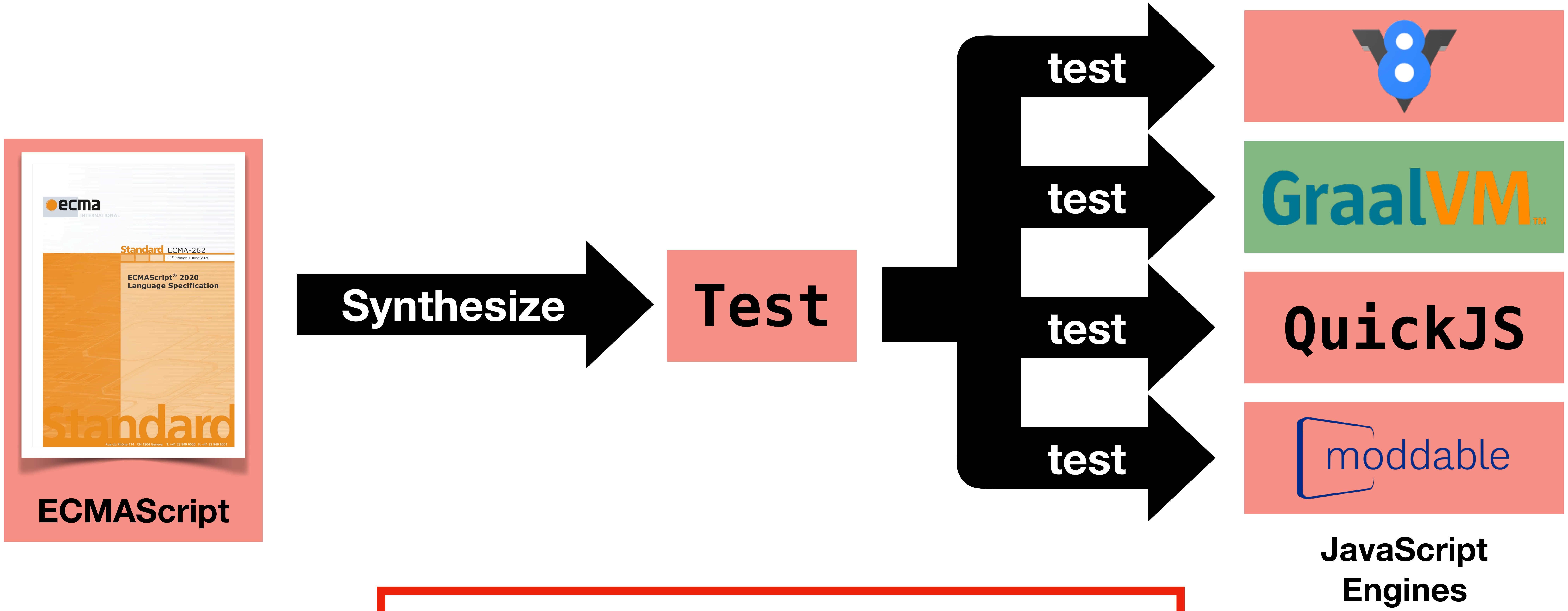
test

QuickJS

JavaScript Engines

A specification bug in ECMAScript

N+1-version Differential Testing

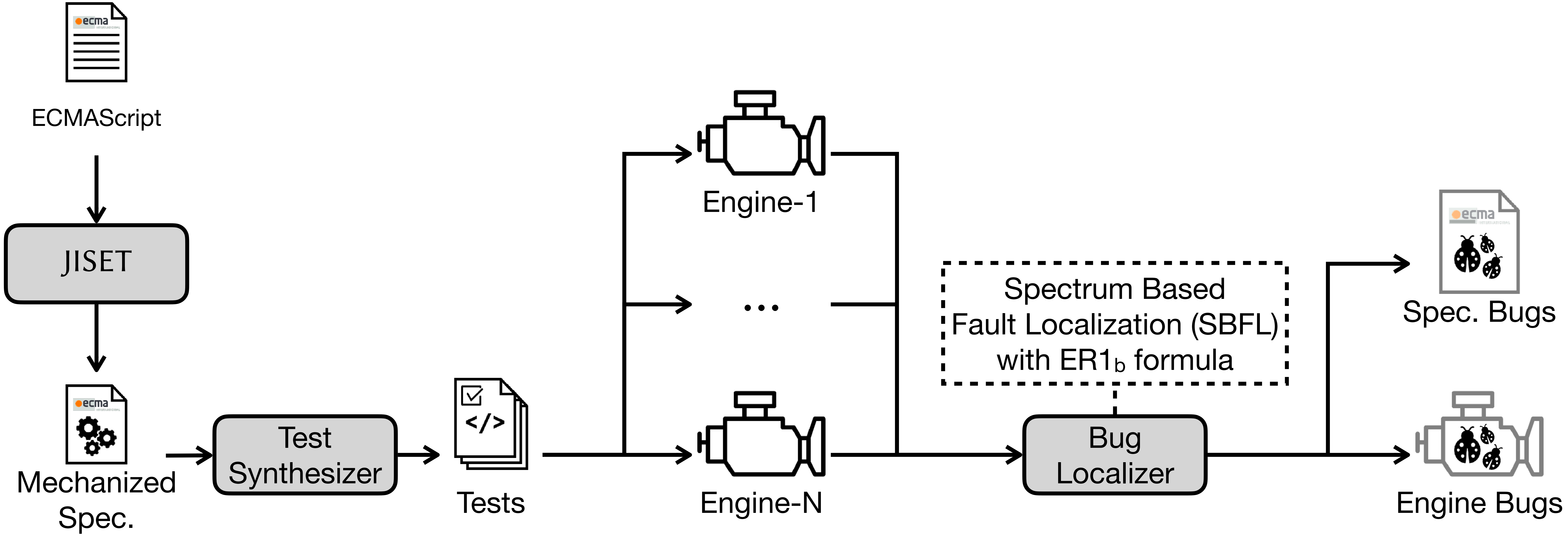


A specification bug in ECMAScript

An engine bug in GraalVM

JEST

JavaScript Engines and Specification Tester



