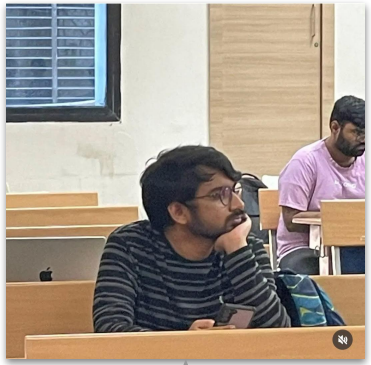
What does an IR for **JavaScript** Static analysis look like?

Advisor ⇝ **Dr Manas Thakur**
Presenter ⇝ **Meetesh Kalpesh Mehta, PhD**

Venue ⇝ IICT 2025, IISc
Date ⇝ 28th Sep, 25

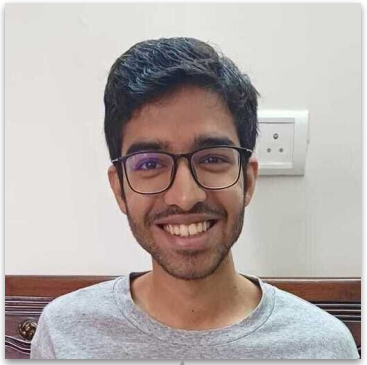
PLATO

Team



Me etesh ✌️

Anirudh (BTech, IITB) 🧑‍💻



Aneeket (BTech, IITD) 🧑‍💻

Dr Manas (Advisor, IITB) 🧙‍♂️

Goal

construct an

Intermediate Representation for JavaScript

Goal

construct ~~an~~ a
general-purpose

Intermediate Representation for JavaScript

Goal

construct ~~an~~ a
general-purpose
analyzable

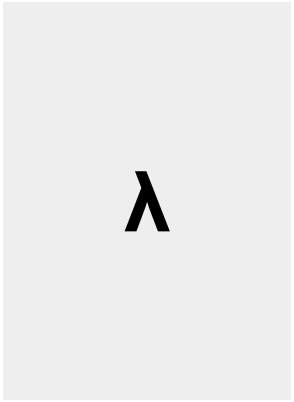
Intermediate Representation for JavaScript

Goal

construct ~~an~~ a
general-purpose
analyzable
executable

Intermediate Representation for JavaScript

Use Case



Amazon LLRT (Low Latency Runtime)

- **Experimental**
- **Lightweight**
- Address the growing demand for **fast and efficient serverless applications**.

Use Case

Amazon LLRT (Low Latency Runtime)

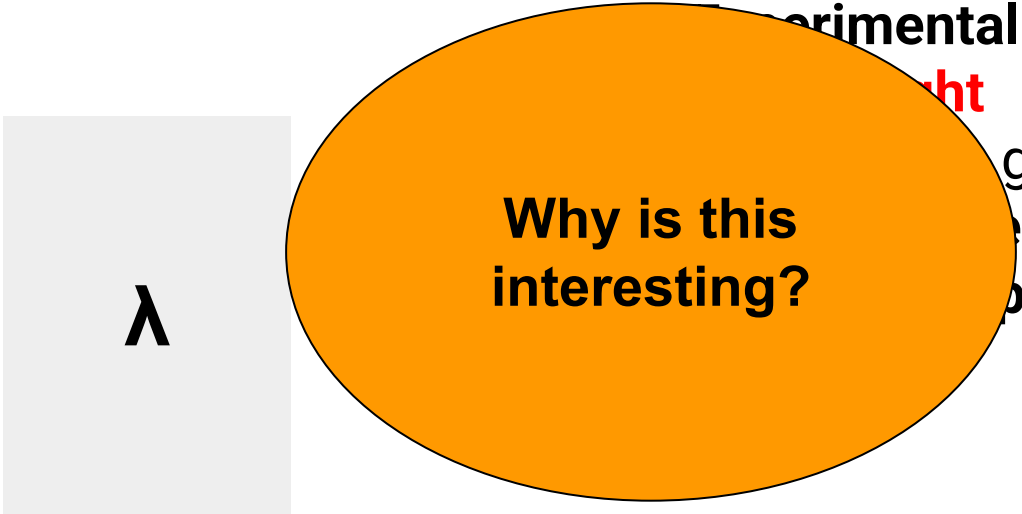
rimental

ht

growing demand

fficient

pplications.

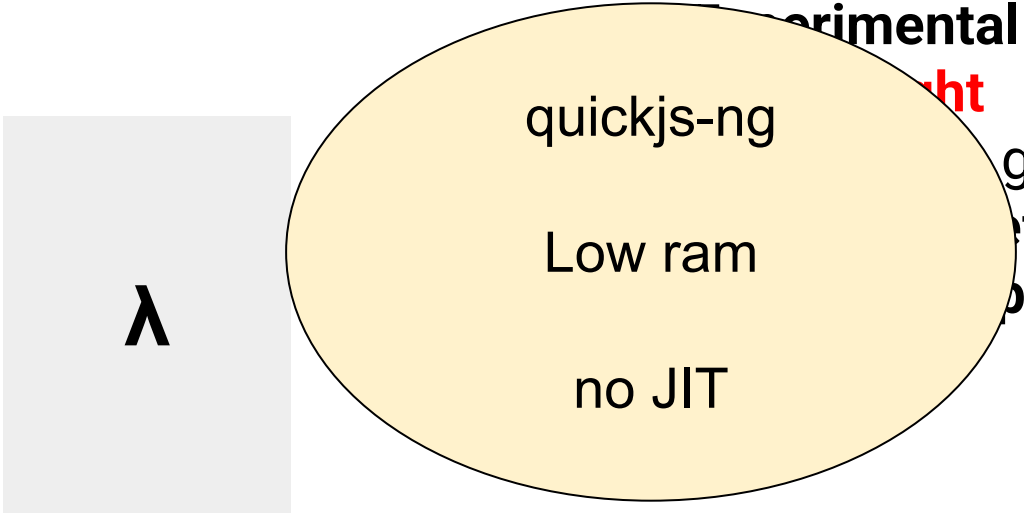


Use Case

Amazon LLRT (Low Latency Runtime)

