KOREA UNIVERSITY

기계화 명세를 이용한 자바스크립트 언어의 설계와 구현

컴퓨터학과 2023년 봄학기 콜로퀴움

박지혁

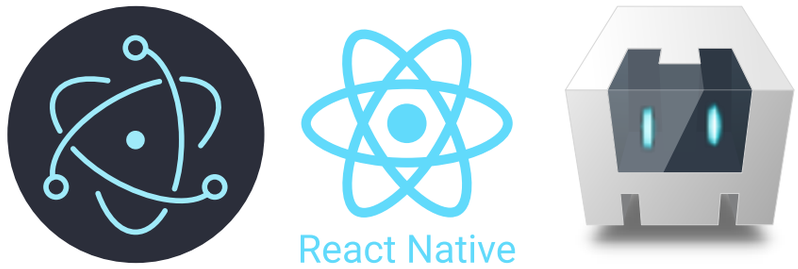
고려대학교 컴퓨터학과
프로그래밍 언어 연구실

2023. 03. 15

자바스크립트는 어디에나 있다

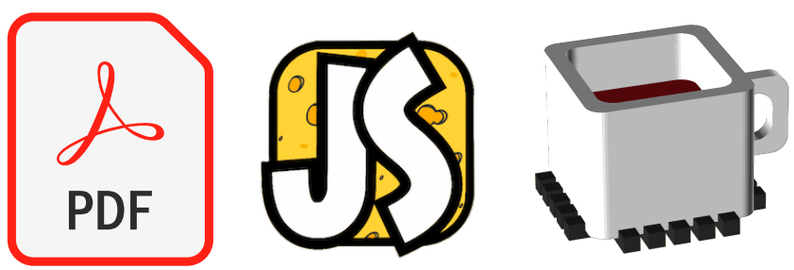
클라이언트-사이드 프로그래밍

JS



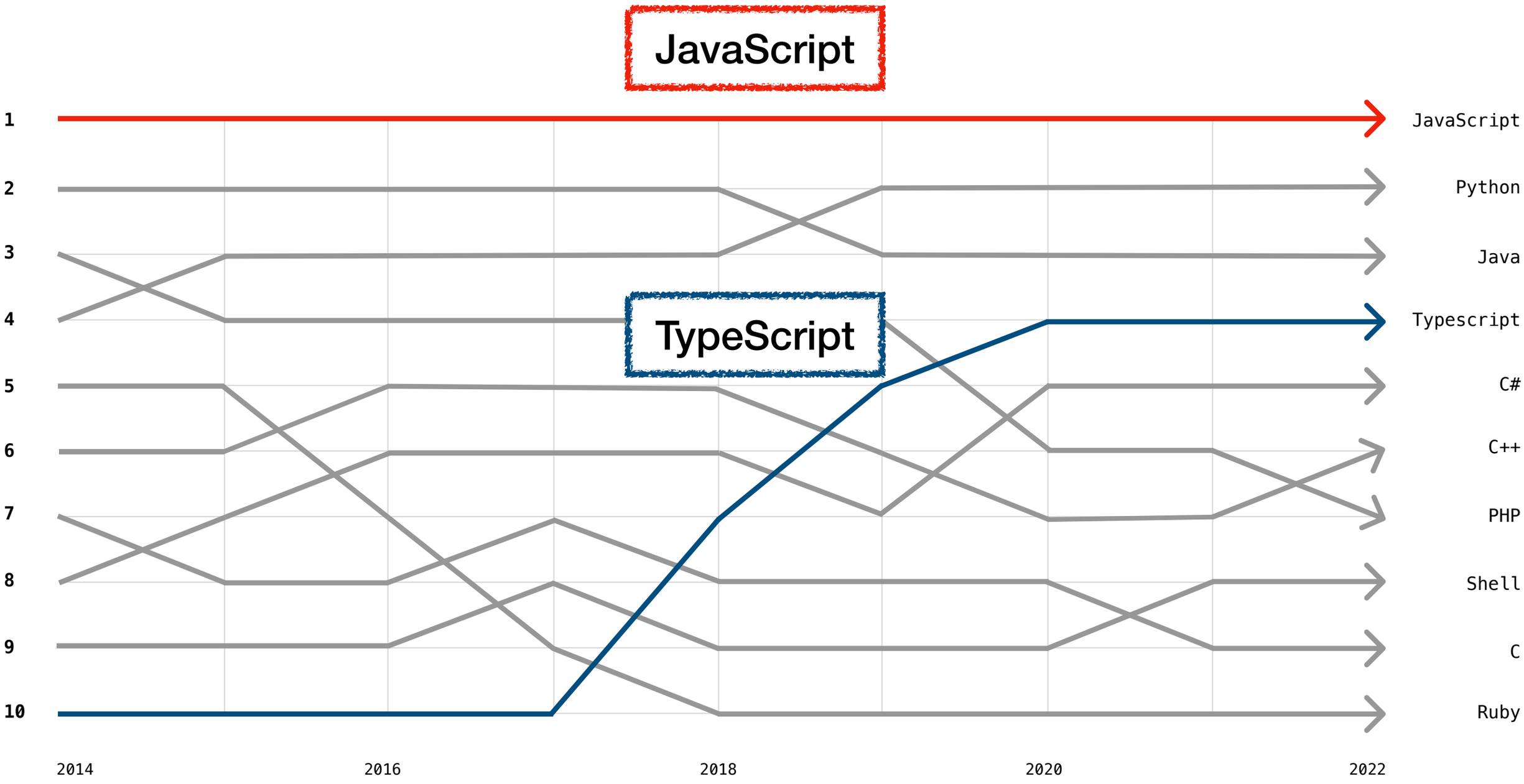
모바일/데스크톱 어플리케이션

서버-사이드 프로그래밍



그 외 (PDF, 사물 인터넷, 마이크로컨트롤러, etc.)

자바스크립트는 어디에나 있다



https://octoverse.github.com/

하지만, 자바스크립트는 복잡하다..

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

언제나 `false`를 반환할까?

NO!!

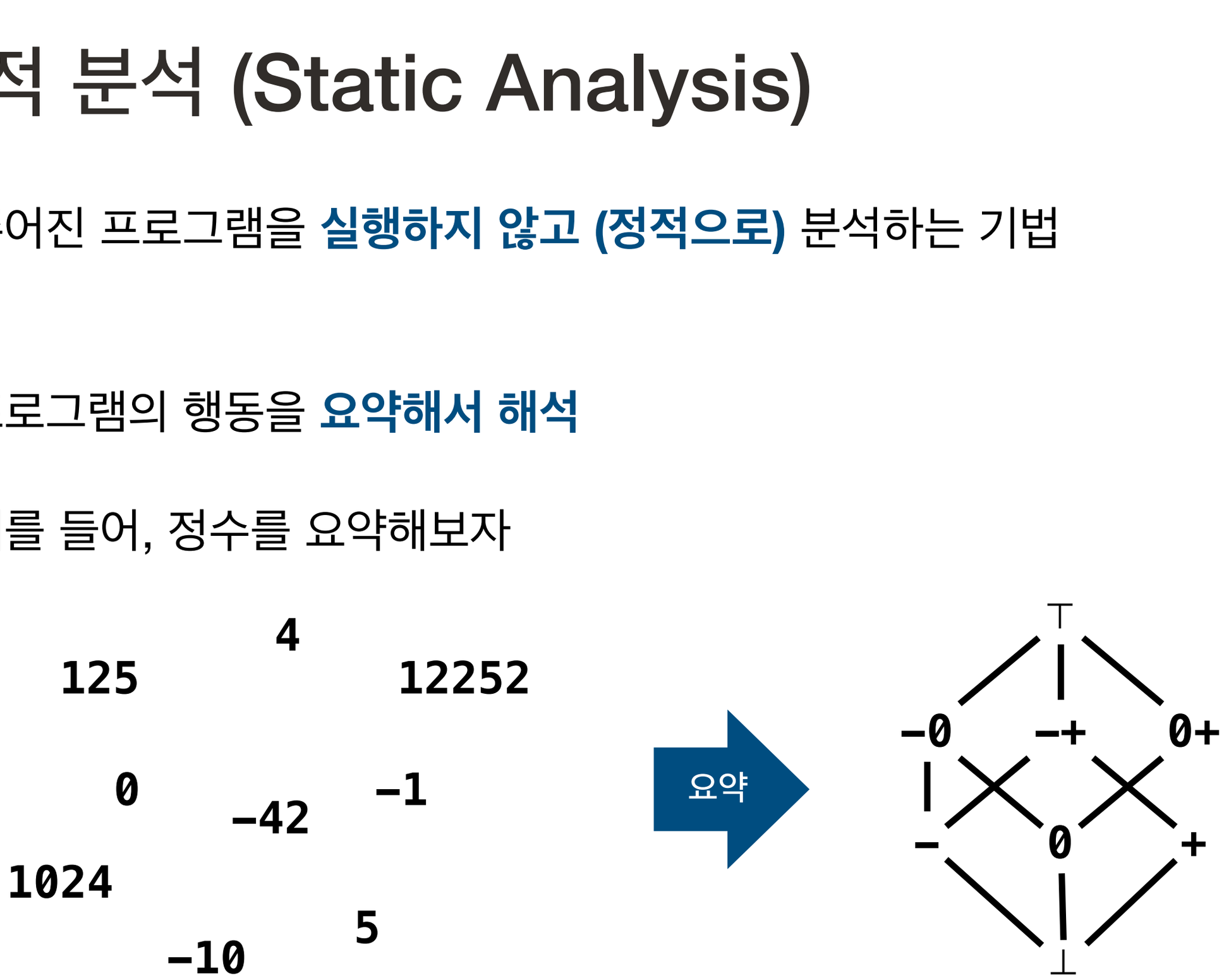
```
f([]) -> [] == ![]
      -> [] == false
      -> +[] == +false
      -> 0 == 0
      -> true
```

정적 분석 (Static Analysis)

- 주어진 프로그램을 **실행하지 않고 (정적으로)** 분석하는 기법

- 프로그램의 행동을 **요약해서 해석**

  예를 들어, 정수를 요약해보자



정적 분석 (Static Analysis)

```
function f(x) {
  // x == ⊤
  if (x == 0) {
    // x == 0
    return 0;
    // [RETURN] 0
  } else if (x < 0) {
    // x == -
    return -x;
    // [RETURN] +
  } else {
    // x == +
    return x;
    // [RETURN] +
  }
}// [RETURN] 0+
```