JEST

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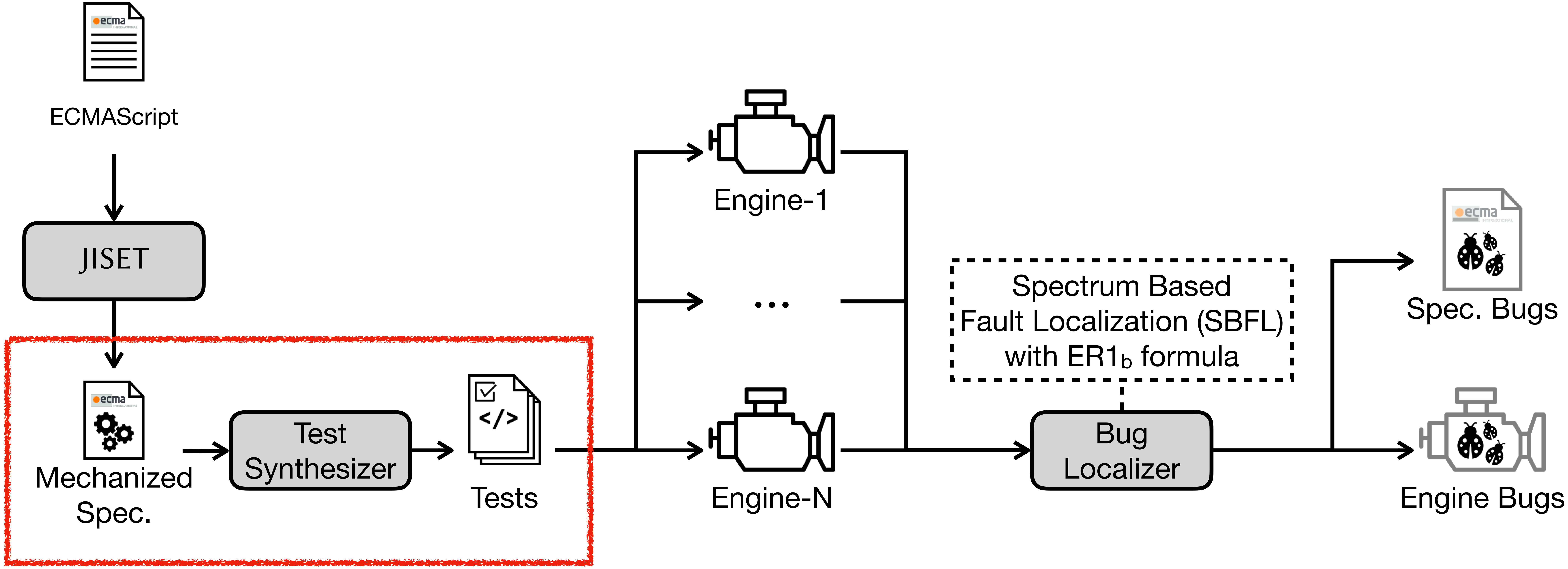
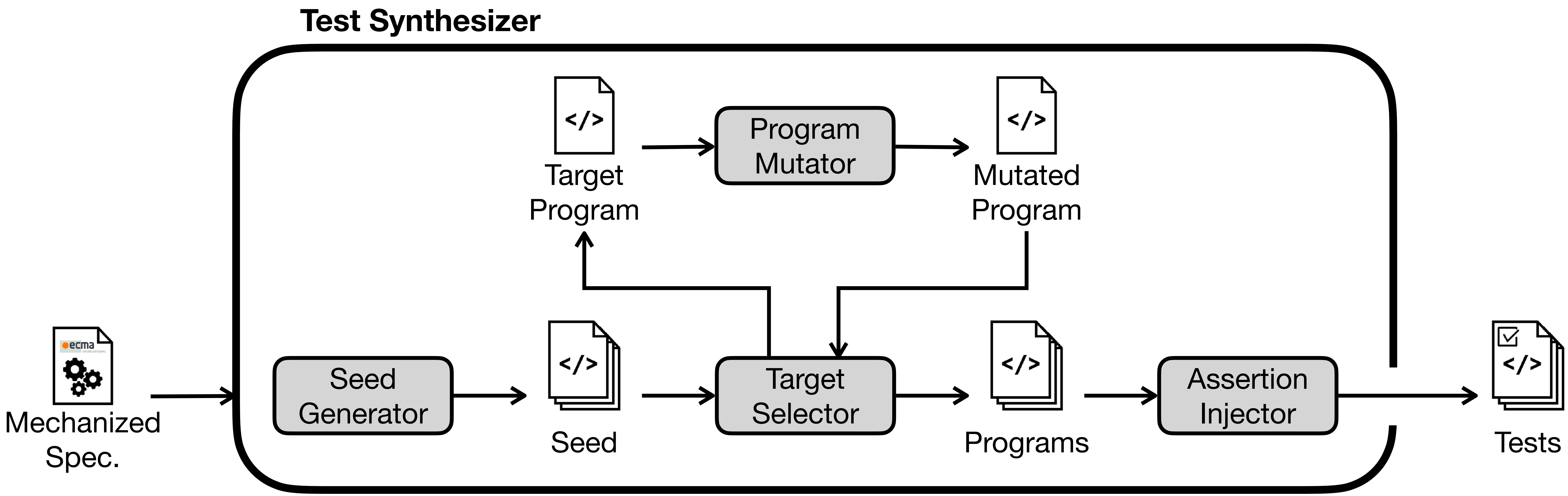


Conformance Test Synthesis



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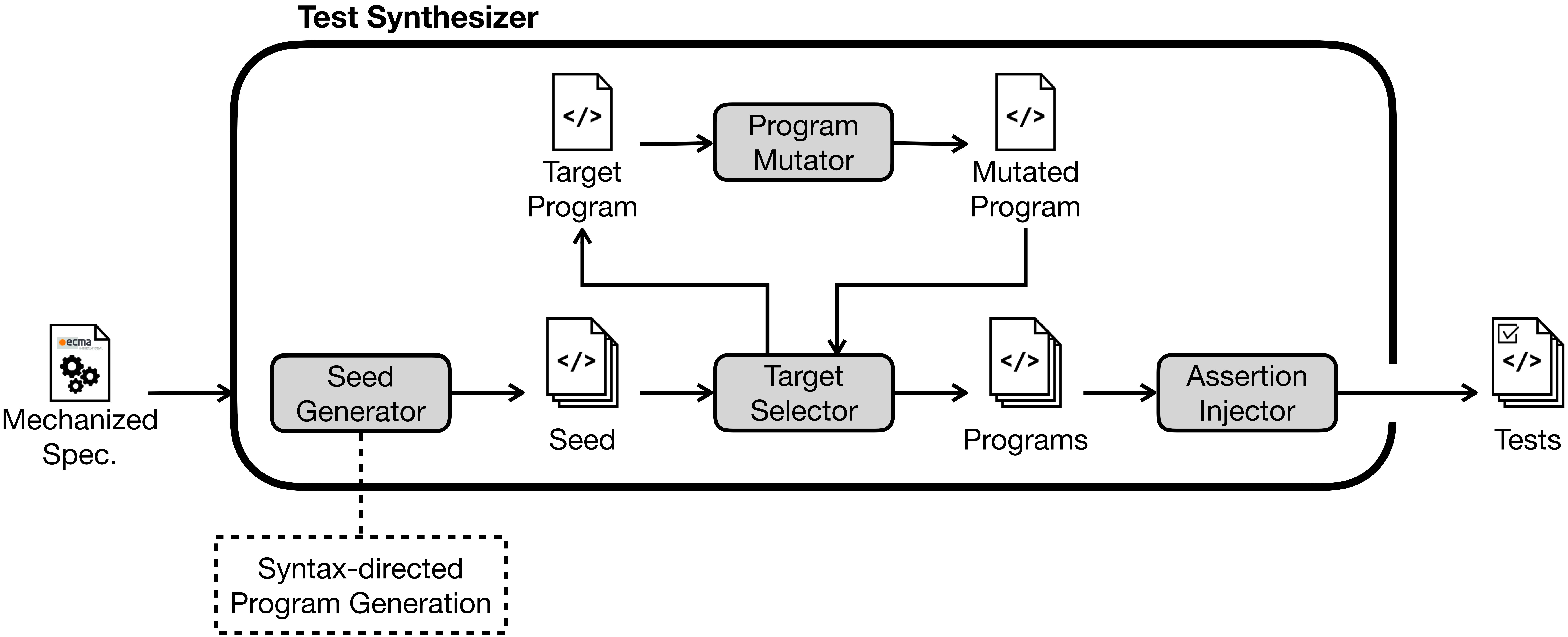