erimental

ht



growing demand

fficient

pplications.

Use Case

Amazon LLRT (Low Latency Runtime)

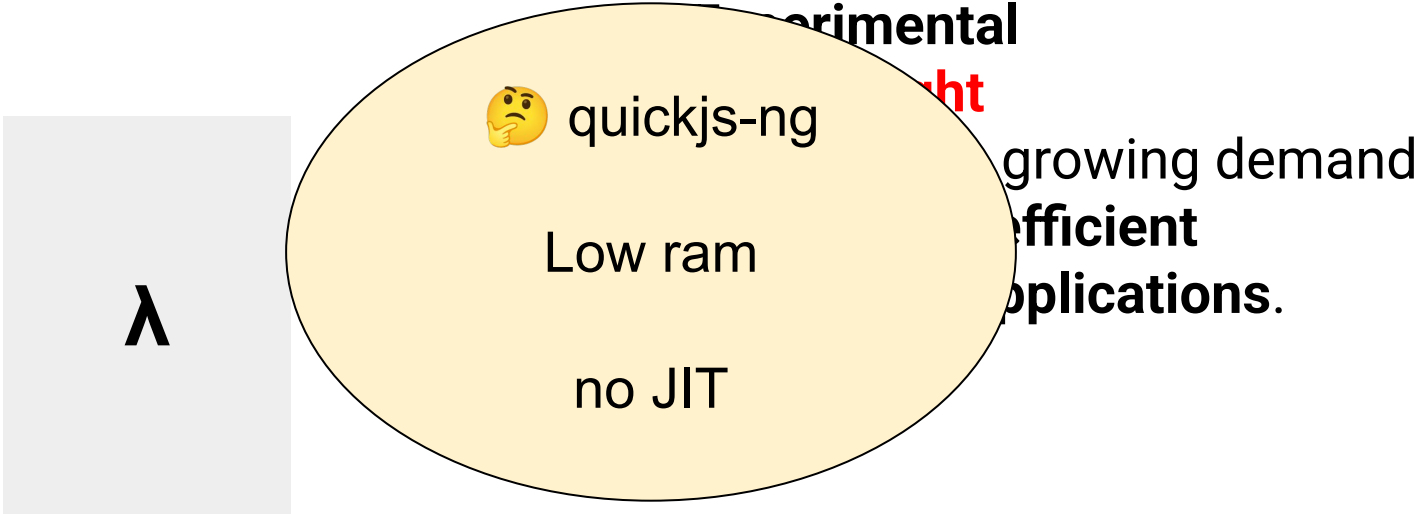
rimental

ht

growing demand

fficient

pplications.



Use Case

Amazon LLRT (Low Latency Runtime)

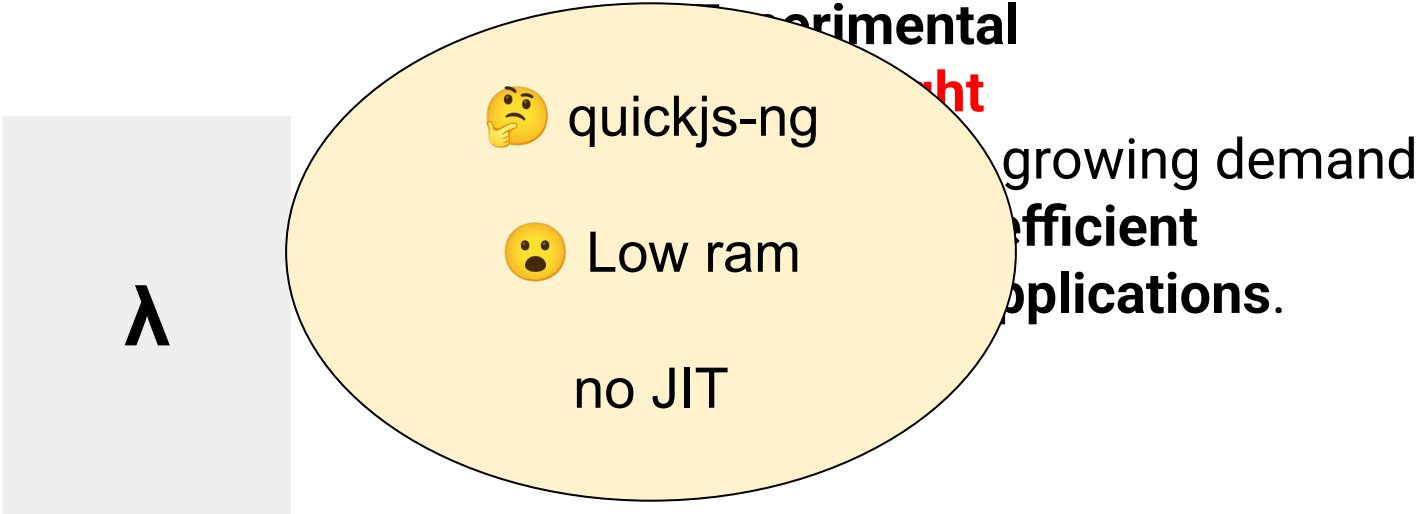
rimental

ht

growing demand

fficient

pplications.