실제 실행

f(-4) = 4 **f(0) = 0**

. . . **f(-42) = 42**

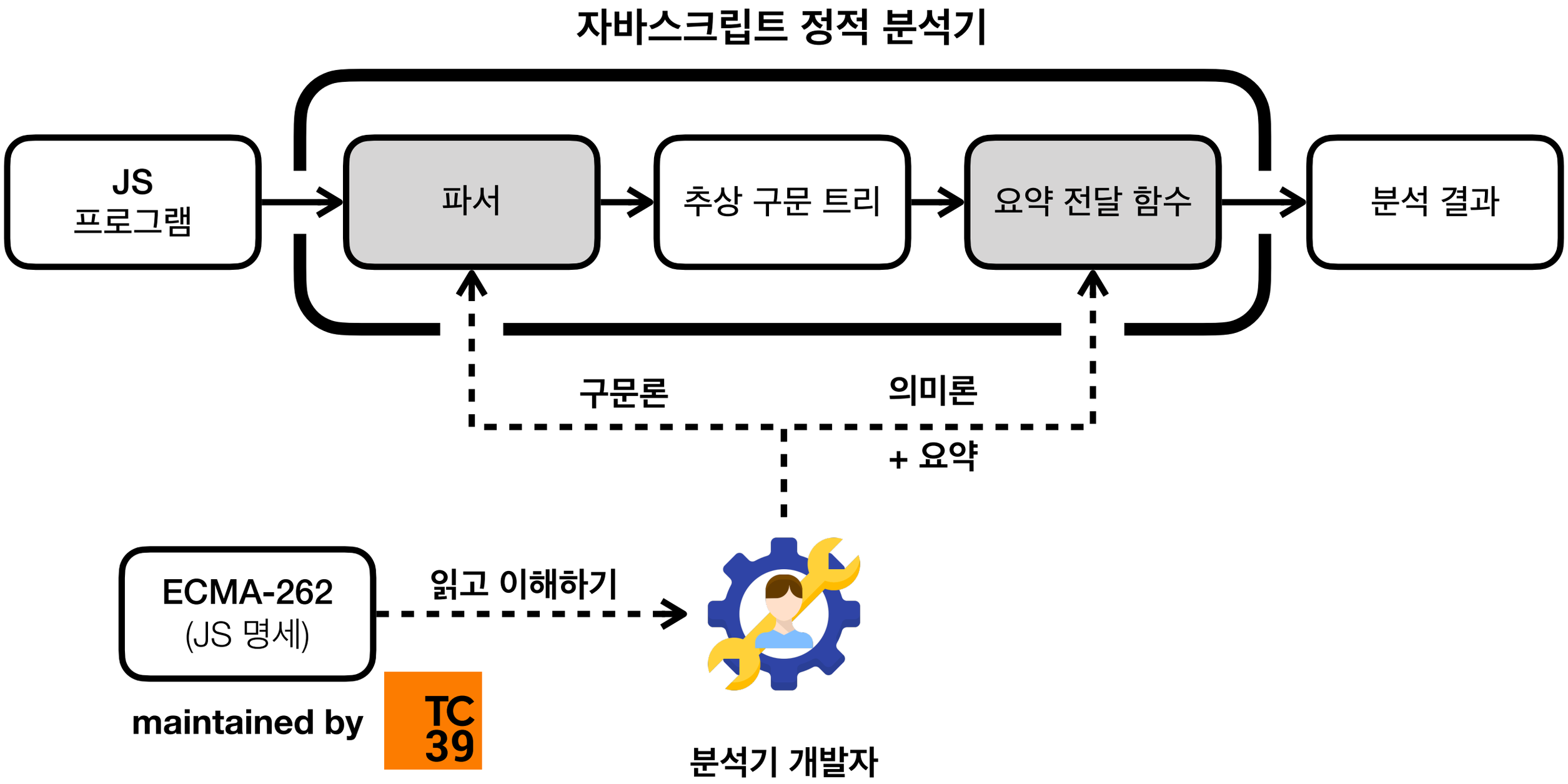
f(5) = 5 **. . .**

요약 해석

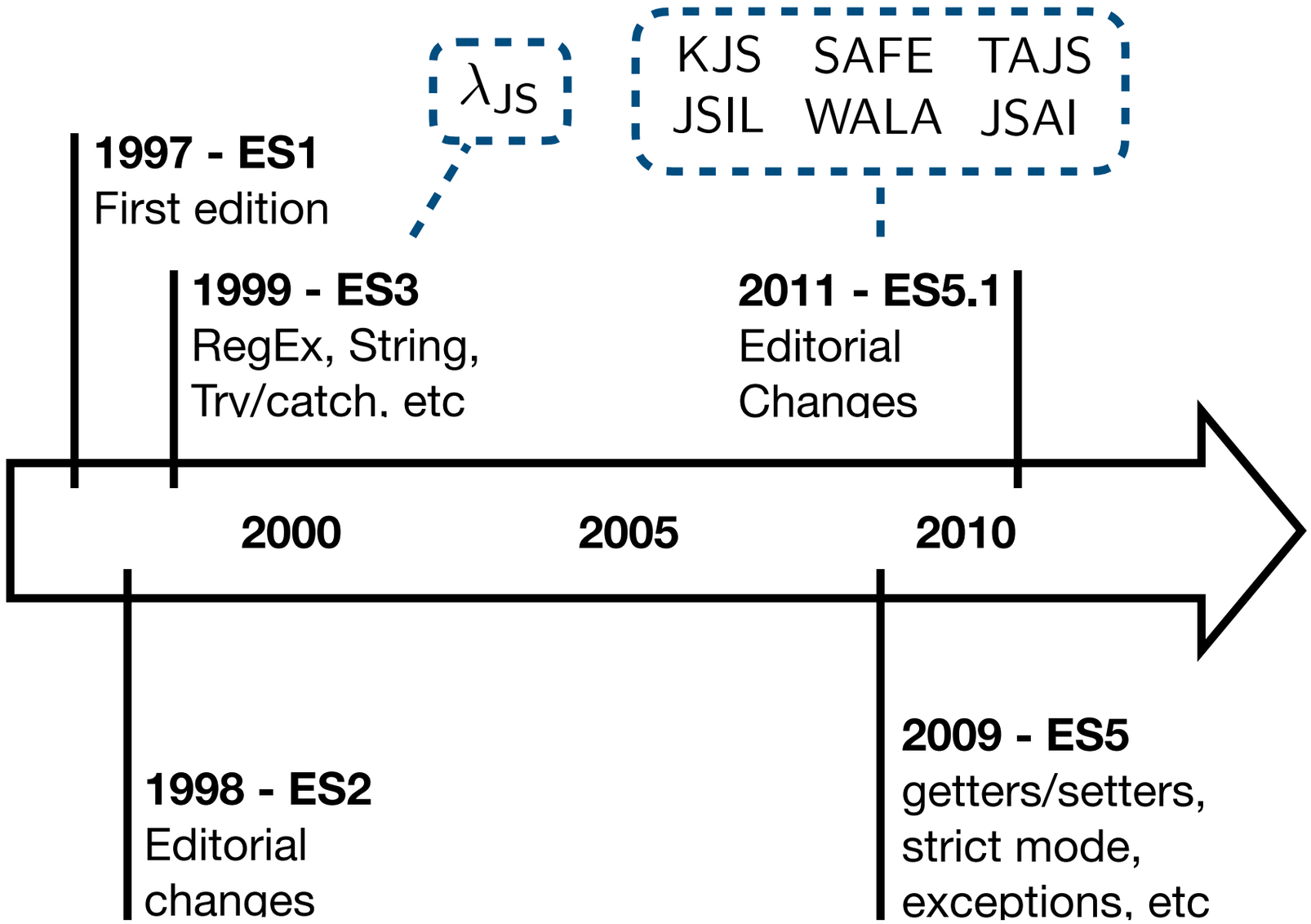
f(⊤) = 0+

타입 추론 (분석) ⊆

자바스크립트를 위한 정적 분석



문제: 빠르게 성장하는 자바스크립트



문제: 빠르게 성장하는 자바스크립트

TC 39

λ_{JS}

KJS SAFE TAJS
JSIL WALA JSAI

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

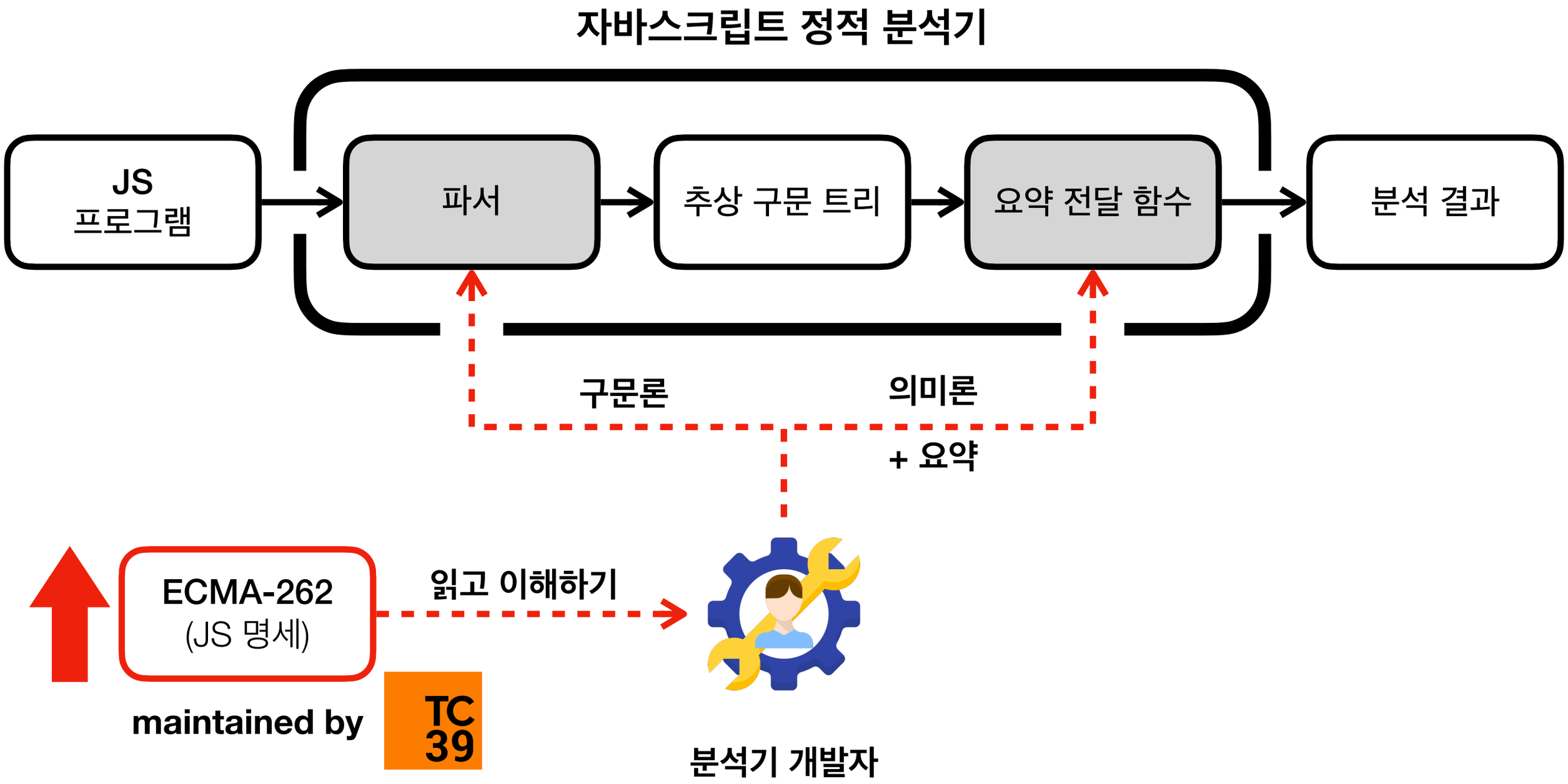
2022 - ES13

2000 2005 2010 2015 2020

ES2022 (ES13) - 833 pages

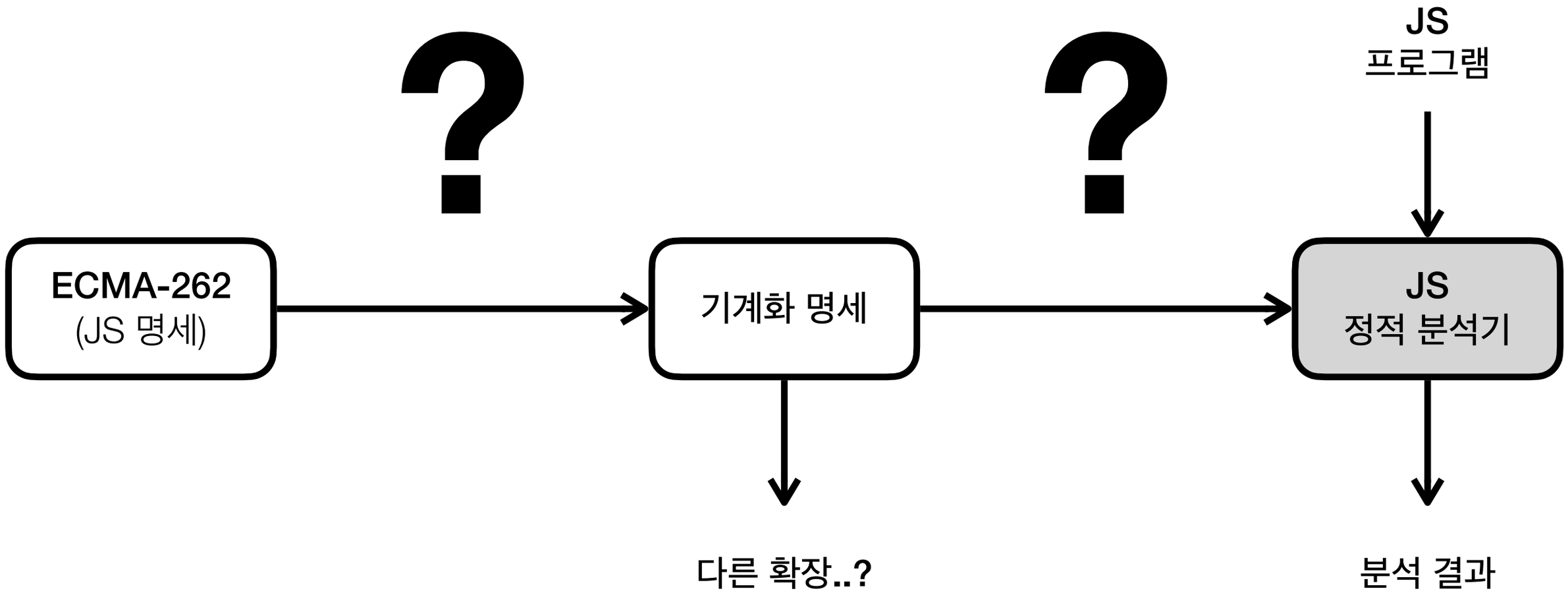
Annual Update

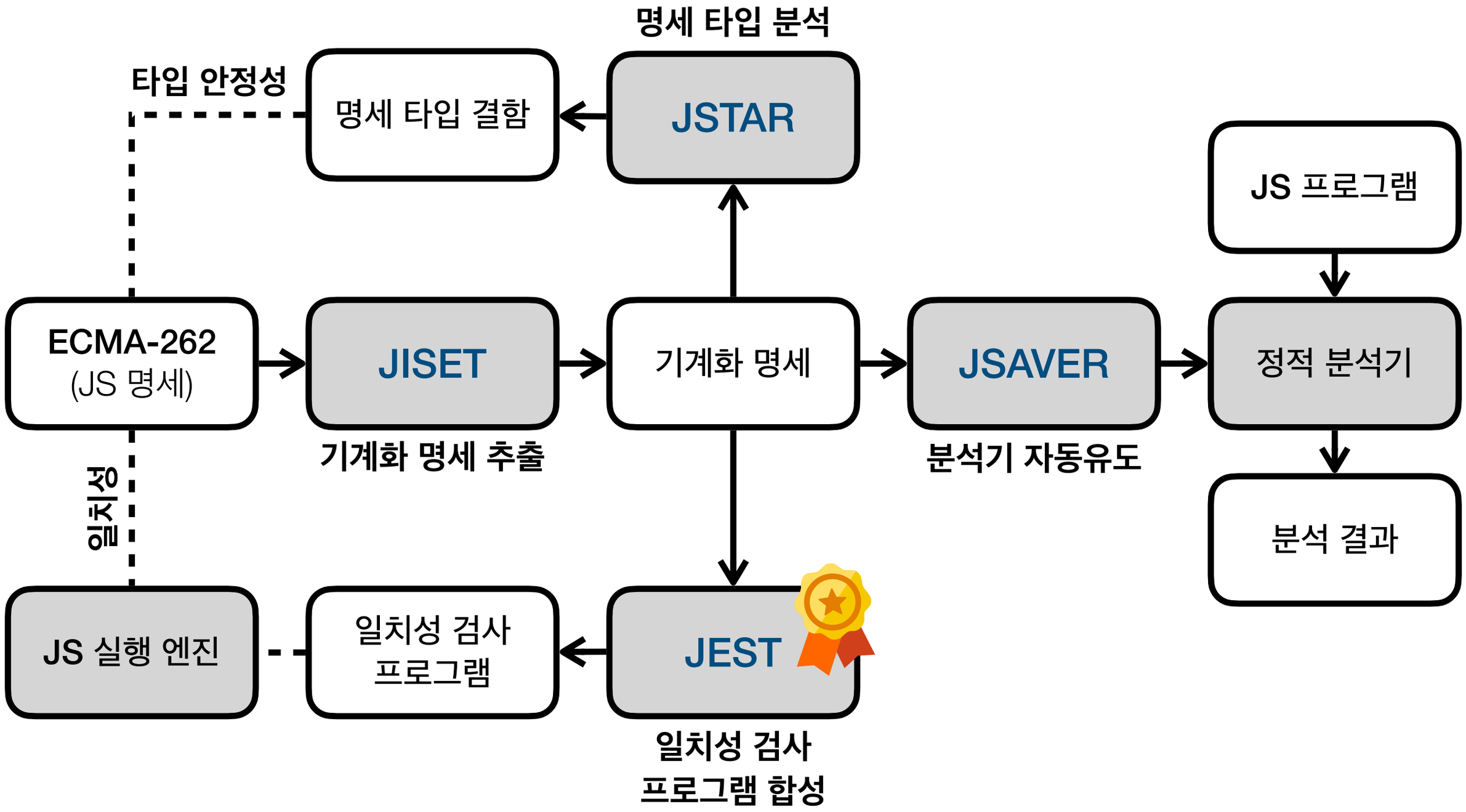
문제: 수동으로 분석기 갱신

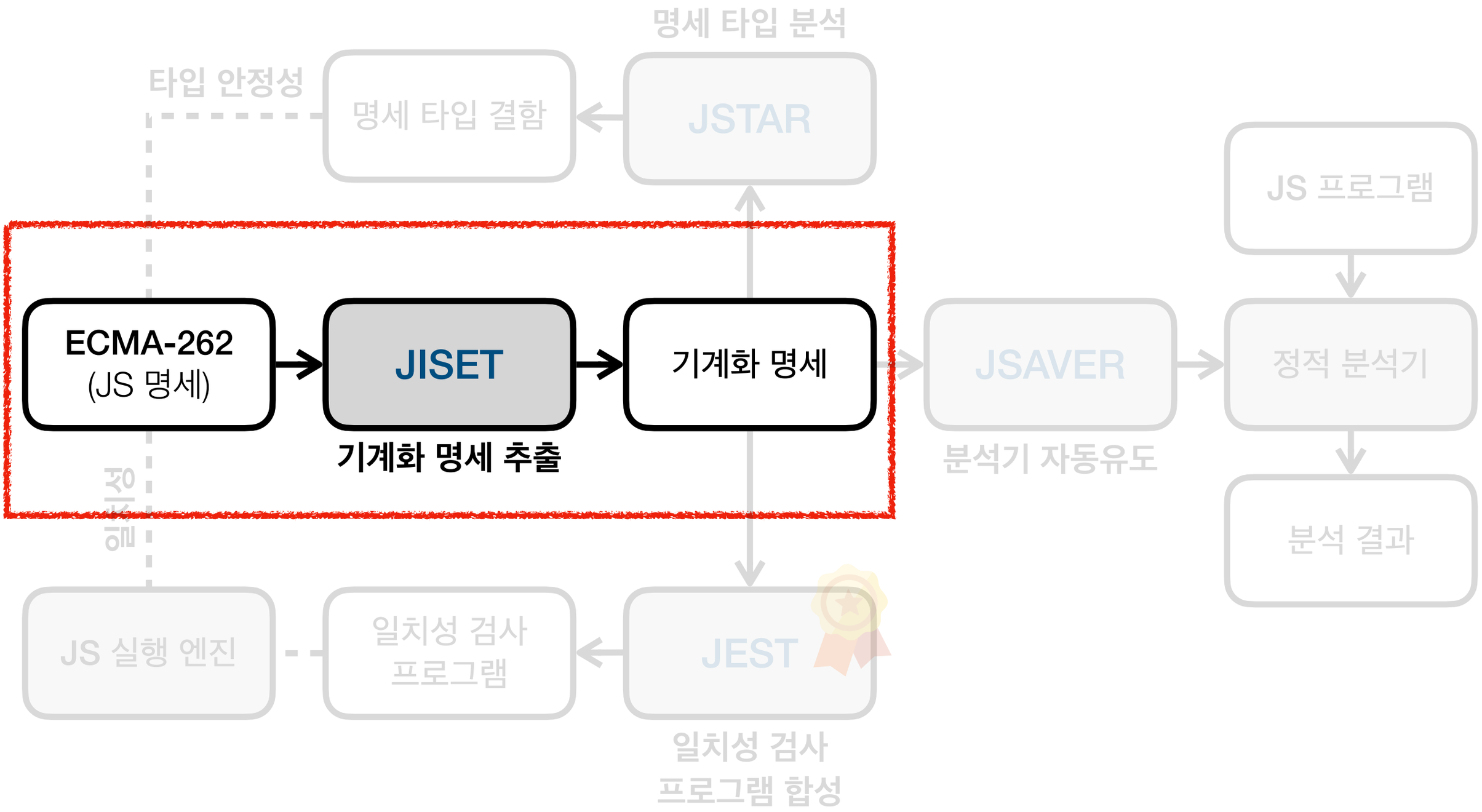


분석기를 자동으로 유도하기?

아이디어: 기계화 명세




명세 타입 분석
타입 안정성
명세 타입 결함
JSTAR
JS 프로그램
ECMA-262
(JS 명세)
JISET
기계화 명세
JSAVER
정적 분석기
기계화 명세 추출
분석기 자동유도
분석 결과
일치성
JS 실행 엔진
일치성 검사
프로그램
JEST
일치성 검사
프로그램 합성



[ASE'20] J. Park, et al. "JISET: JavaScript IR-based Semantics Extraction Toolchain"

ECMA-262 (자바스크립트 명세)

ArrayLiteral[Yield, Await] :

[*Elision*opt]

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

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

구문론

TC 39

The production of *ArrayLiteral* in ES13

13.2.5.2 Runtime Semantics: Evaluation

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

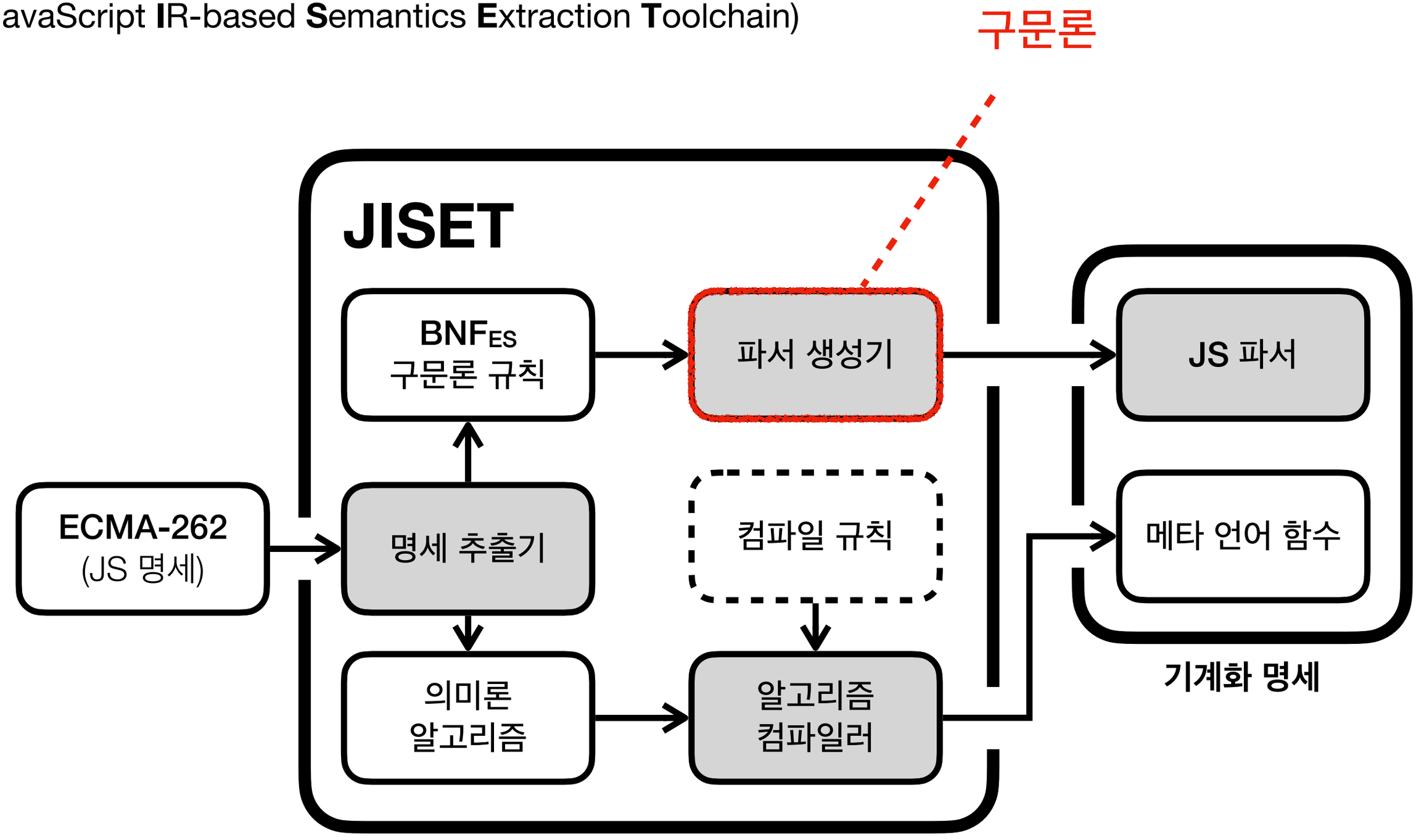
1. Let *array* be ! ArrayCreate(0).