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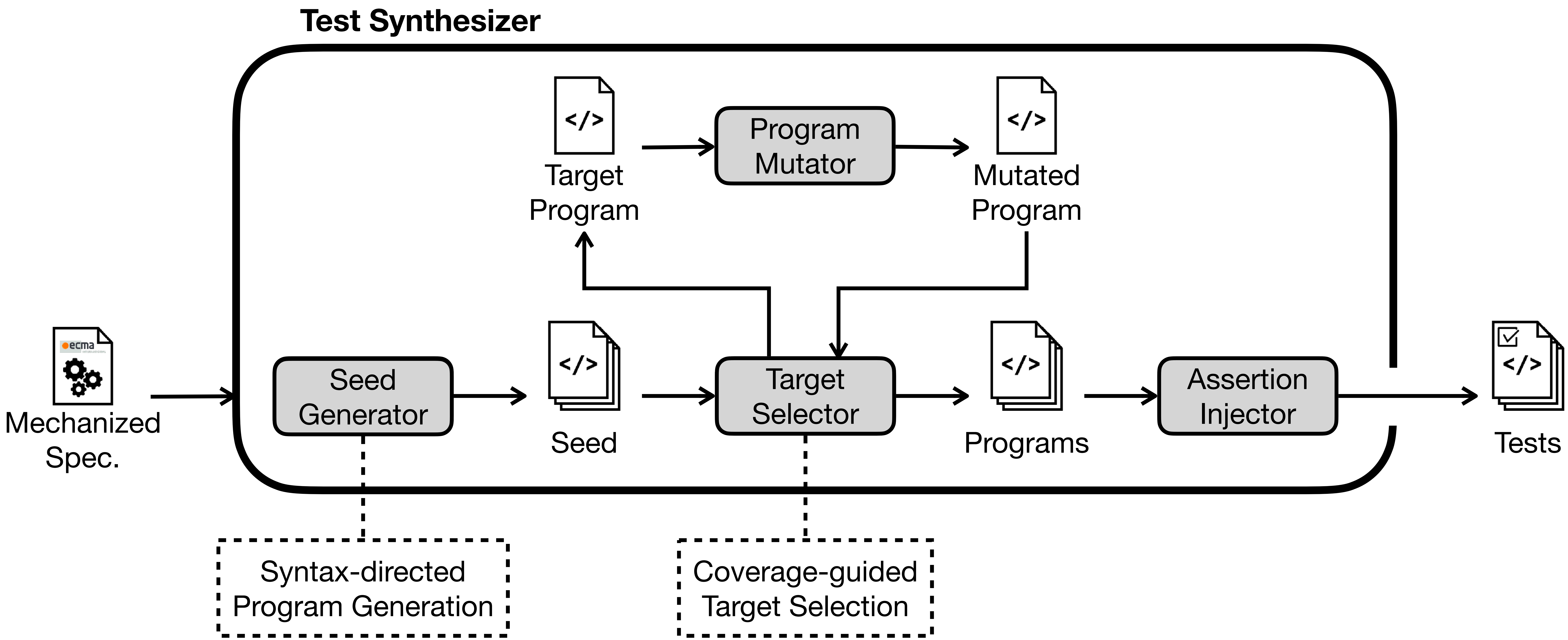

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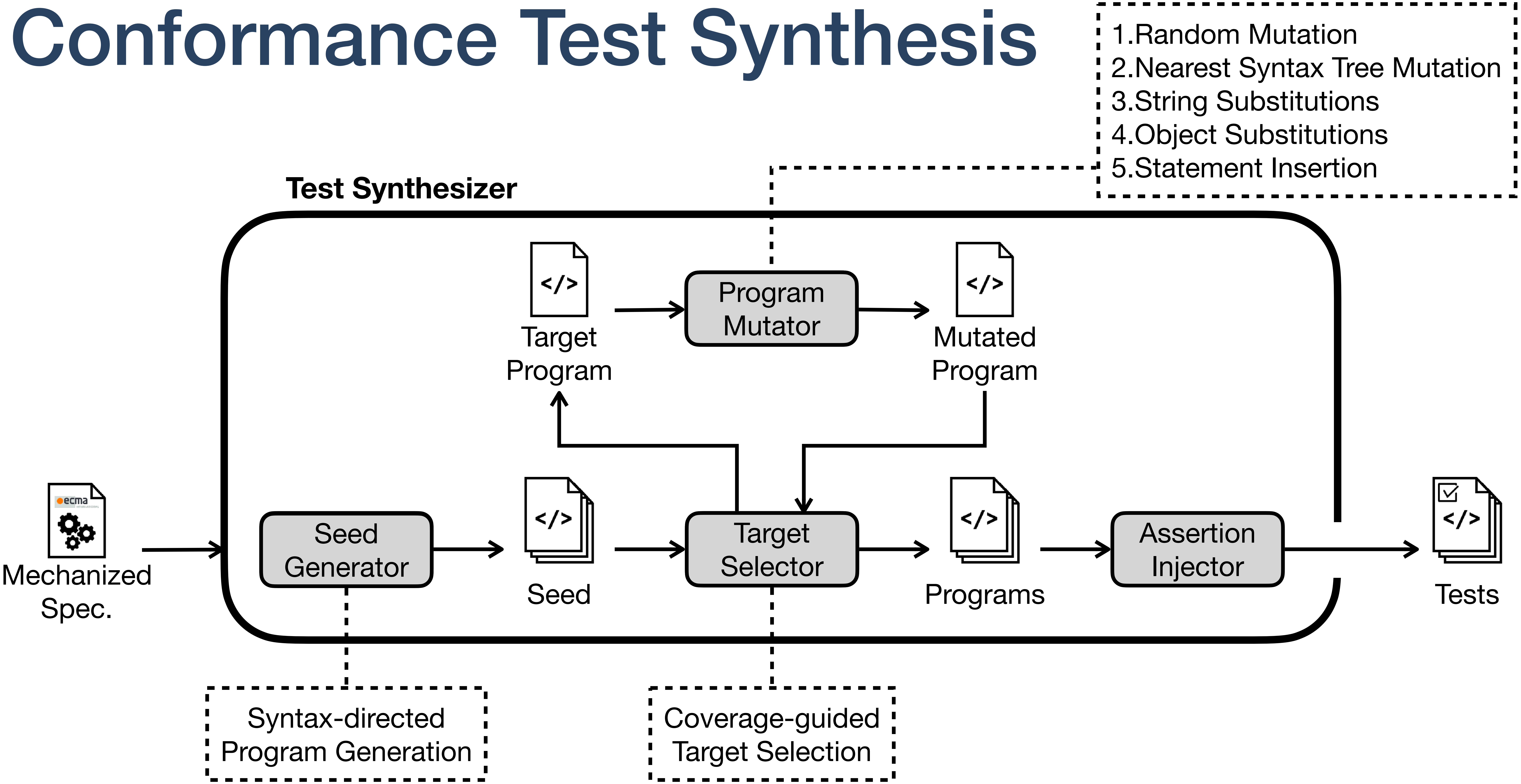