Use Case

Amazon LLRT (Low Latency Runtime)

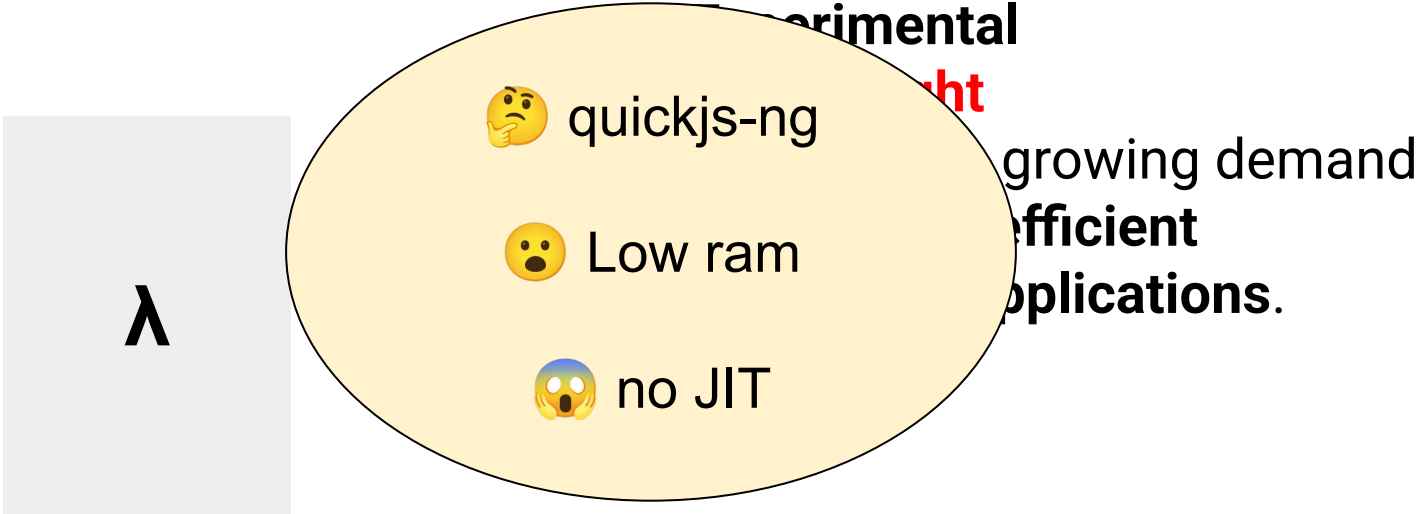
rimental

ht

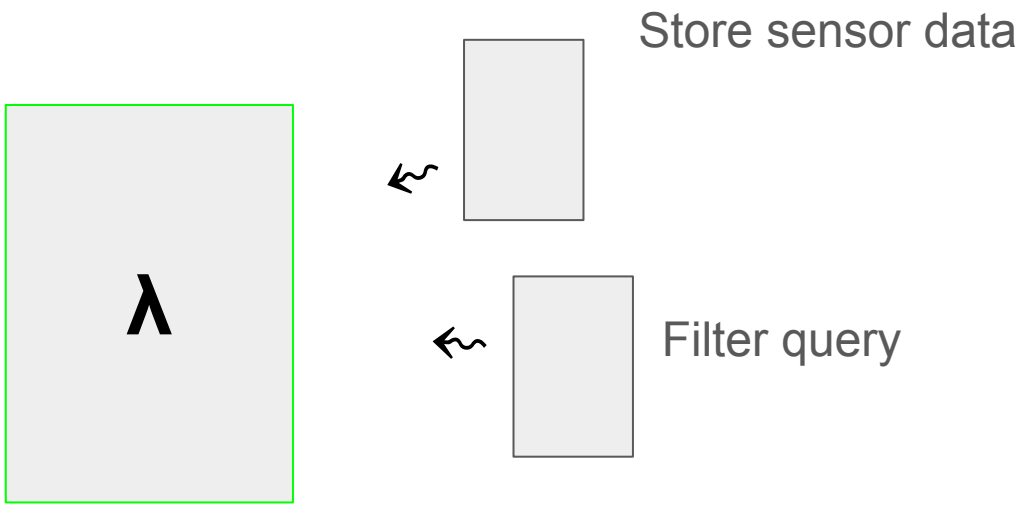
growing demand

fficient

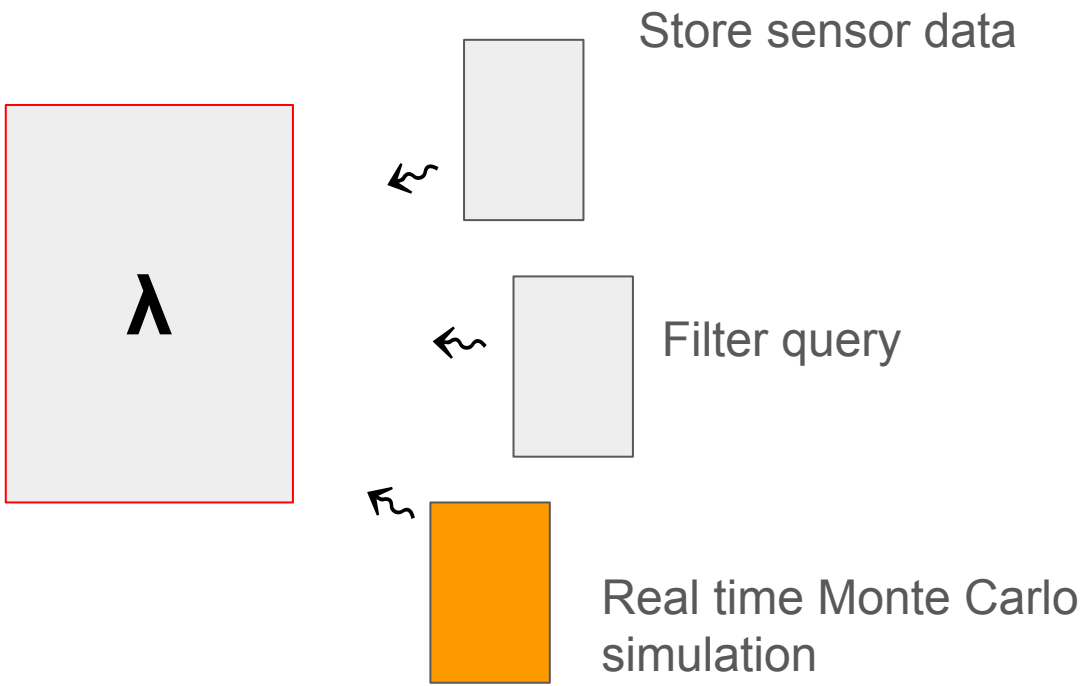
pplications.



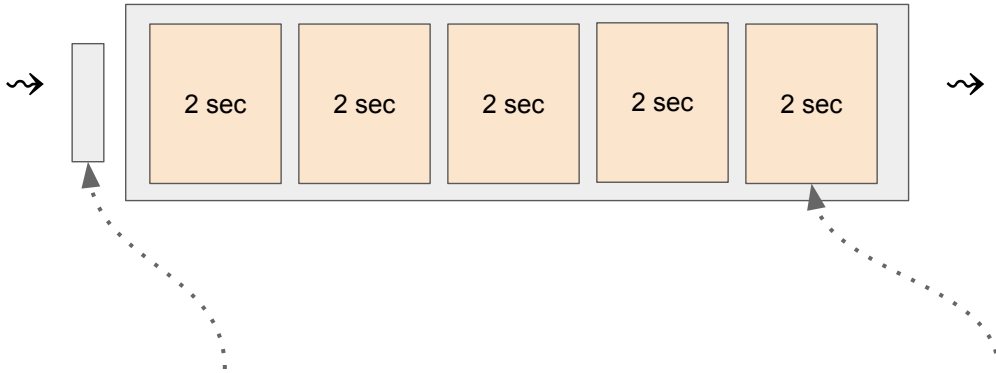
Use Case



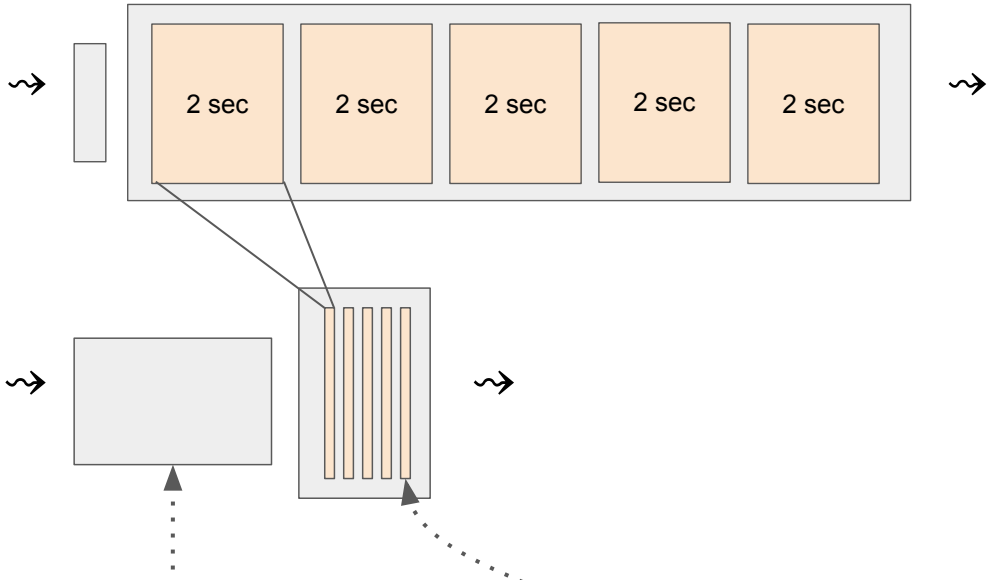
Use Case


λ
Store sensor data
Filter query
Real time Monte Carlo simulation

Hypothesising the Behaviour



One JIT Wonder



Just In Time Compilation

Static Analysis
+
Optimized Code Generation

Why no JIT?

Poor security (code region memory is sacred)

- **Chrome on your phone says so!**
- **Apple won’t allow it!**

Why no JIT?