2. Let *nextIndex* be the result of performing ArrayAccumulation for *ElementList* with arguments *array* and 0.
3. ReturnIfAbrupt(*nextIndex*).
4. If *Elision* is present, then
   a. Let *len* be the result of performing ArrayAccumulation for *Elision* with arguments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

의미론

The Evaluation **algorithm for the third alternative of *ArrayLiteral* in ES13**

JISET - ASE'20

(**J**avaScript **I**R-based **S**emantics **E**xtraction **T**oolchain)



JISET - 자동 파서 생성 (구문론)

ArrayLiteral[Yield, Await] :

[*Elision*opt]

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

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

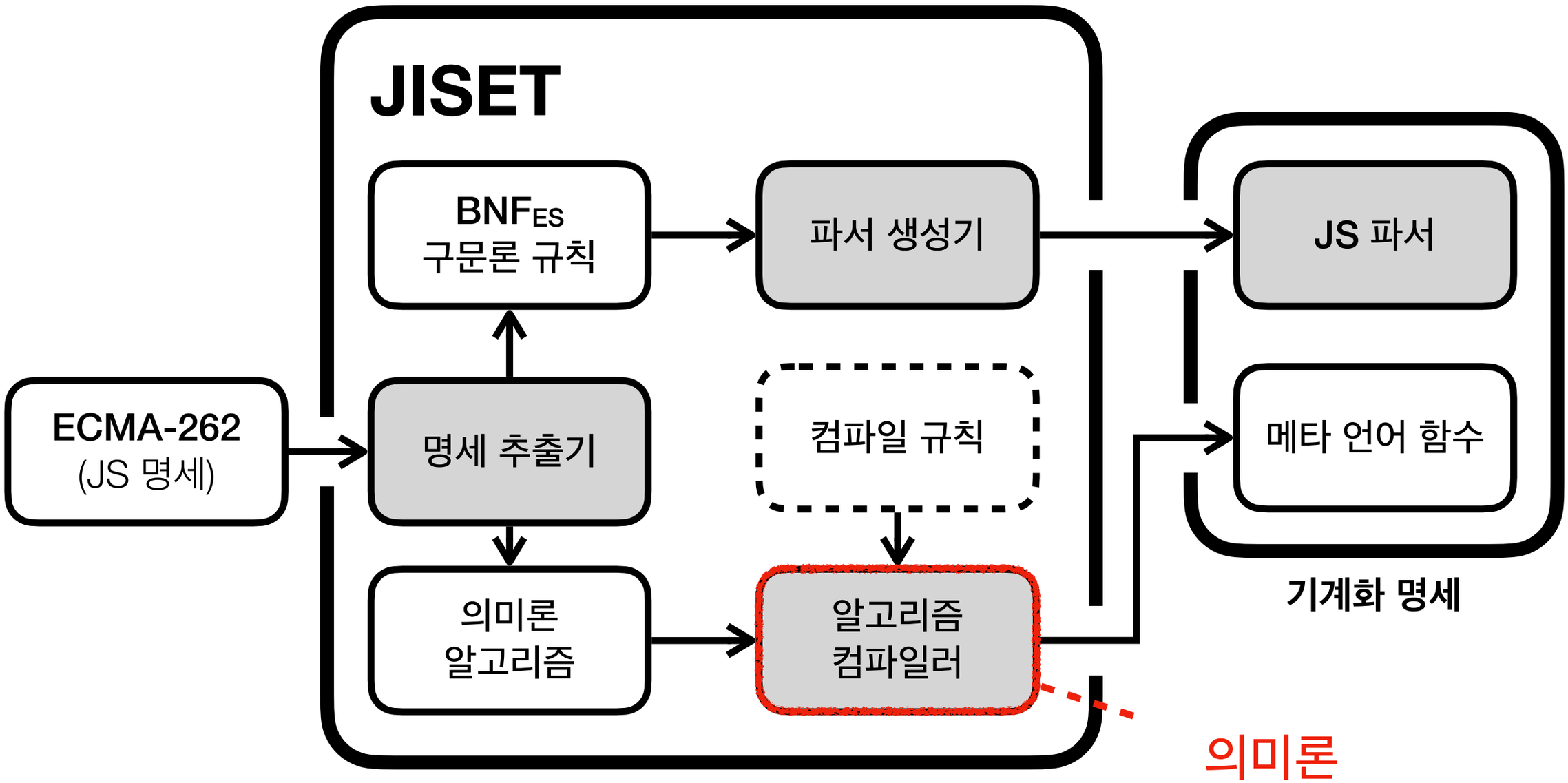
Parsing Expression Grammar (PEG)

```
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] B. Ford, "Parsing Expression Grammars: A Recognition-based Syntactic Foundation"

JISET - ASE'20

(**J**avaScript **I**R-based **S**emantics **E**xtraction **T**oolchain)



JISET - ECMA-262를 위한 메타 언어

- ECMA-262의 추상 알고리즘을 표현하기 위한 **메타 언어**를 정의

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

• • •

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

• • •

JISET - 알고리즘 컴파일러 (의미론)

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*.

추상 알고리즘을 메타 언어로
컴파일하기 위한
118 가지 컴파일 규칙