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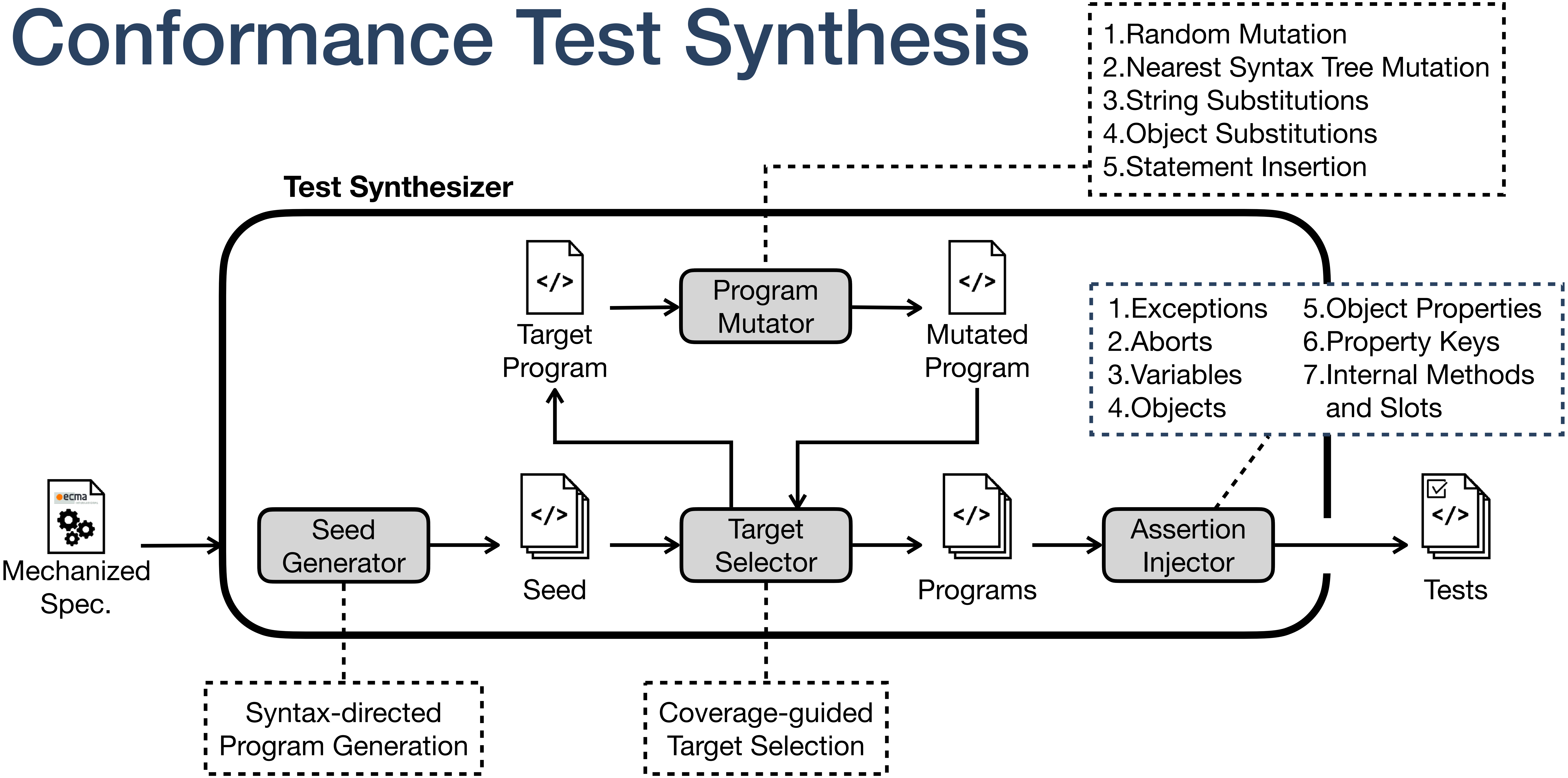
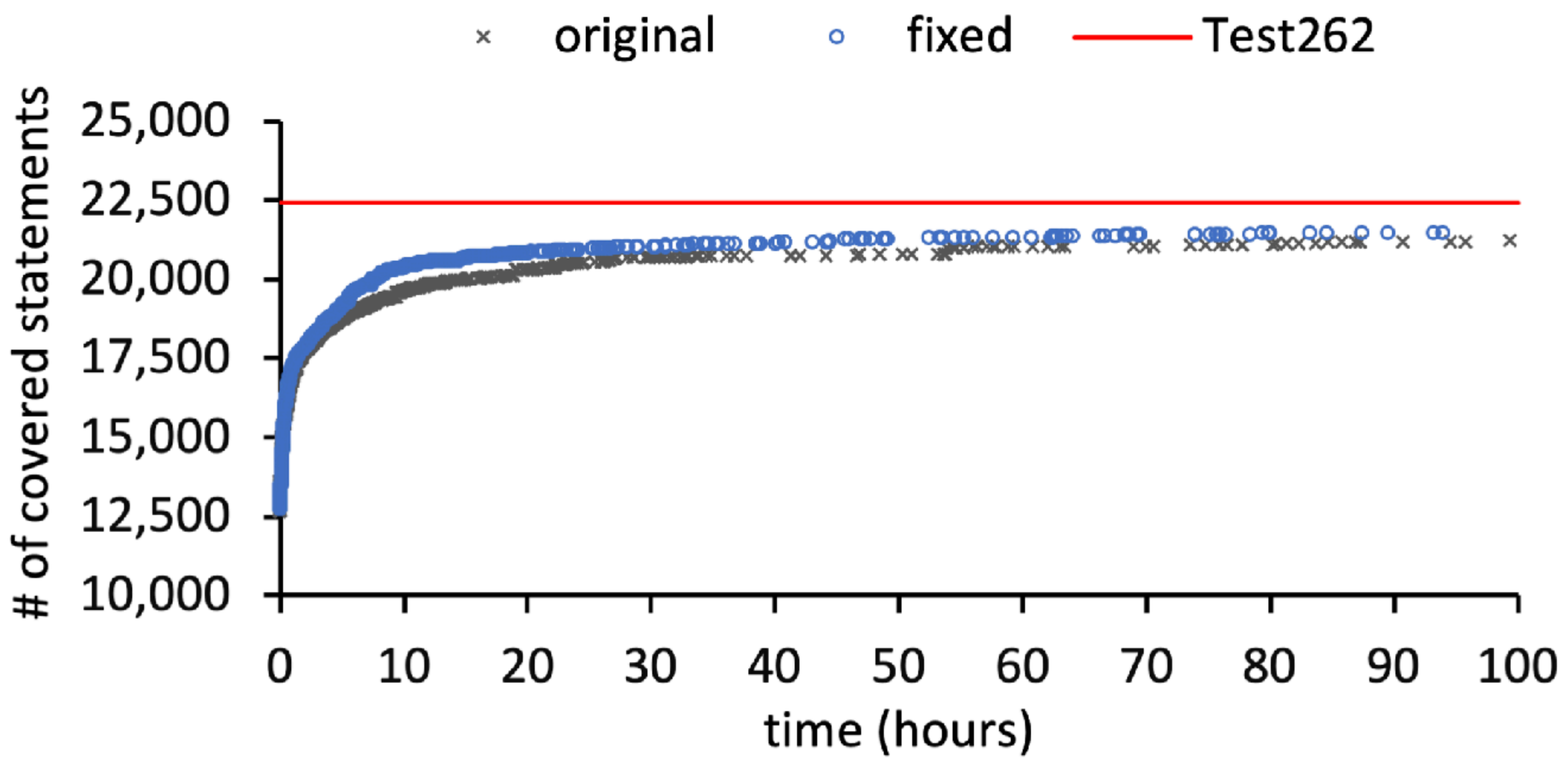