Poor security (code region memory is sacred)

Unpredictable (2s or 20s)

- **Amortization is not always guaranteed**
  - **Regression** cases!!
    - Most JITs have their WIP lists!

Why no JIT?

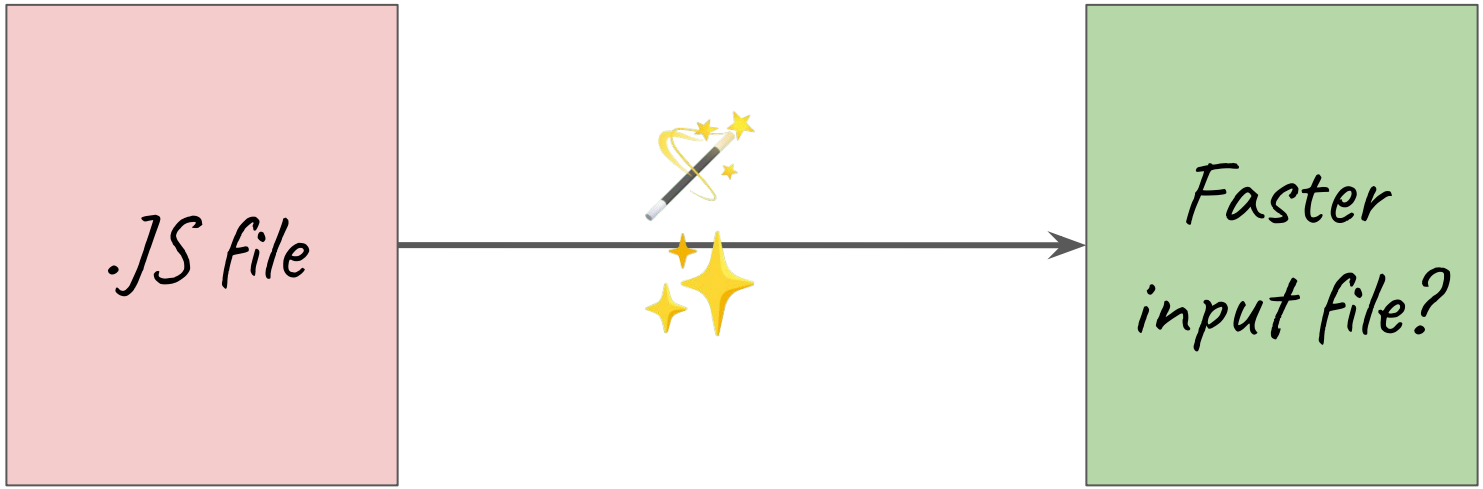
Poor security (code region memory is sacred)

Unpredictable (2s or 20s)

Not suitable for all workloads

- **High Throughput** ↑ >>> Optimal Code ↓

The Plan



Our Pipeline

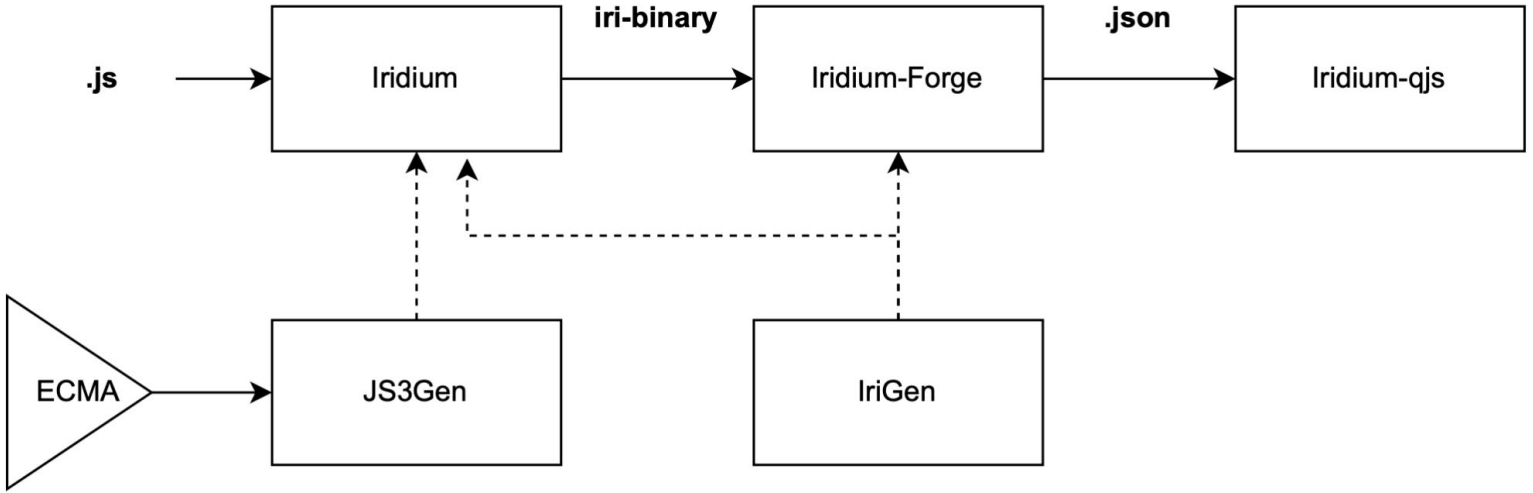


Figure 3.1: Overview of the Iridium architecture.