```
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

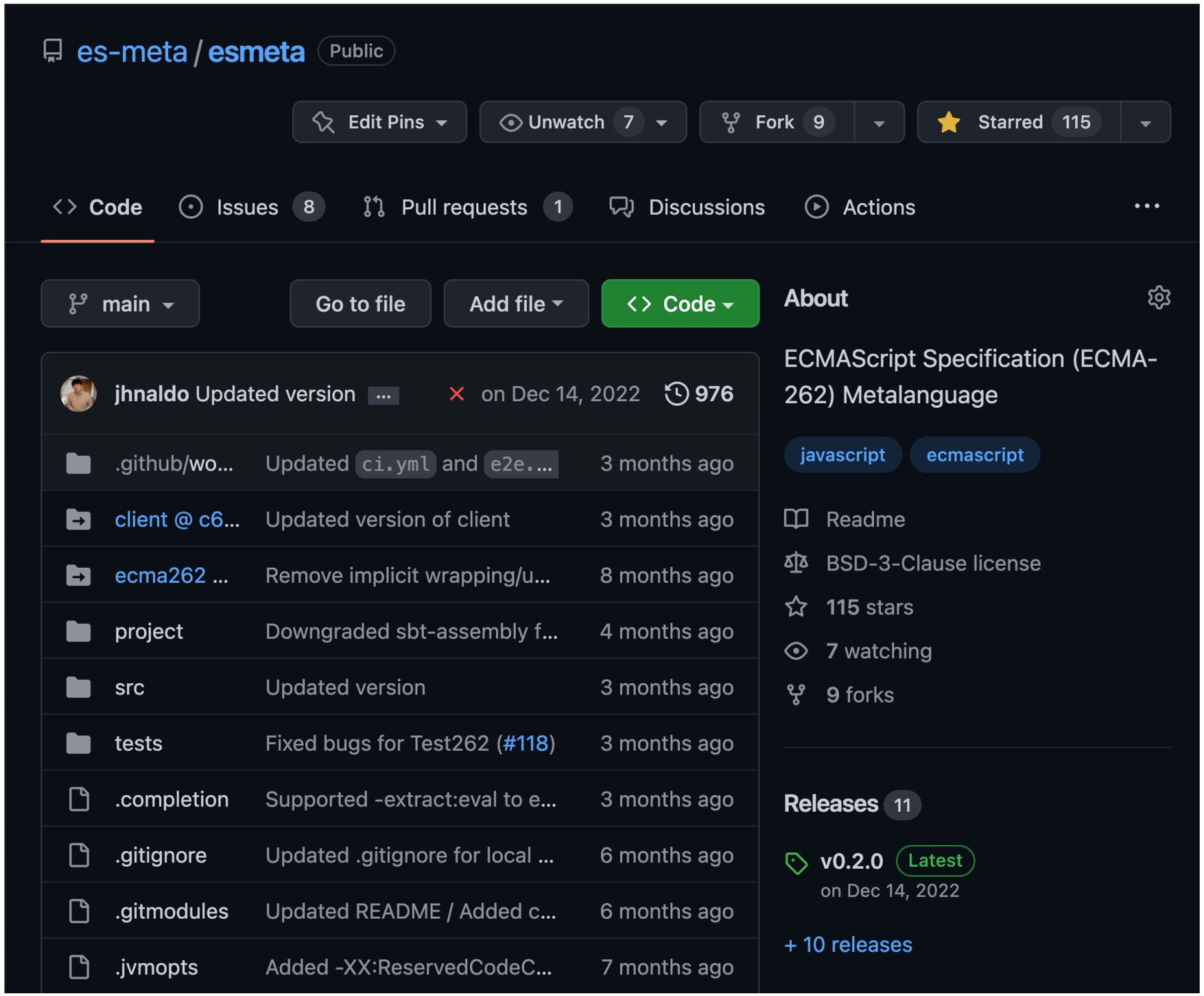
≈ 96% 자동 컴파일

auto manual

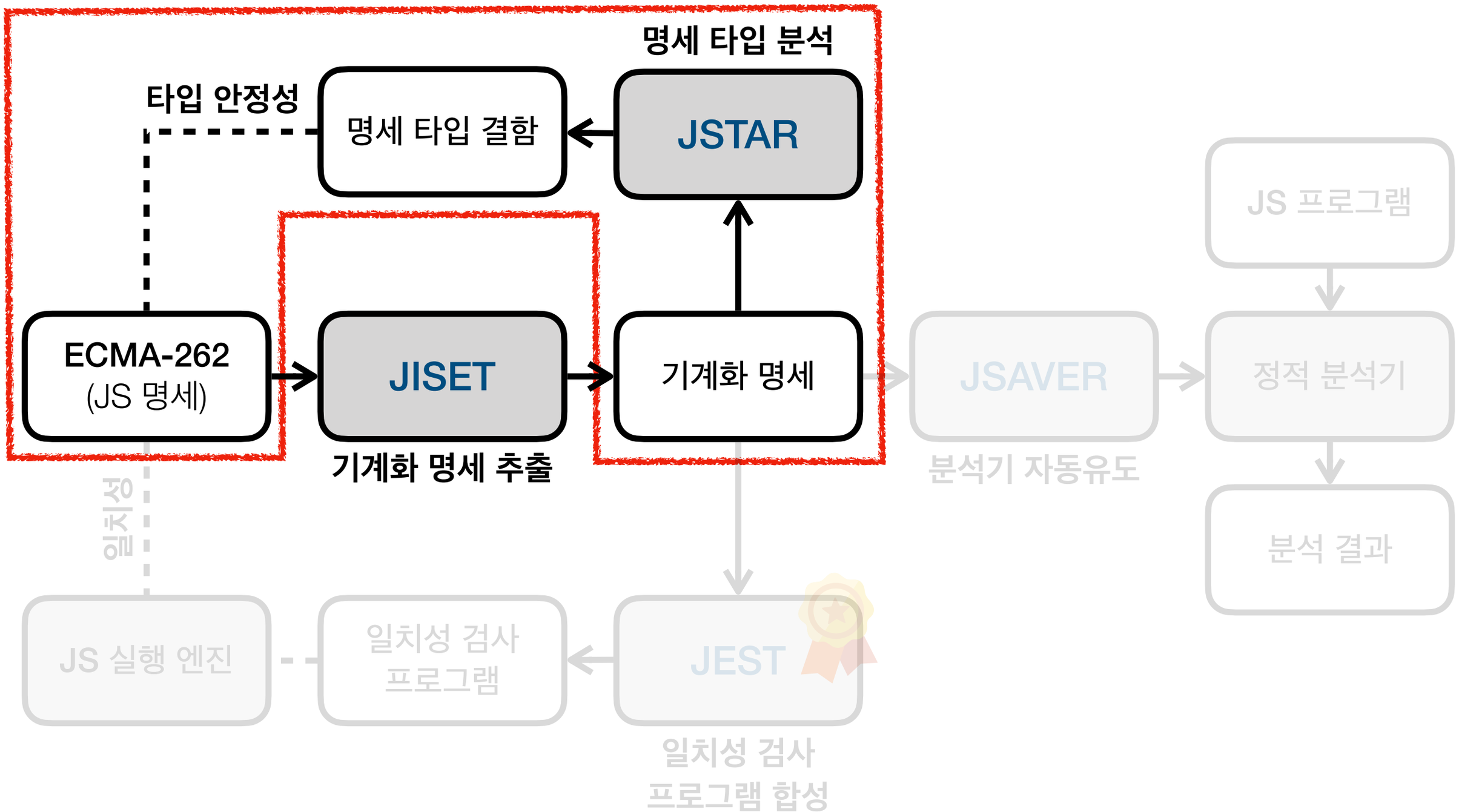
T: Total **L**: Core Language Semantics **B**: Built-in Libraries

Version	# Algo.		auto	manual
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%)

ESMeta



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



[ASE'21] J. Park, et al. "JSTAR: JavaScript Specification Type Analyzer using Refinement"

Types in ECMA-262

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

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

`>` 연산 타입 불일치
(숫자만 가능)

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

• • •

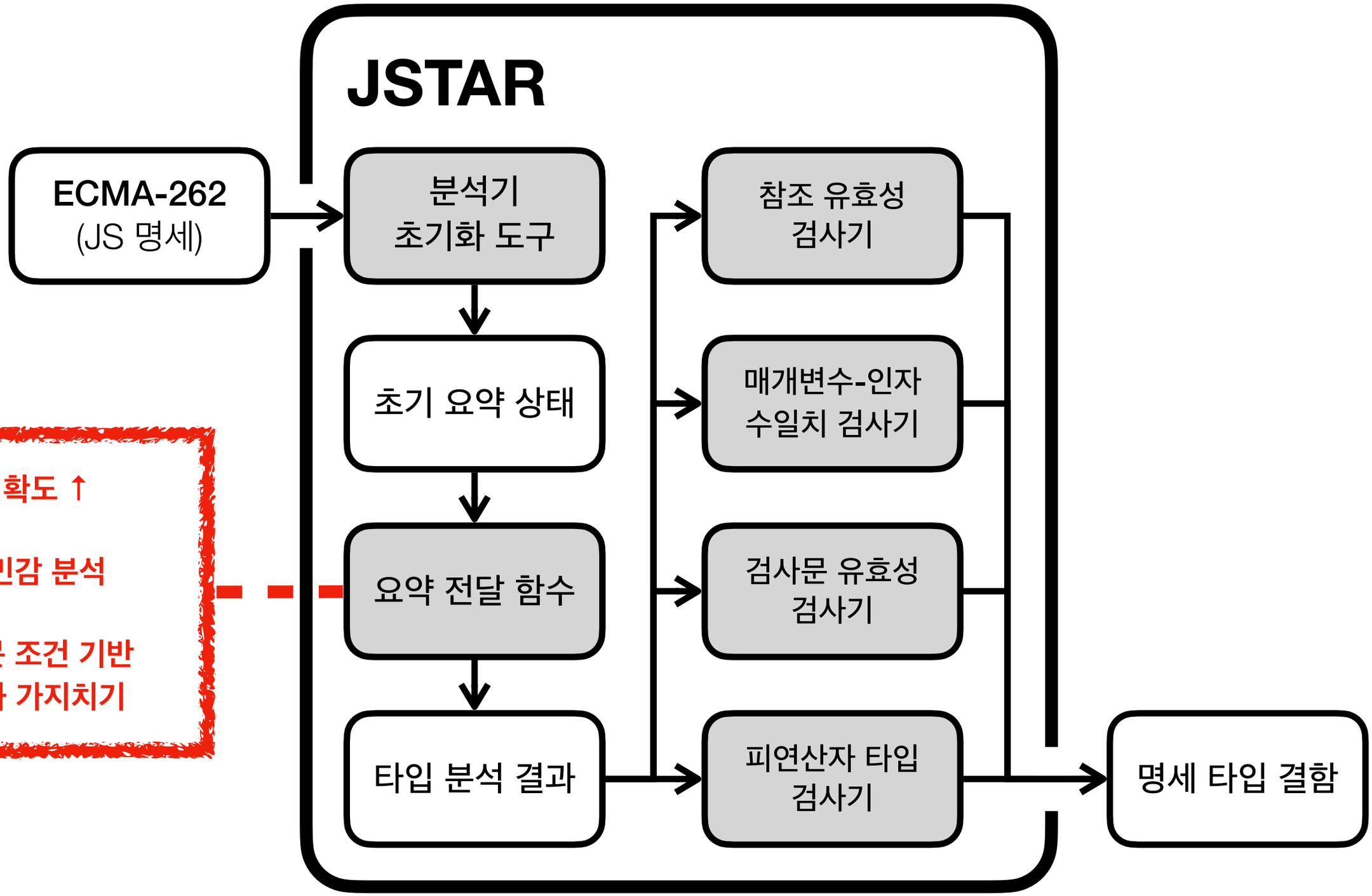
3. If $n < 0.5$ and $n > 0$, return **+0**.
4. If $n < 0$ and $n \geq -0.5$, return **-0**.