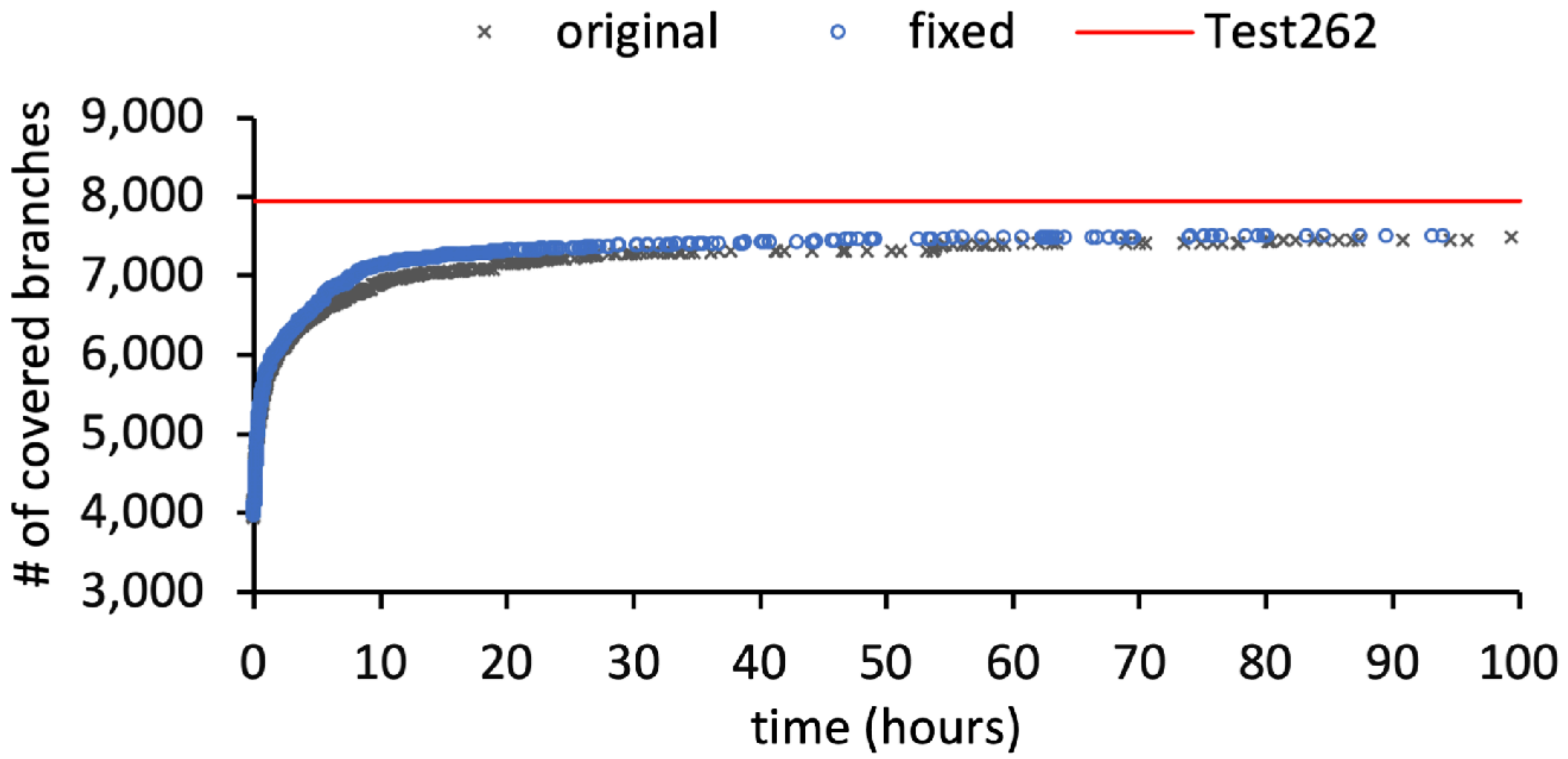
Evaluation

- **JavaScript Specification**
  - ECMAScript 2020 (ES11) - released in June 2020
- **JavaScript Engines**
  - V8 - v8.3 by Google
  - GraalJS - v20.1.0 by Oracle
  - QuickJS - 2020-04-12 by Fabrice Bellard
  - Moddable XS - v10.3.0 by Moddable Tech Inc.

RQ1: Coverage of Synthesized Tests



(a) Statement coverage



(b) Branch coverage

- 1,700 **Synthesized Tests in** 100 hours
- **Syntax Coverage:** 97.79% (397 / 406)
- **Semantics Coverage**
  - Statement: 86.67% (21,230 / 24,495)
  - Branch: 77.95% (7,480 / 9,596)

RQ2: Bug Detection in JavaScript Engines

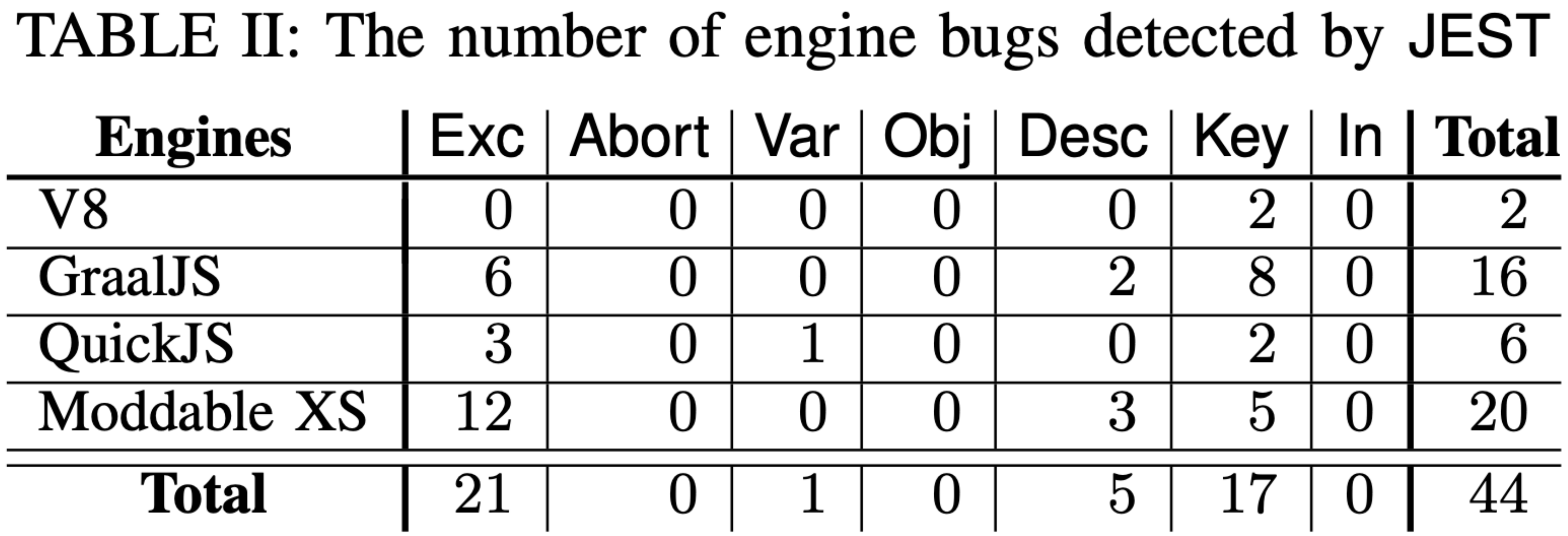
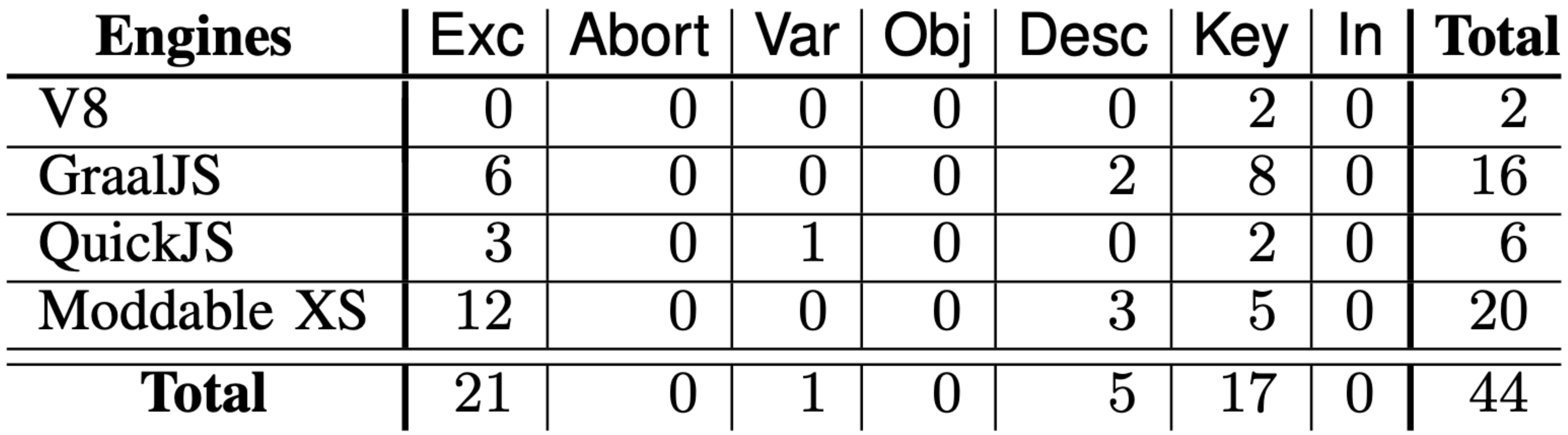