Our Pipeline

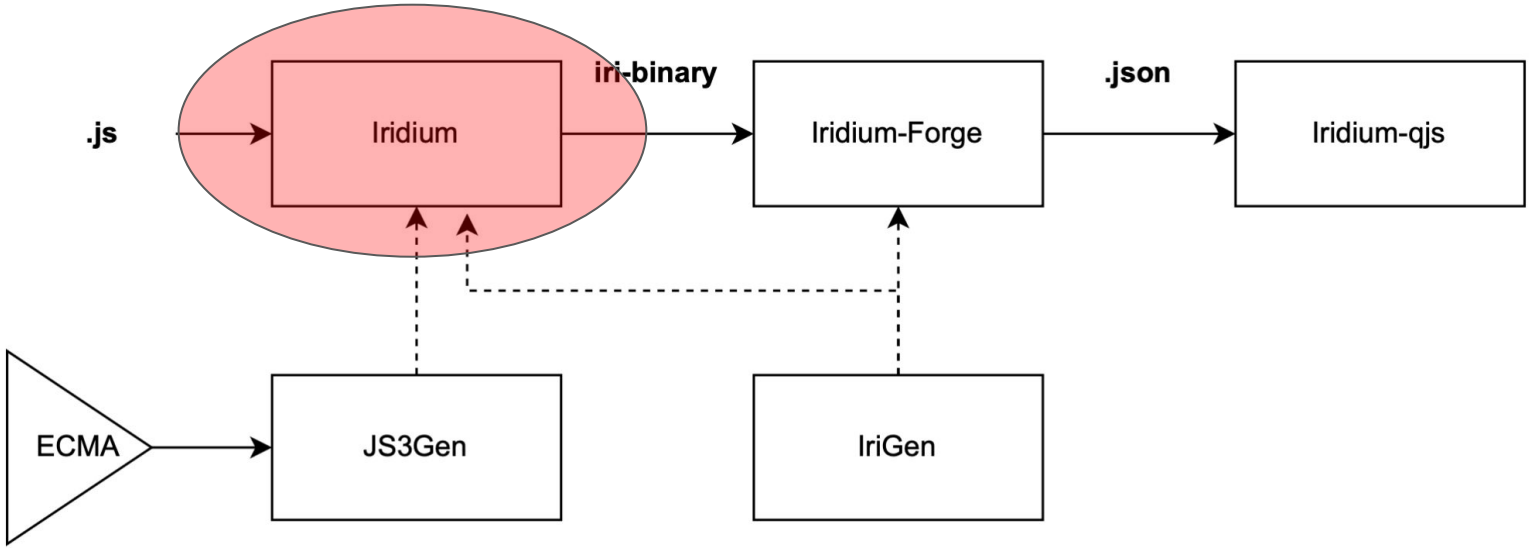


Figure 3.1: Overview of the Iridium architecture.

Our Pipeline

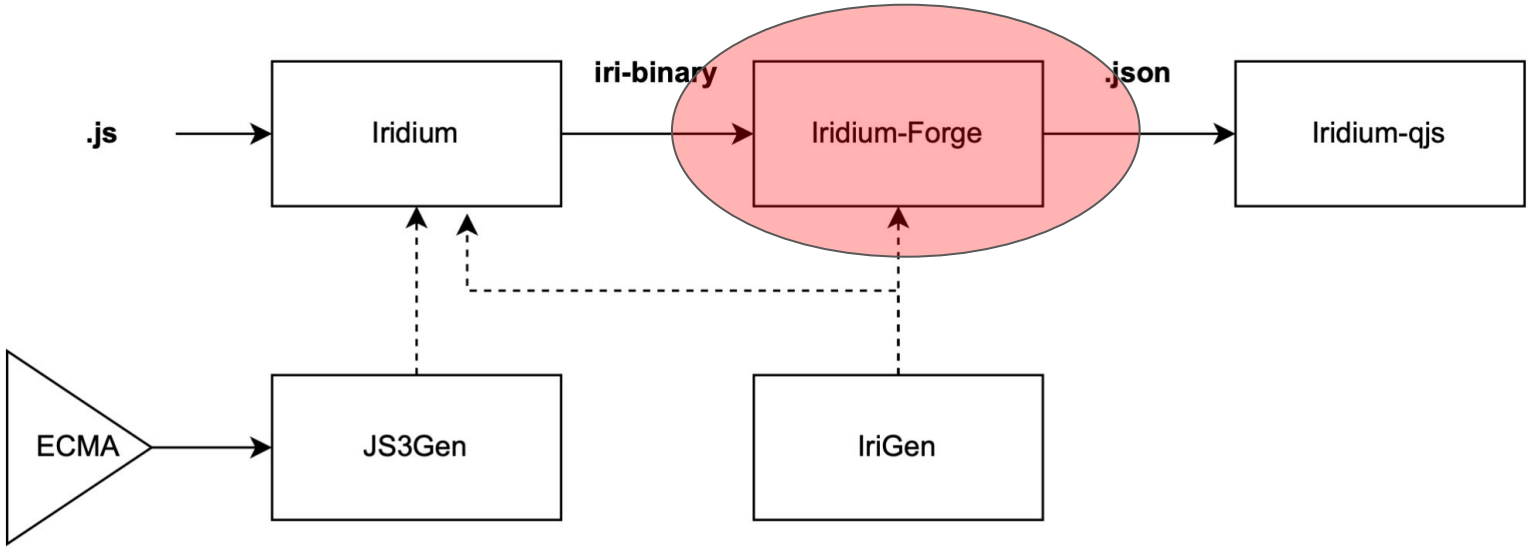


Figure 3.1: Overview of the Iridium architecture.