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

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

JSTAR - ASE'21

(**J**avaScript **S**pecification **T**ype **A**nalyzer using **R**efinement)



정확도 ↑

1. 타입 민감 분석

2. 분기문 조건 기반
분석 결과 가지치기

JSTAR - 실험 결과

59.2% 정확도

타입 결함 93개 검출

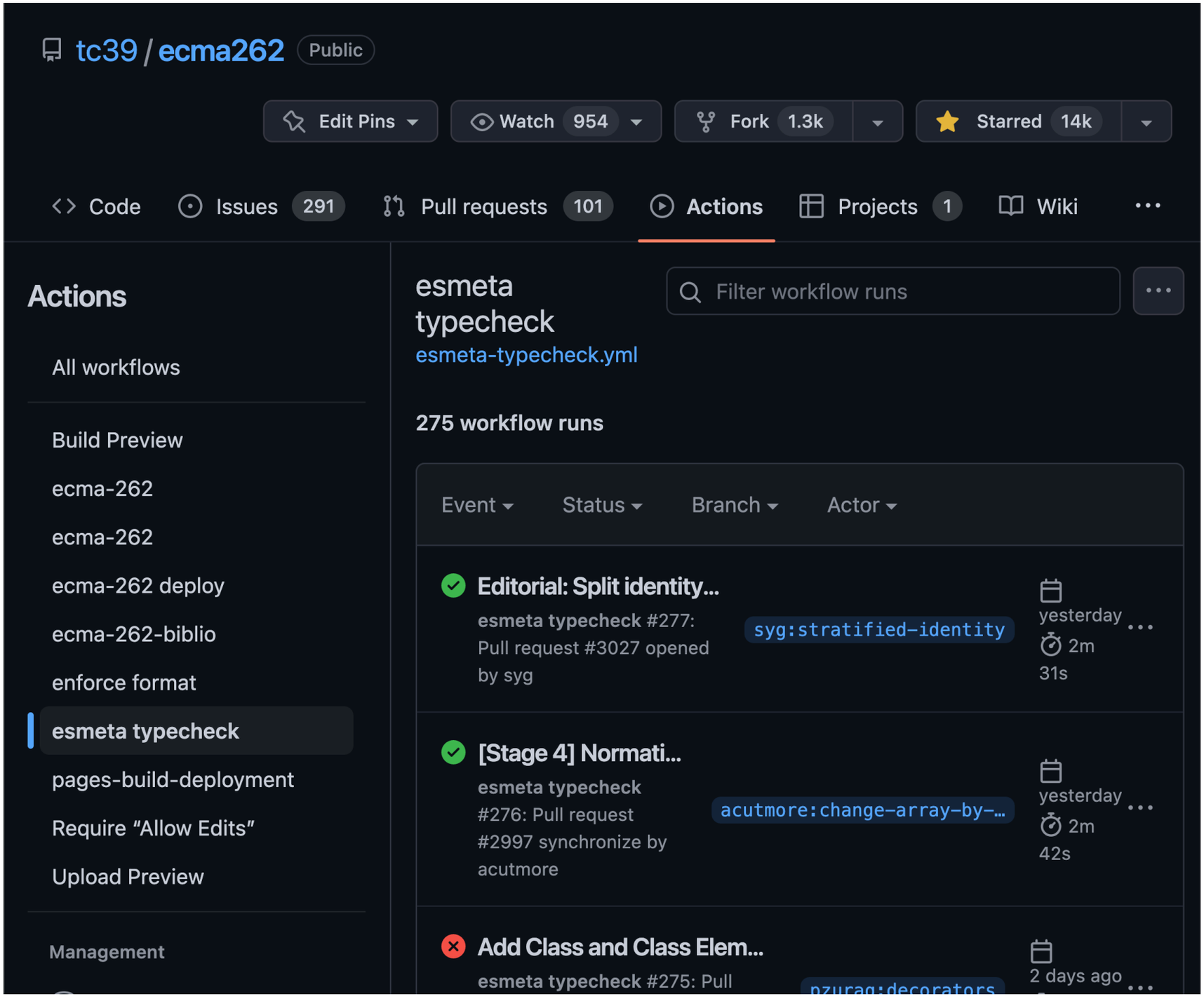
- **검사 대상**: 3년 동안 864개의 다른 ECMA-262 버전

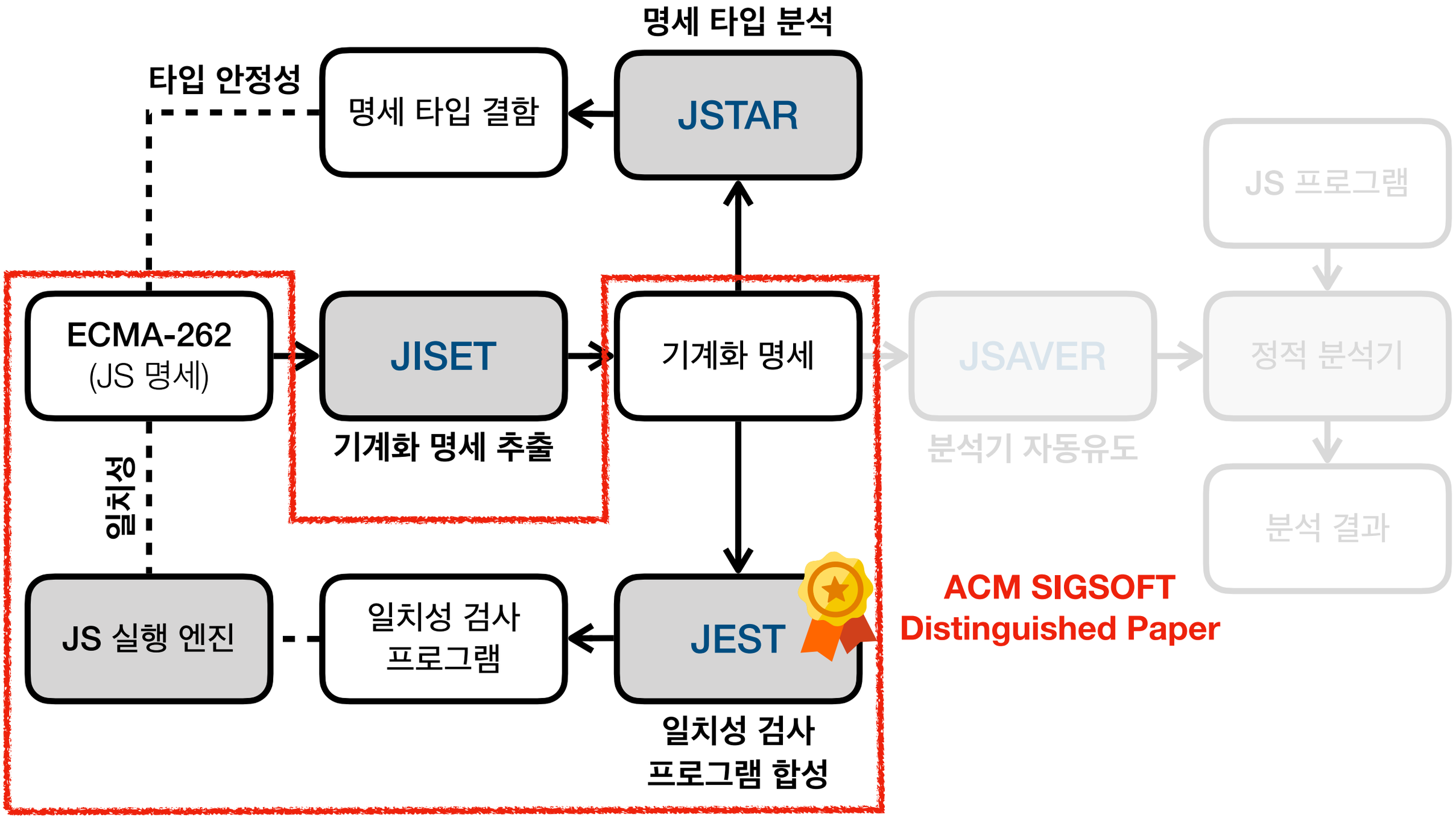
Checker	Bug Kind	Precision = (# True Bugs) / (# Detected Bugs)					
		no-refine		refine		Δ	
Reference	UnknownVar	62 / 106	17 / 60	63 / 78	17 / 31	+1 / -28	/ -29
	DuplicatedVar		45 / 46		46 / 47		+1 / +1
Arity	MissingParam	4 / 4	4 / 4	4 / 4	4 / 4	/	/
Assertion	Assertion	4 / 56	4 / 56	4 / 31	4 / 31	/ -25	/ -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

ES12에서 결함 14개

ECMA-262 공식 CI 시스템으로 선정





[ICSE'21] J. Park, et al. "JEST: N+1-version Differential Testing of Both JavaScript Engines"

JS 명세와 실행 엔진 간의 일치성

ECMA-262
(JS 명세)

?