TABLE II: The number of engine bugs detected by JEST

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

RQ2: Bug Detection in JavaScript Engines

TABLE II: The number of engine bugs detected by JEST



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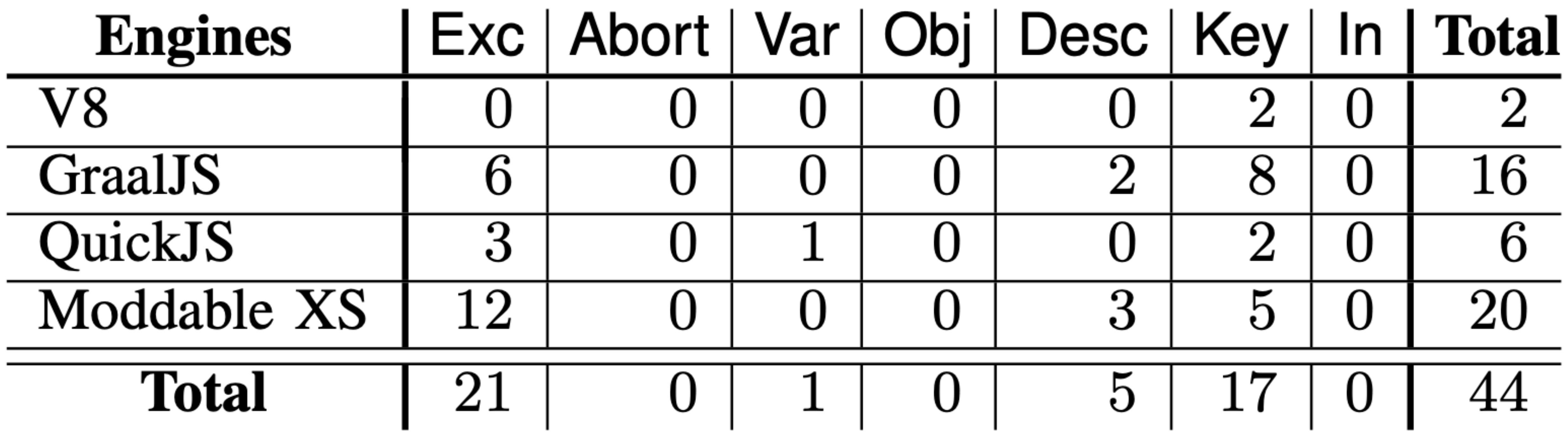
Total	21	0	1	0	5	17	0	44

```
function f (... { x = x }) { return x; } var y = f();
```

QuickJS initializes 'x' with 'undefined' instead of throwing a 'ReferenceError'

RQ2: Bug Detection in JavaScript Engines

TABLE II: The number of engine bugs detected by JEST



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function f (... { x = x }) { return x; } var y = f();
```

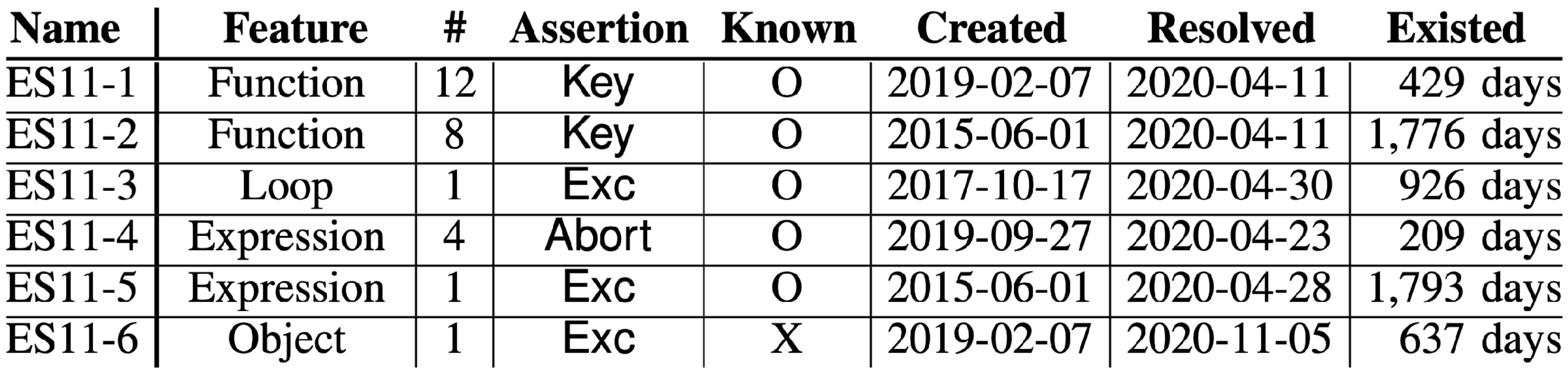
QuickJS initializes '`x`' with '`undefined`' instead of throwing a '`ReferenceError`'

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

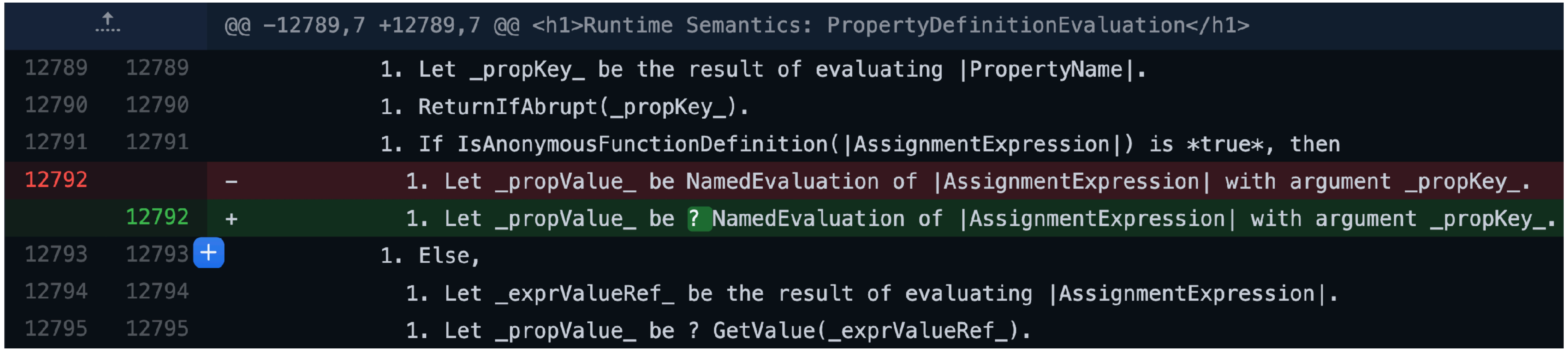
GraalJS crashes with an exception '`java.lang.IllegalStateException`'

RQ3: Bug Detection in ECMAScript

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