Our Pipeline

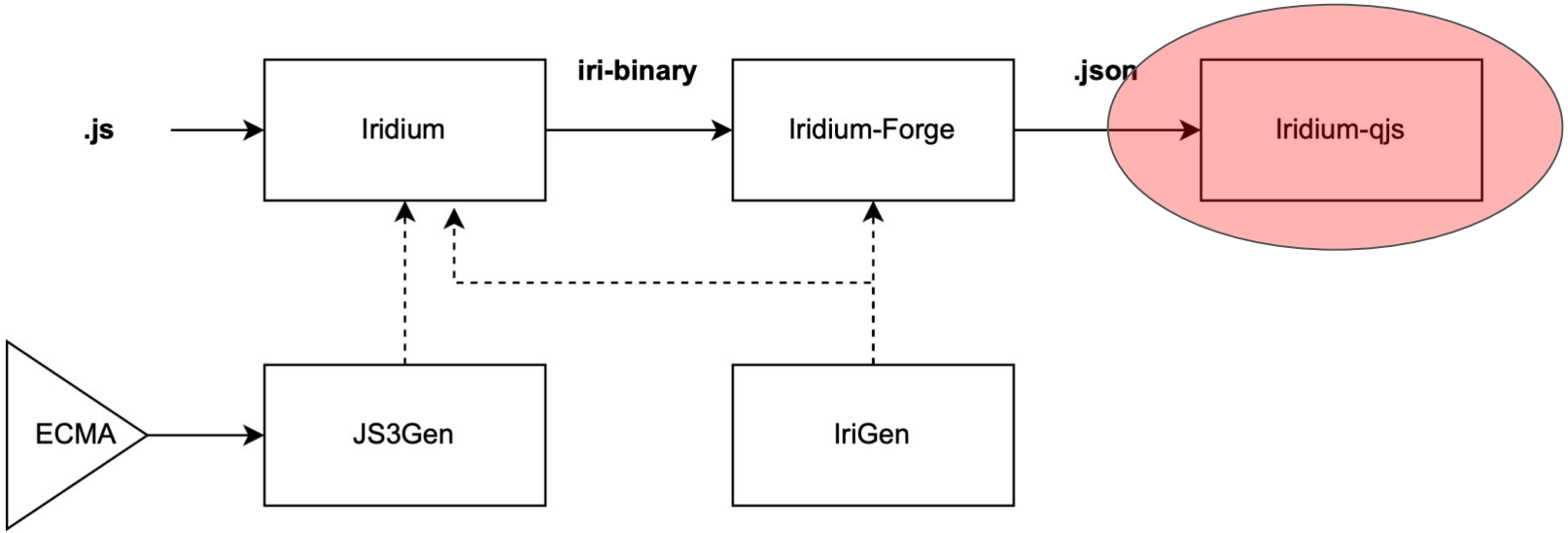
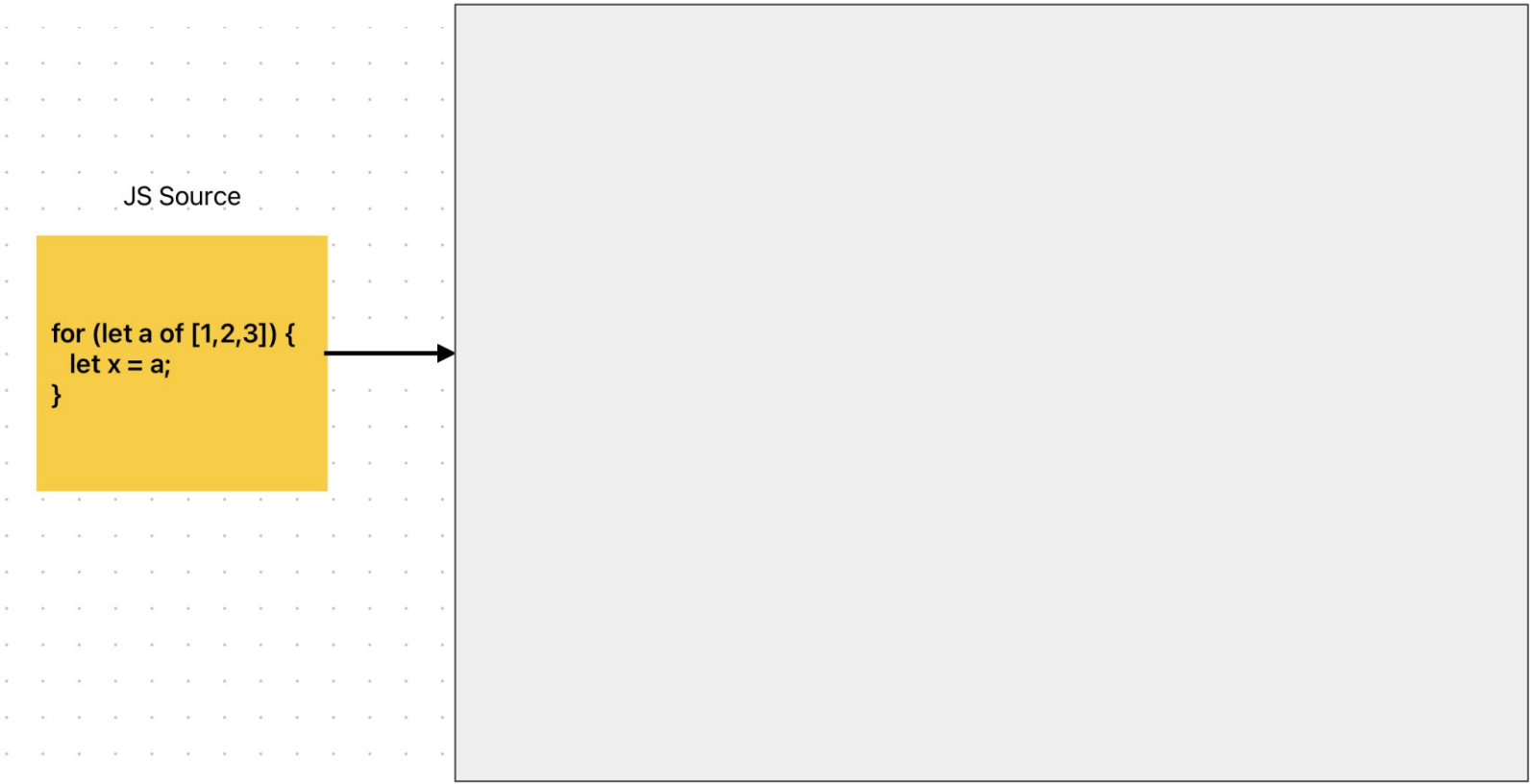