일치

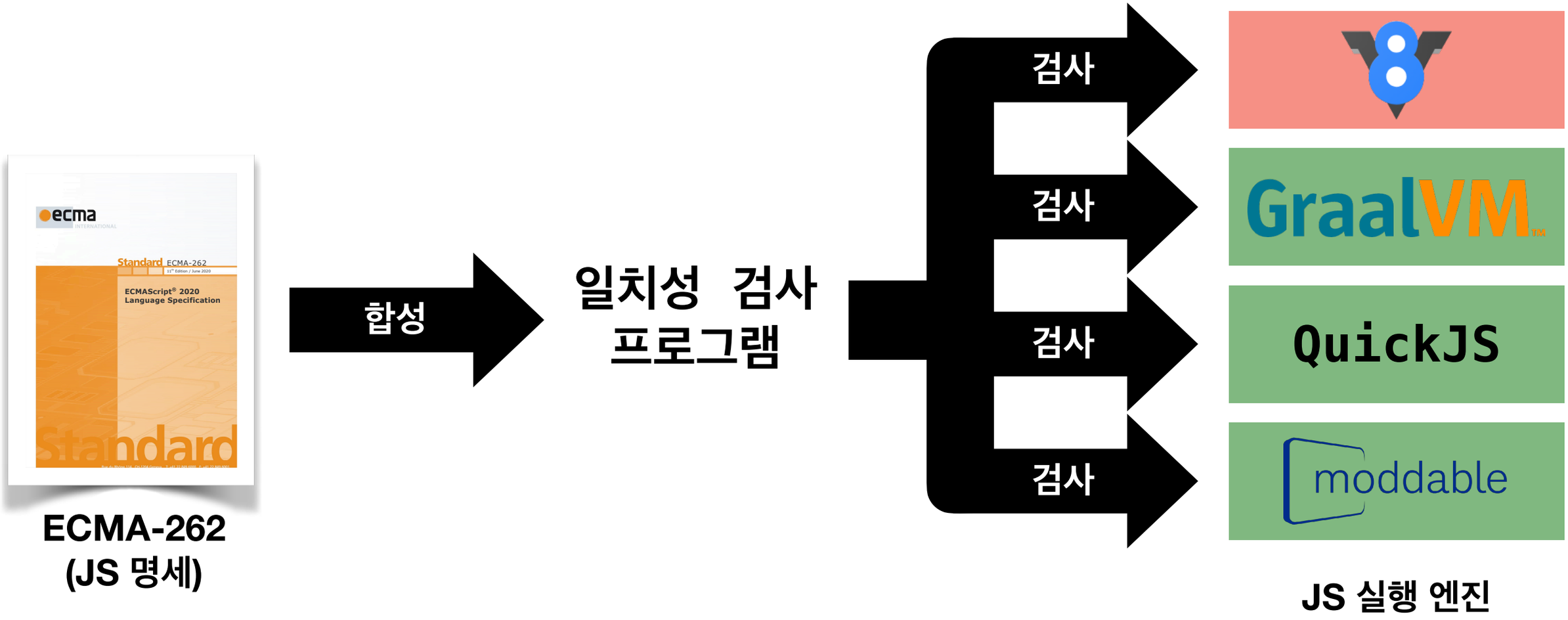
GraalVM

QuickJS

moddable

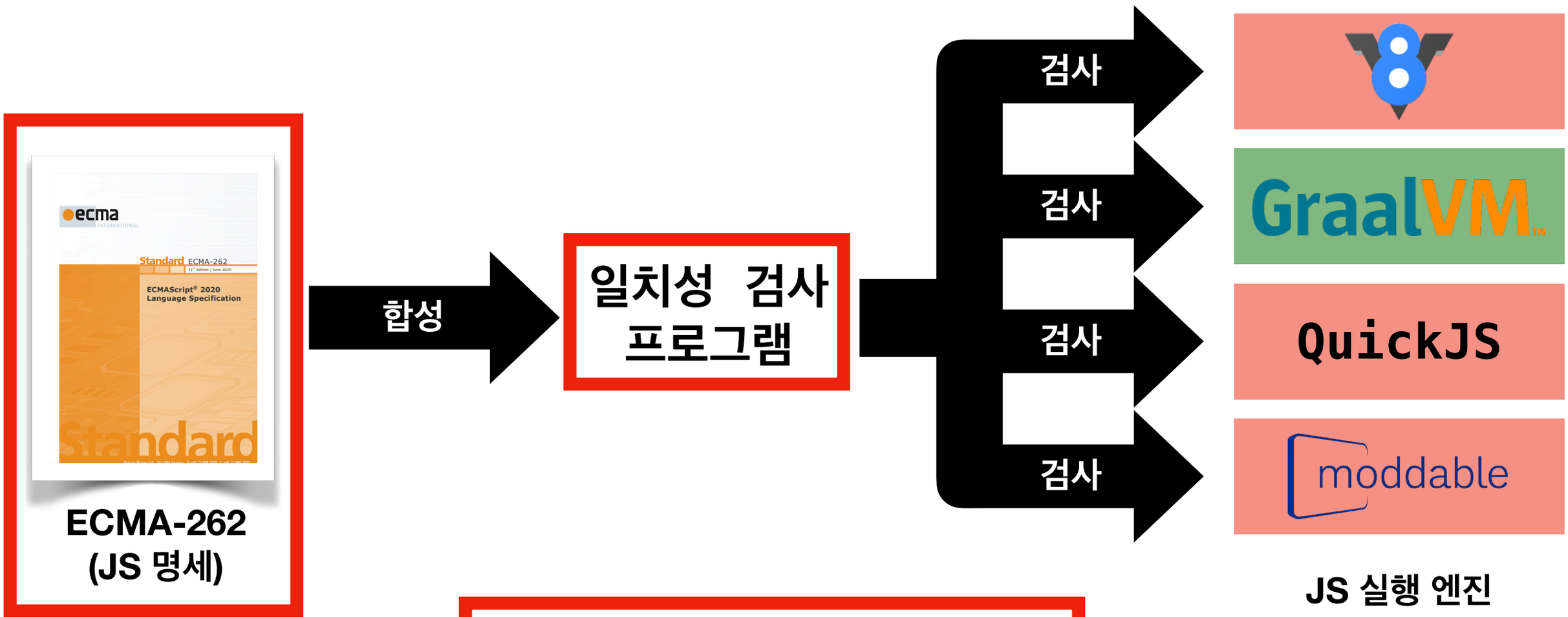
JS 실행 엔진

아이디어: N+1-버전 차분 테스팅



JS 실행 엔진의 결함

아이디어: N+1-버전 차분 테스팅

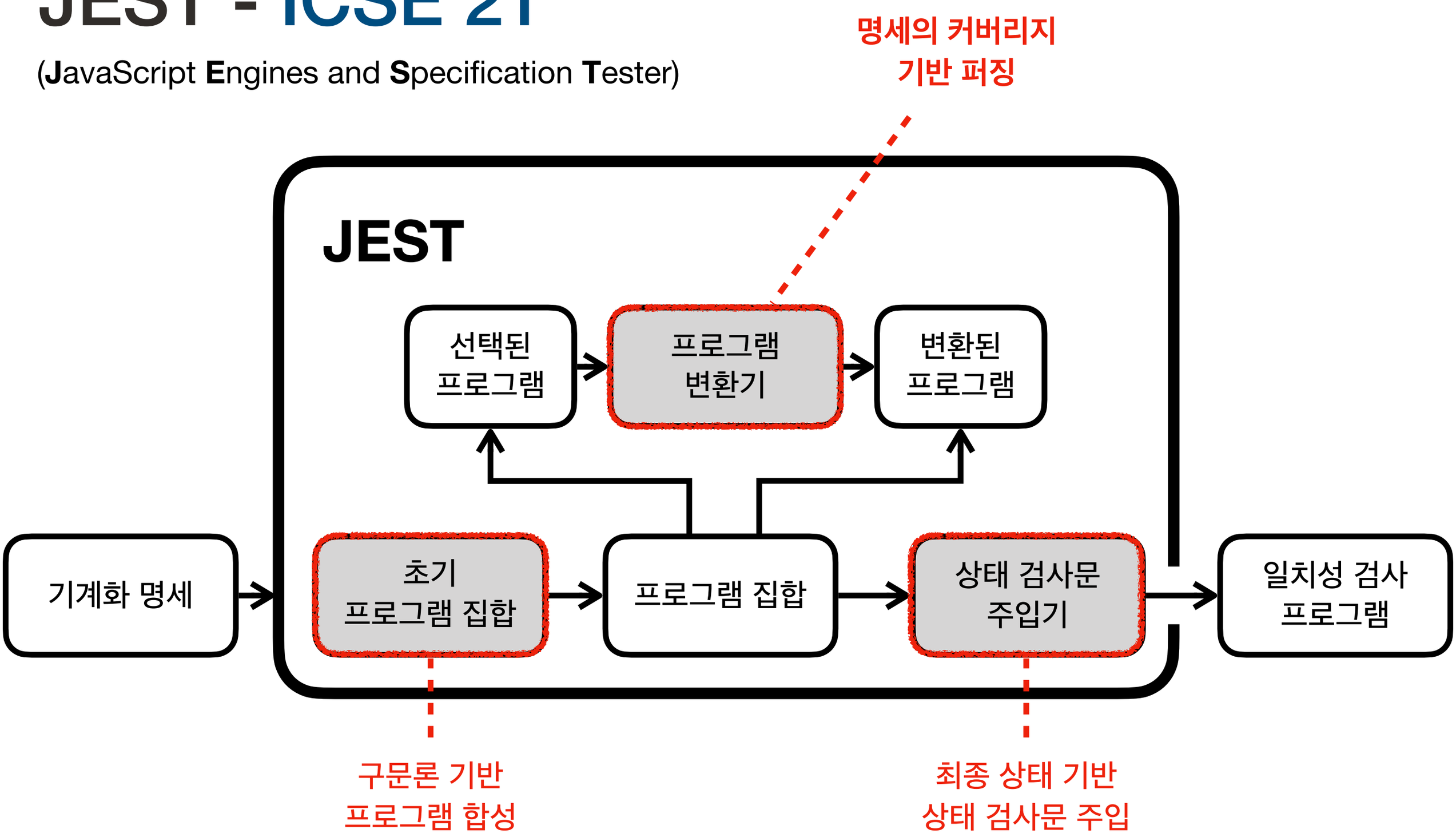


ECMA-262 내의 명세 결함 존재

JS 실행 엔진의 결함 GraalVM

JEST - ICSE'21

(**J**avaScript **E**ngines and **S**pecification **T**ester)



JEST - 명세의 커버리지 기반 퍼징

```
0 + { valueOf() { return 1; }
```

7.1.3 ToNumeric (*value*)

1. Let *primValue* be ? ToPrimitive(*value*, number)
2. If Type(*primValue*) is BigInt, return *primValue*.
3. Return ? ToNumber(*primValue*).

```
0 + { valueOf() { throw 42; }
```