```
@@ -12789,7 +12789,7 @@ <h1>Runtime Semantics: PropertyDefinitionEvaluation</h1>
          1. Let _propKey_ be the result of evaluating |PropertyName|.
          1. ReturnIfAbrupt(_propKey_).
          1. If IsAnonymousFunctionDefinition(|AssignmentExpression|) is *true*, then
-           1. Let _propValue_ be NamedEvaluation of |AssignmentExpression| with argument _propKey_.
+           1. Let _propValue_ be ? NamedEvaluation of |AssignmentExpression| with argument _propKey_.
          1. Else,
            1. Let _exprValueRef_ be the result of evaluating |AssignmentExpression|.
            1. Let _propValue_ be ? GetValue(_exprValueRef_).
```

https://github.com/tc39/ecma262/pull/2130/files

RQ4: Accuracy of Bug Localization

- **64 out of 71 bugs are semantics bugs**

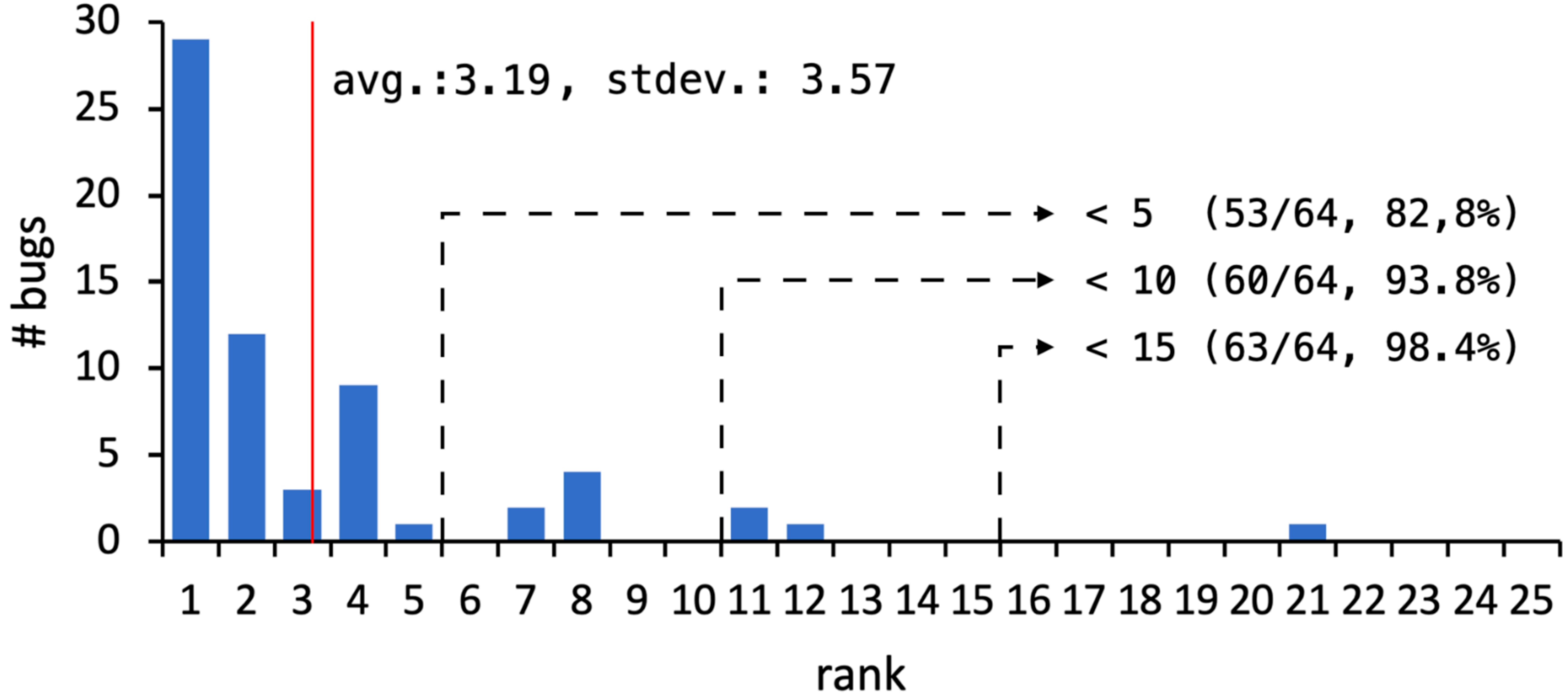
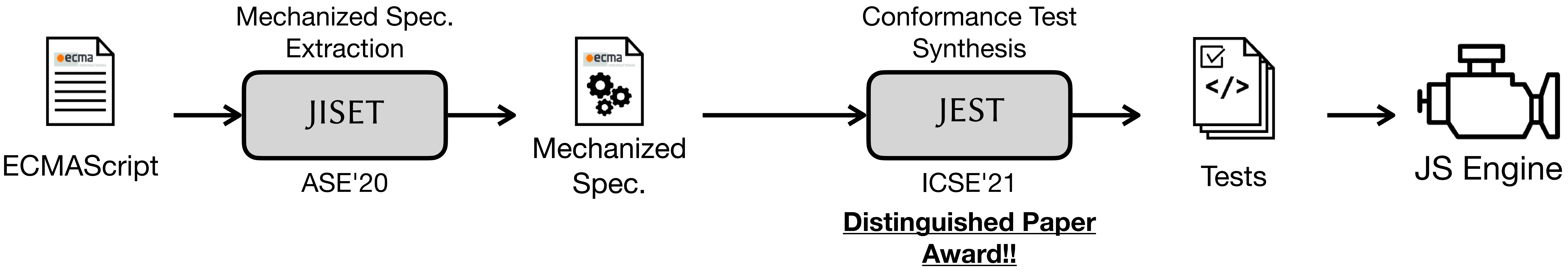


Fig. 5: Ranks of algorithms that caused the bugs detected by JEST

Future Work



Mechanized Spec. Extraction