JEST - 최종 상태 기반 상태 검사문 주입

```
  function f() {}

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

JEST - 실험 결과

- JEST가 성공적으로 ES11에서 1,700 일치성 테스트를 합성

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

실행 엔진 결함 44개

명세 결함 27개

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

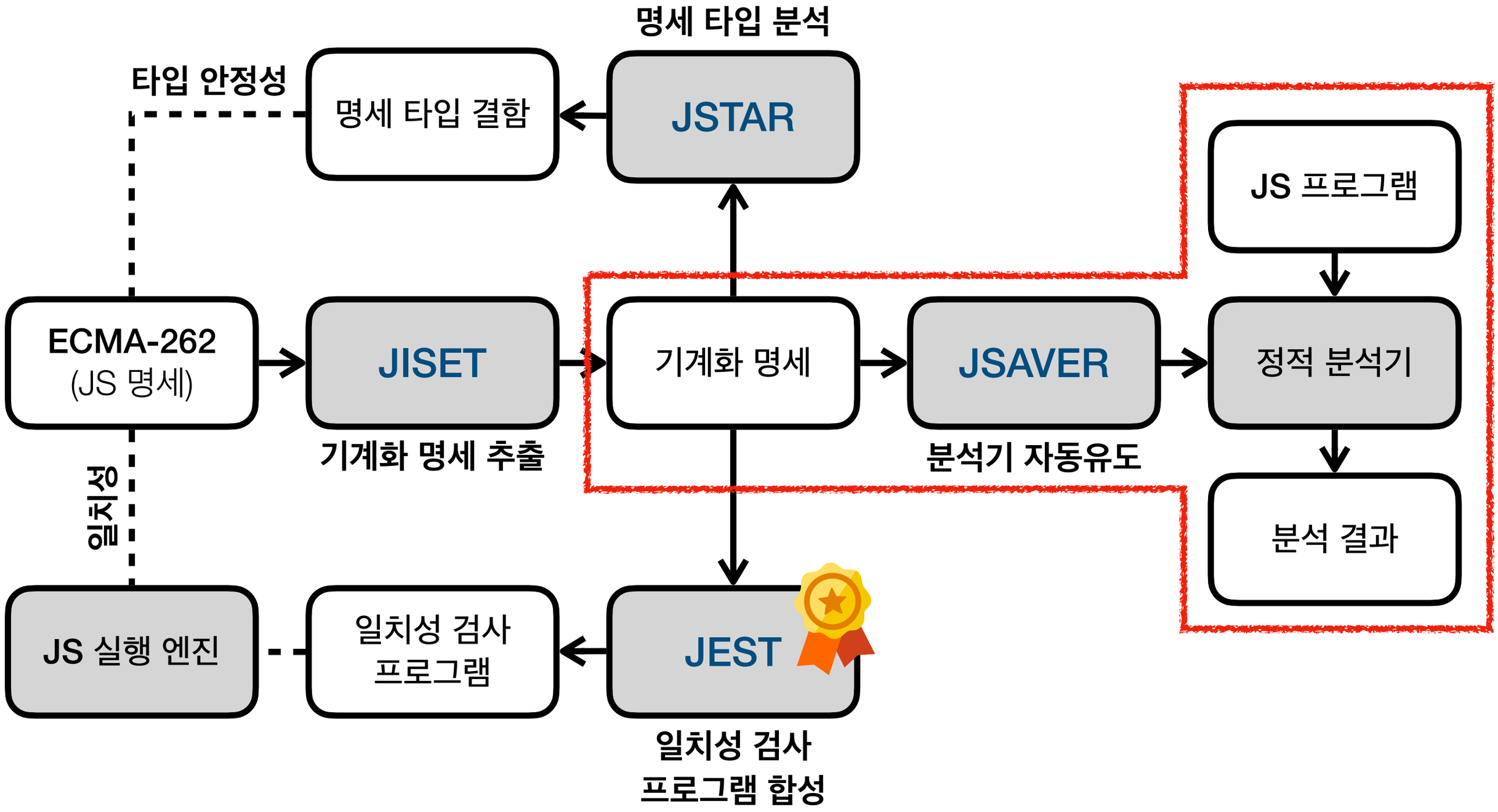
Name	Feature	#	Assertion	Known	Created	Resolved	Existed
ES11-1	Function	12	Key	O	2019-02-07	2020-04-11	429 days
ES11-2	Function	8	Key	O	2015-06-01	2020-04-11	1,776 days
ES11-3	Loop	1	Exc	O	2017-10-17	2020-04-30	926 days
ES11-4	Expression	4	Abort	O	2019-09-27	2020-04-23	209 days
ES11-5	Expression	1	Exc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

JEST - Example in GraalVM


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

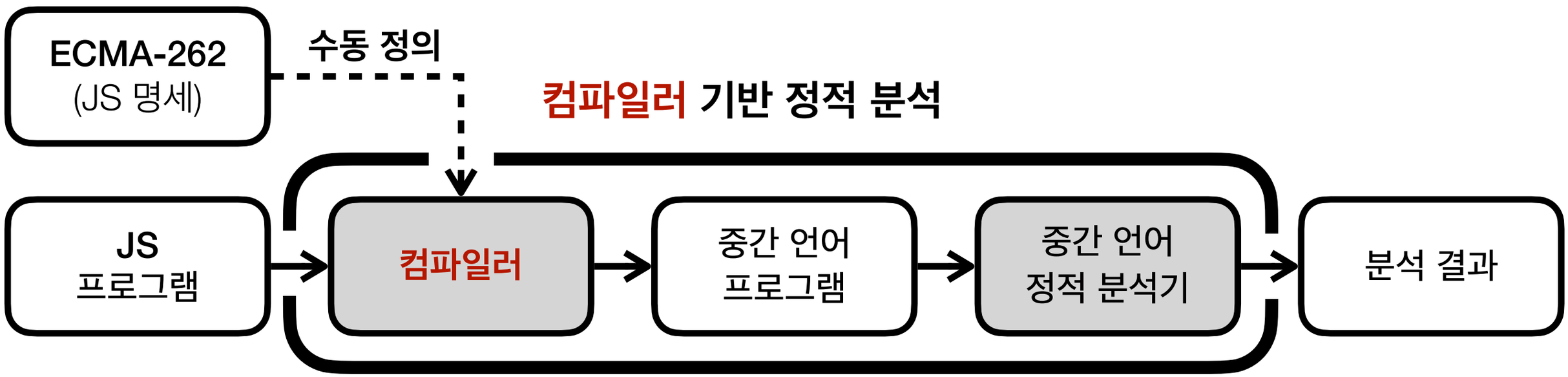
*"Right now, we are running Test262 and the V8 and Nashorn unit test suites in our CI for every change, it might make sense to **add your suite as well**."*

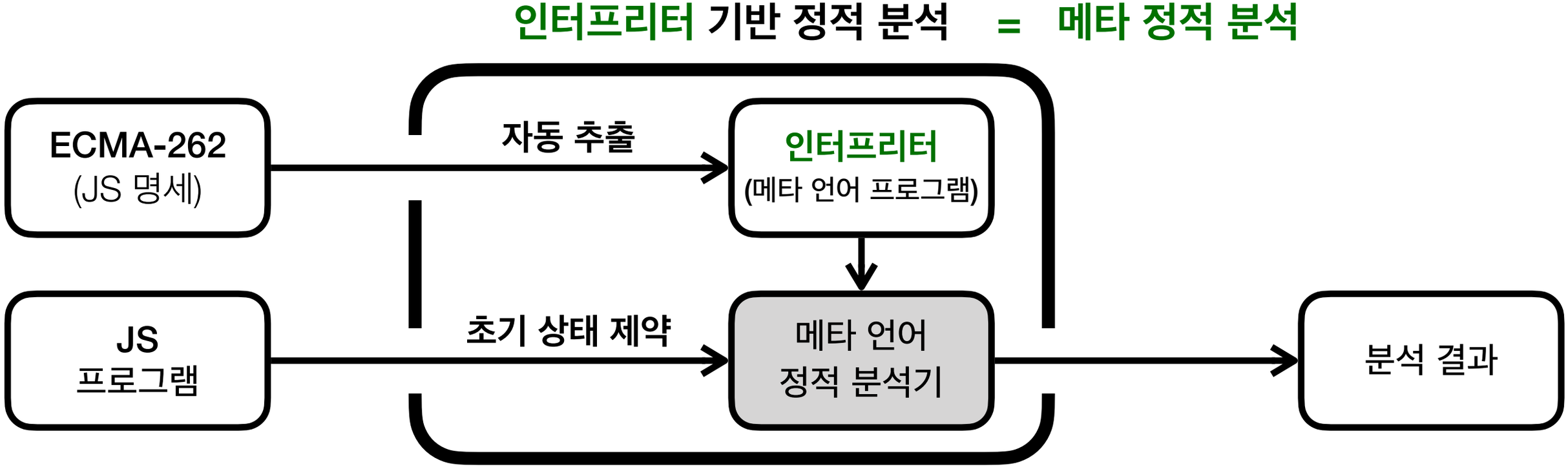
- A Developer of GraalVM



[FSE'22] J. Park, et al. "Automatically Deriving JavaScript Static Analyzers from Language Specifications"

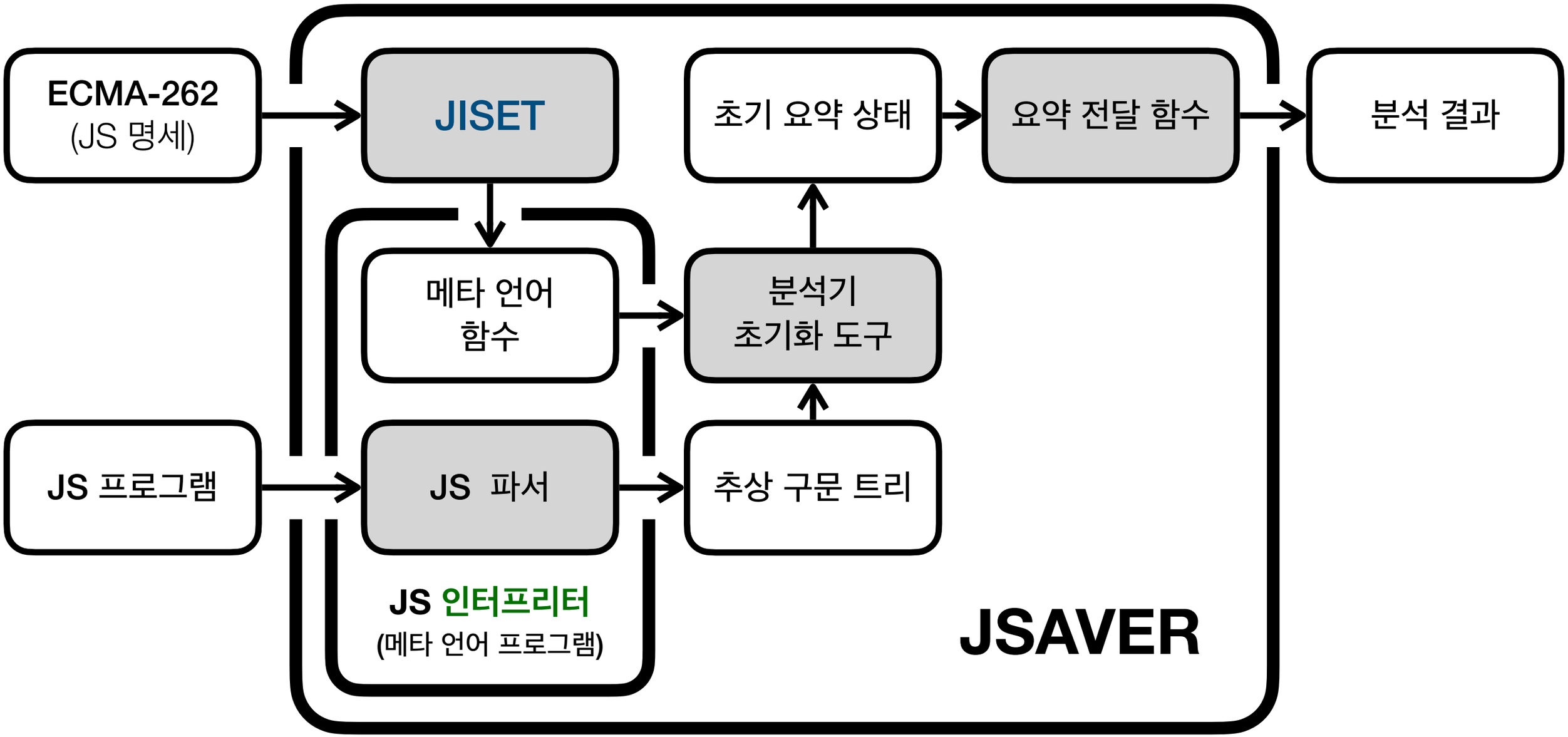
아이디어: 인터프리터 기반 정적 분석



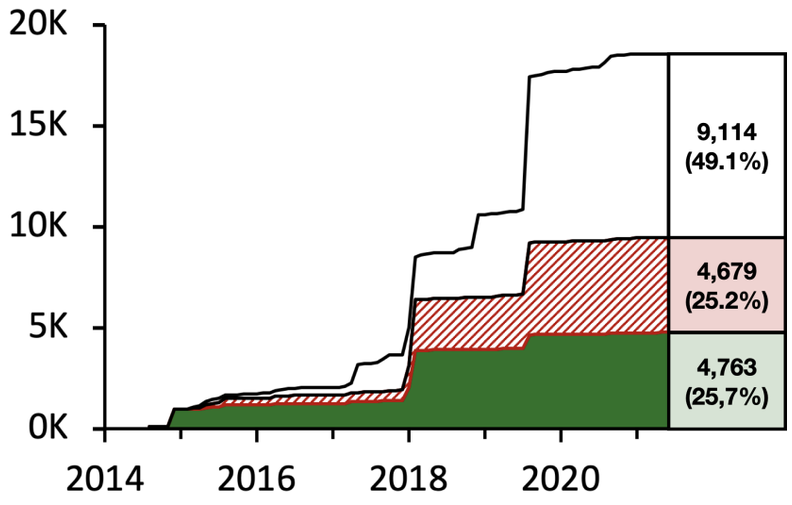


JSAVER - FSE'22

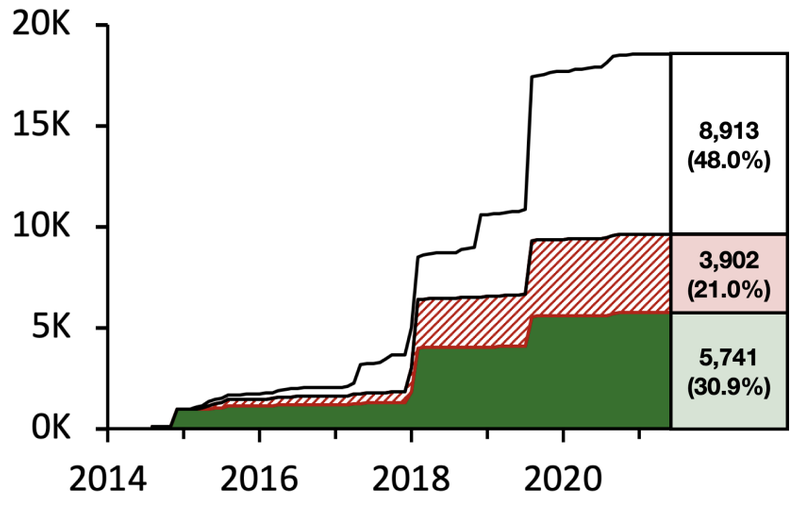
(**J**avaScript **S**tatic **A**nalyzer **v**ia **E**CMAScript **R**epresentation)



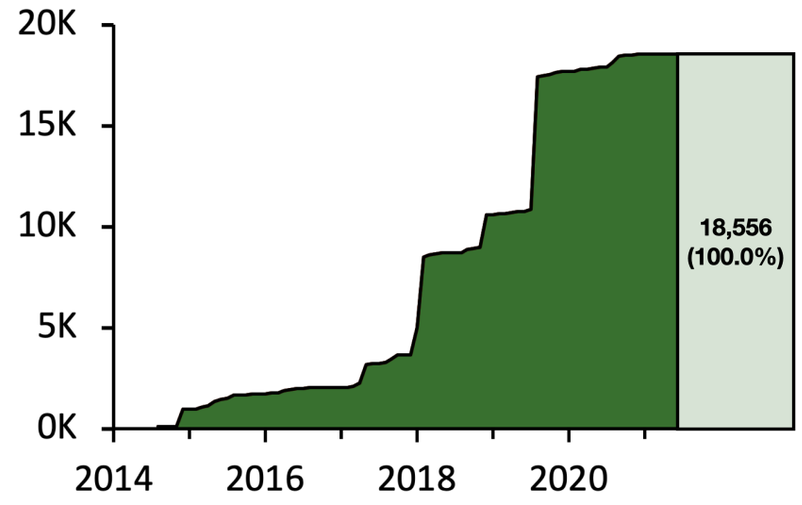
JSAVER - 평가 (RQ1: 올바른 분석)



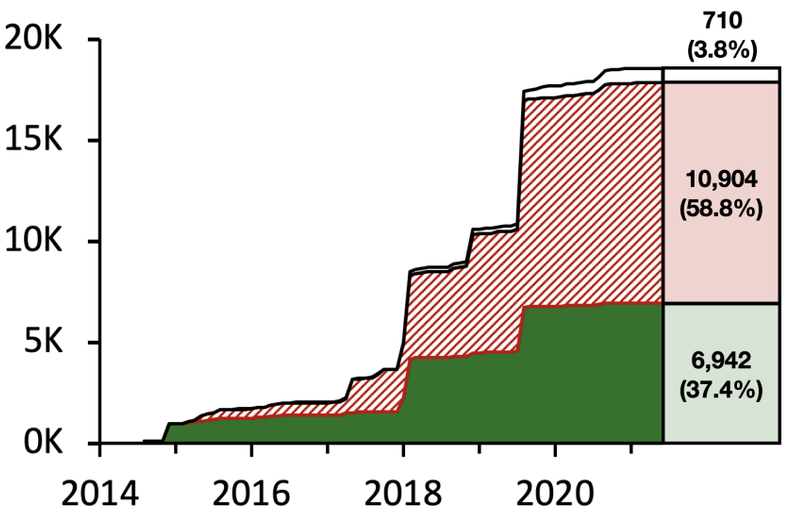
(a) Analysis results of TAJS



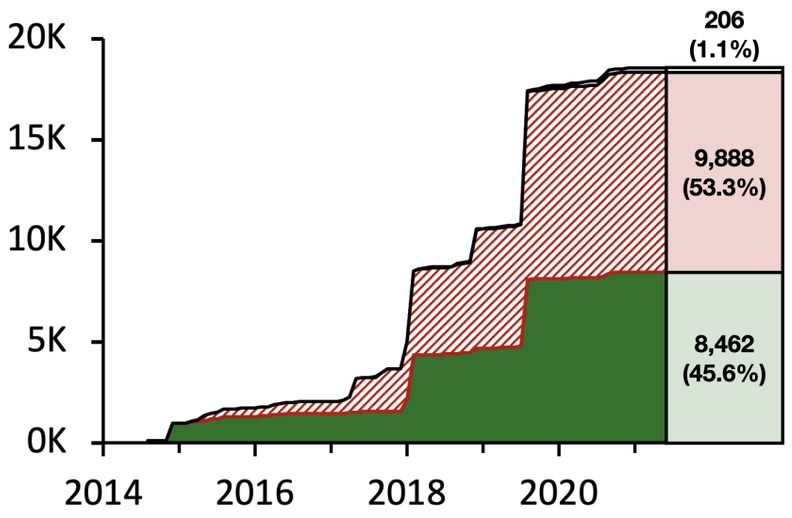
(b) Analysis results of SAFE



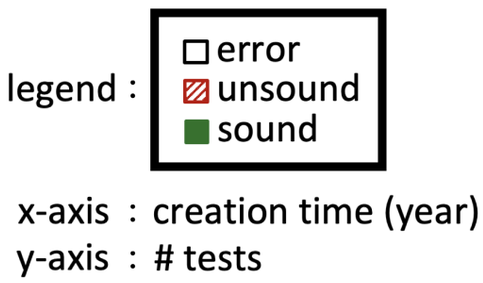
(c) Analysis results of JSA_{ES12}



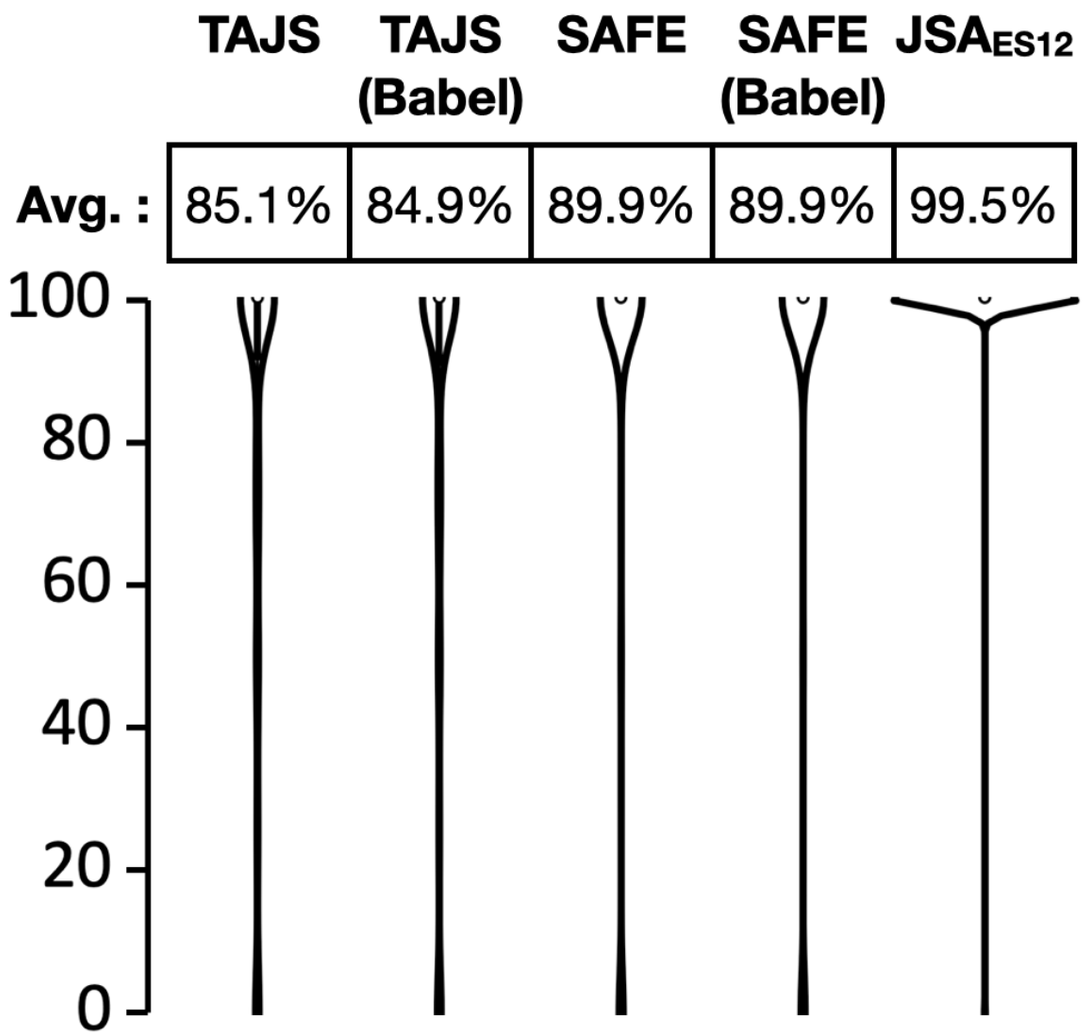
(d) Analysis results of TAJS with Babel



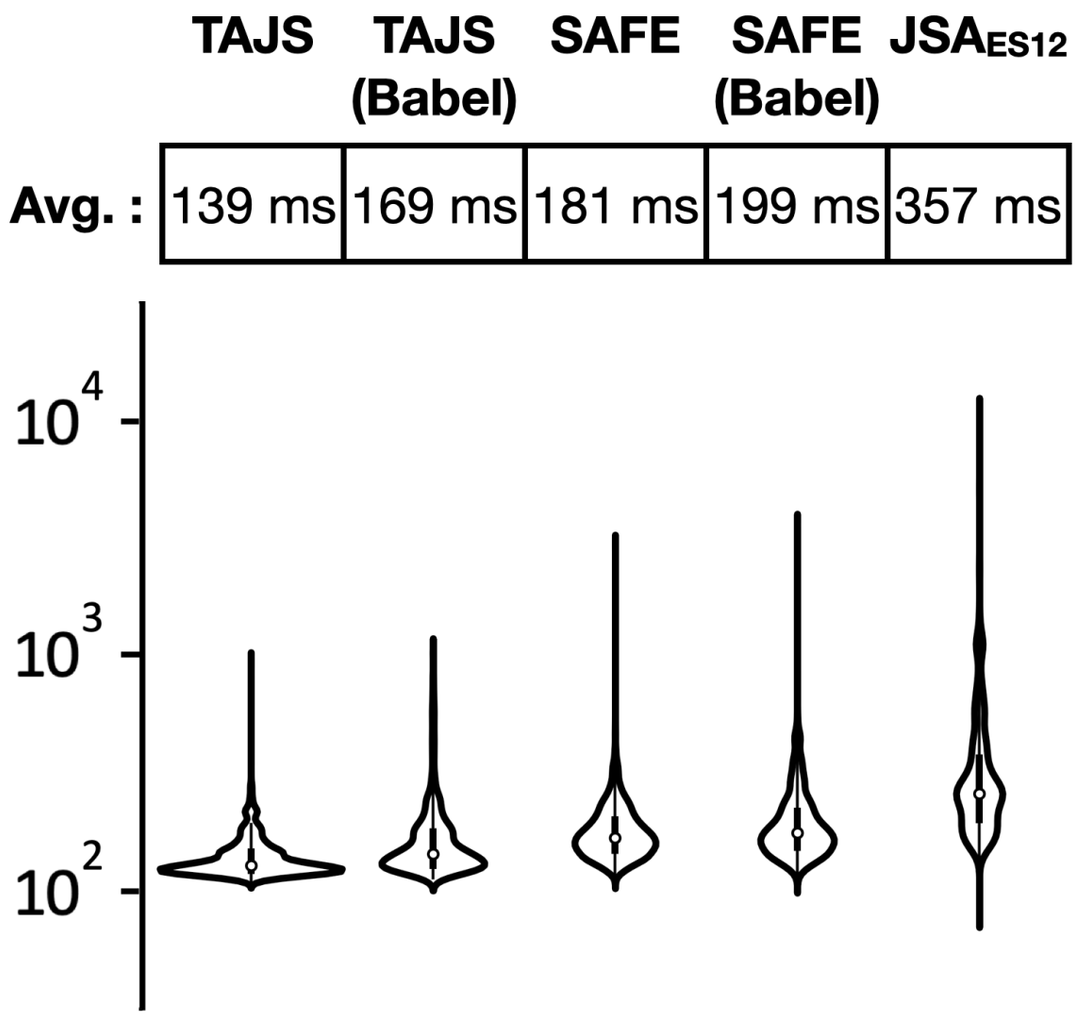
(e) Analysis results of SAFE with Babel



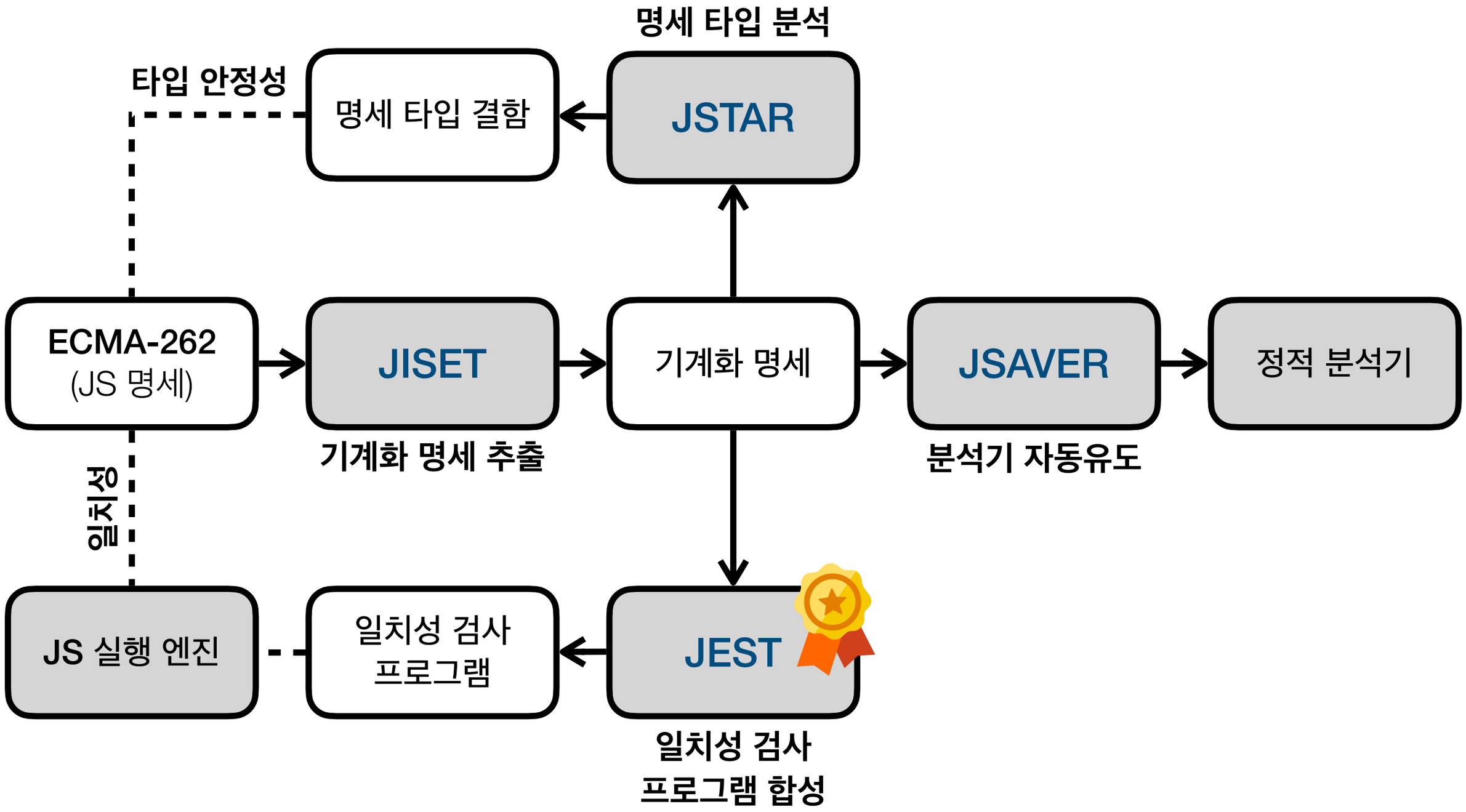
JSAVER - 평가 (RQ2: 정확도 / 속도)



(a) The analysis precision



(b) The analysis performance


명세 타입 분석
타입 안정성
명세 타입 결함
JSTAR
ECMA-262
(JS 명세)
JISET
기계화 명세
JSAVER
정적 분석기
기계화 명세 추출
분석기 자동유도
일치성
JS 실행 엔진
일치성 검사
프로그램
JEST
일치성 검사
프로그램 합성

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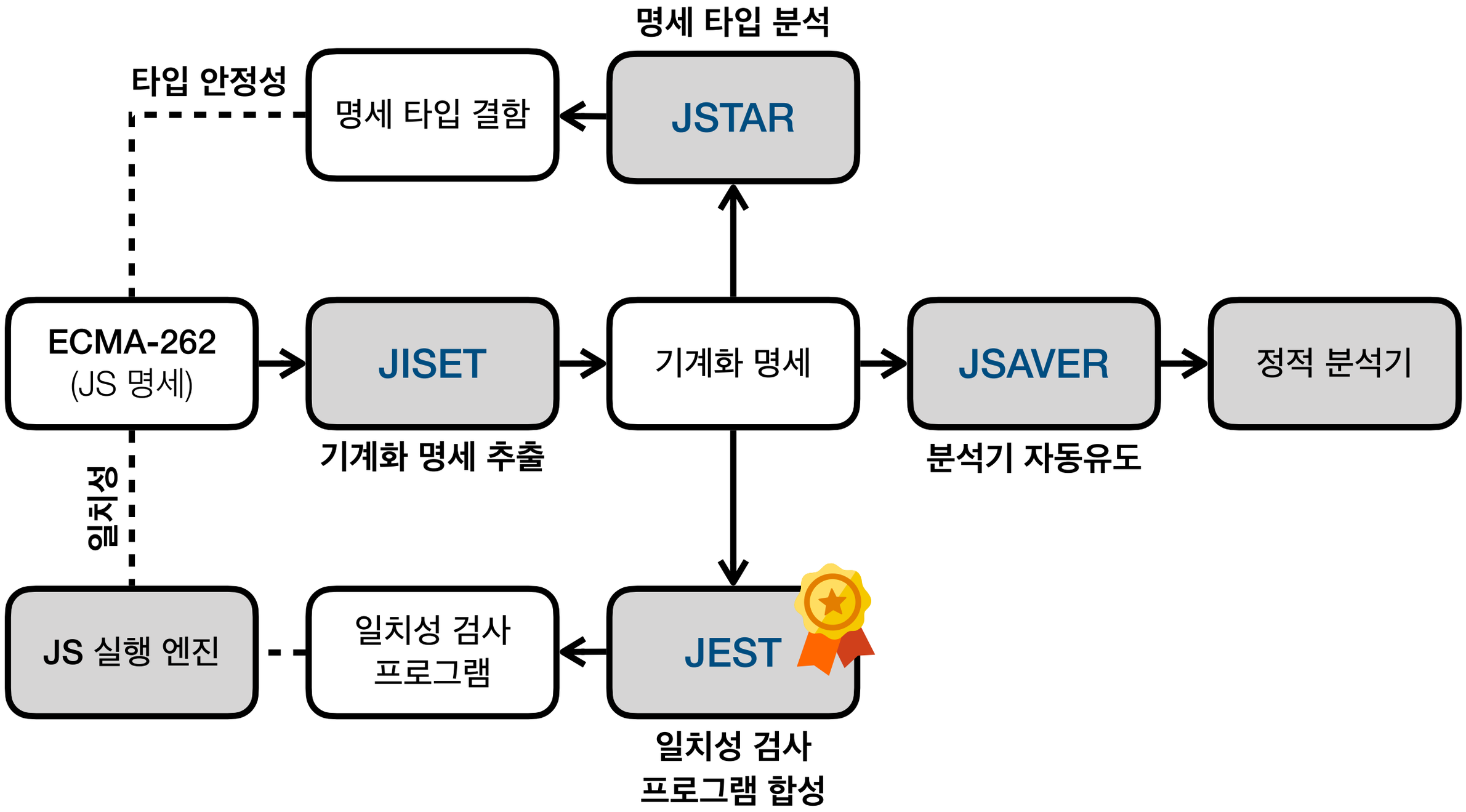
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일치성 검사
프로그램 합성