JISET

ASE'20

Conformance Test Synthesis

JEST

ICSE'21

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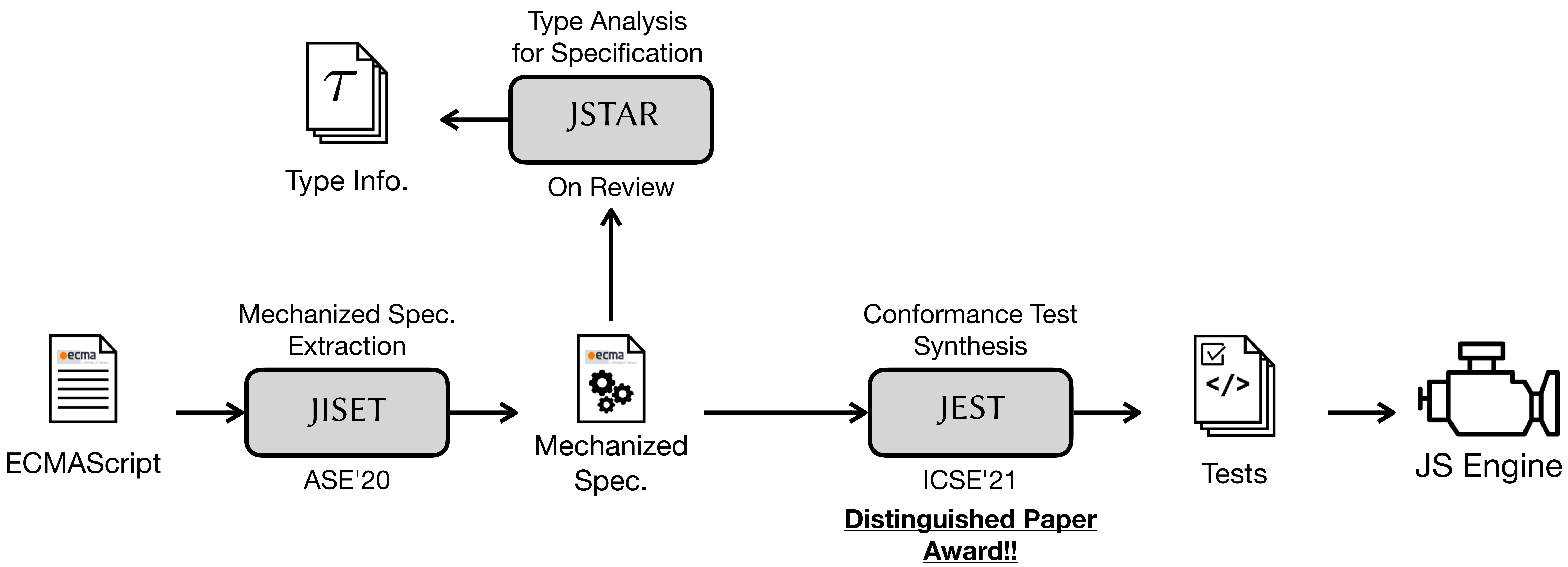
Future Work


Type Analysis
for Specification
JSTAR
On Review
Type Info.
Mechanized Spec.
Extraction
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ASE'20
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Mechanized
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Synthesis
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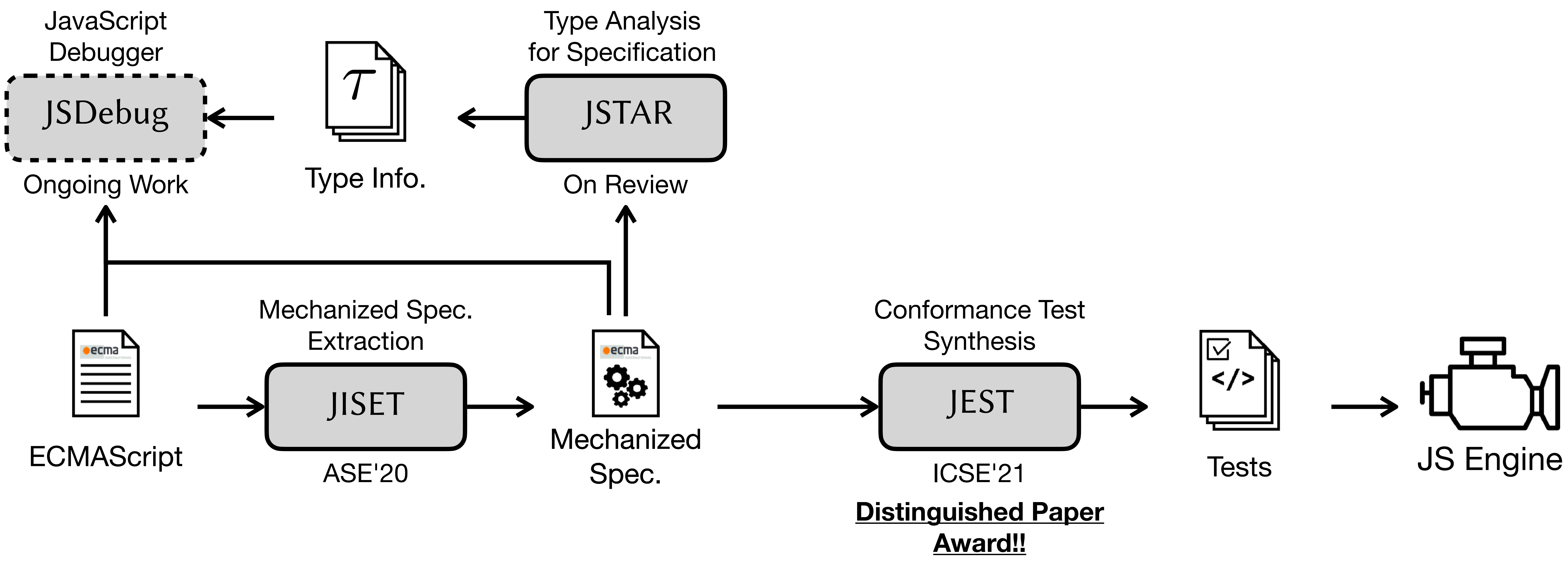
JS Engine

Future Work



JavaScript Debugger

JSDebug

Ongoing Work

Type Info.

Type Analysis for Specification

JSTAR

On Review

ECMAScript

Mechanized Spec. Extraction

JISET

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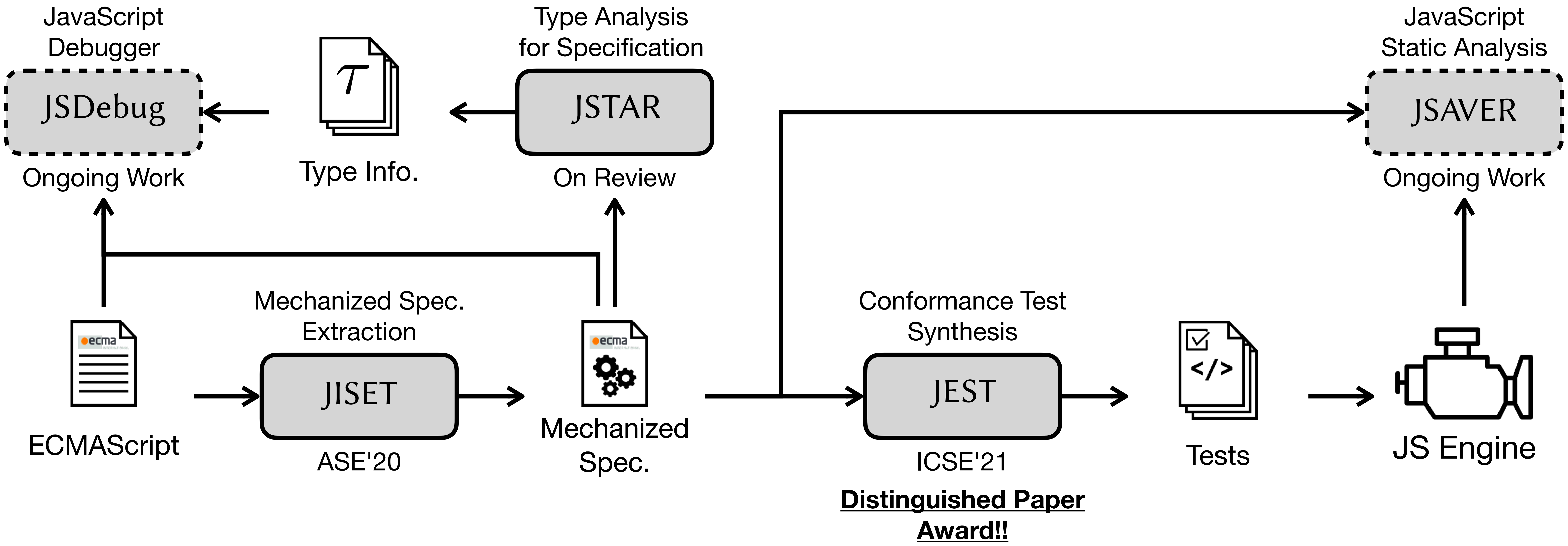
Future Work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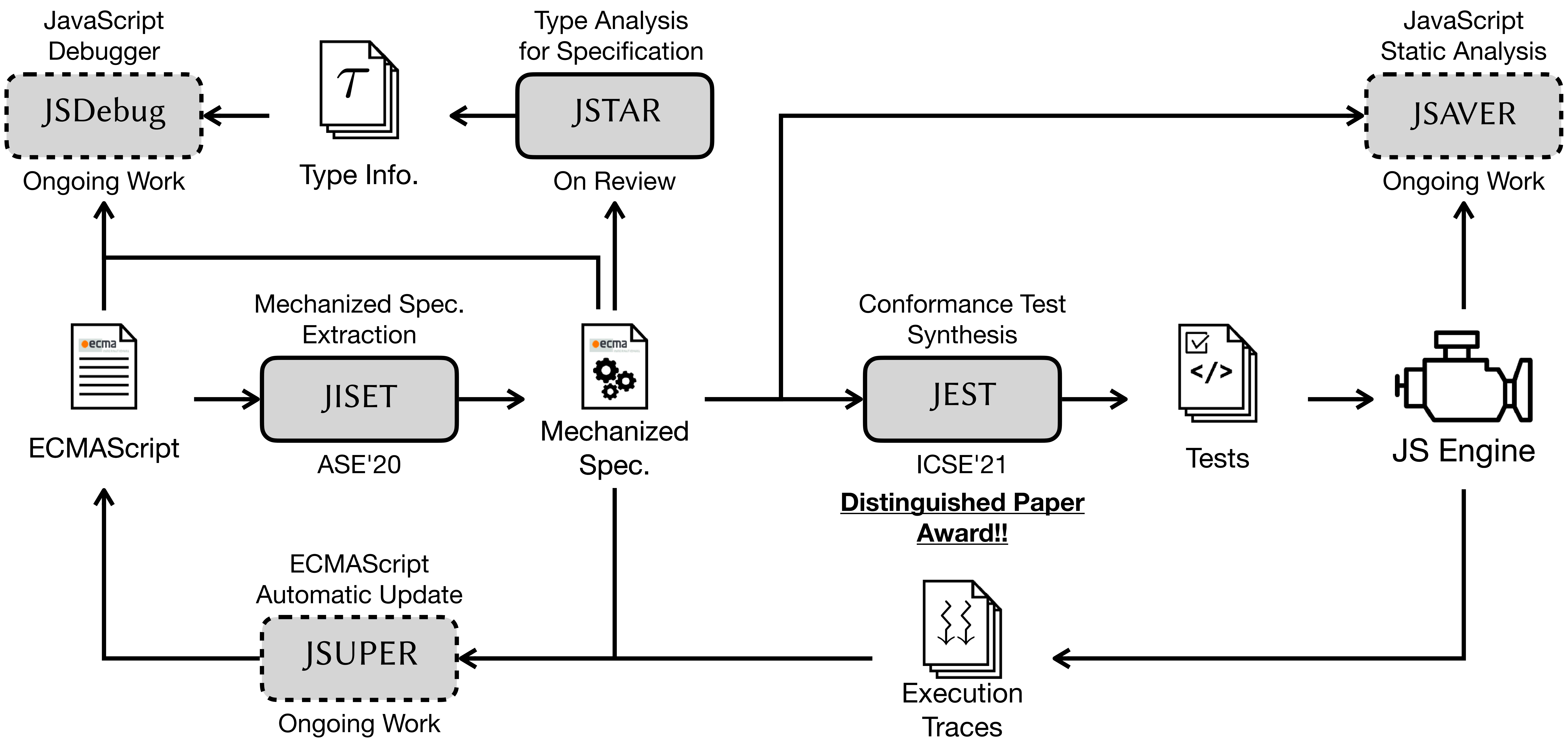

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