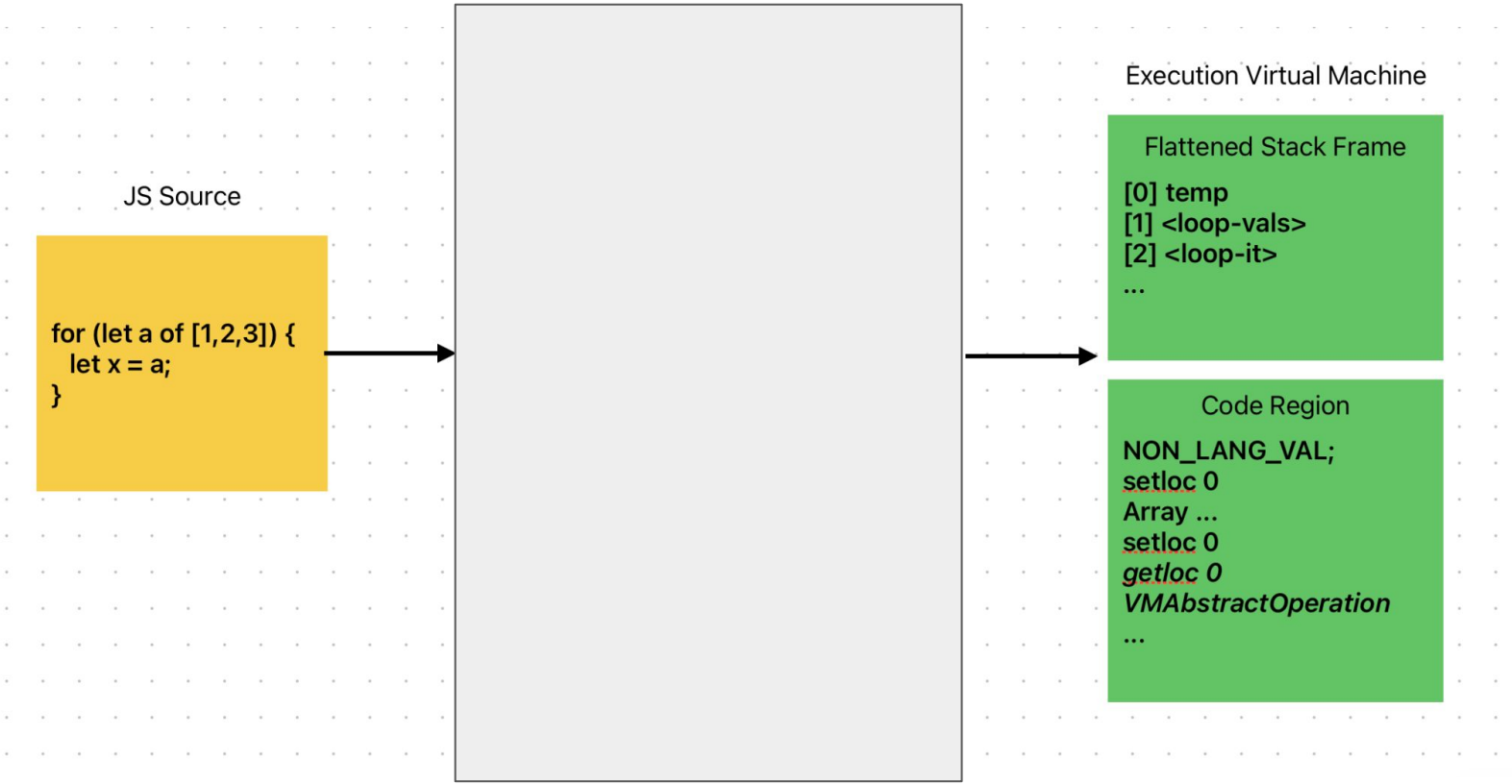
Figure 3.1: Overview of the Iridium architecture.

Frontend.

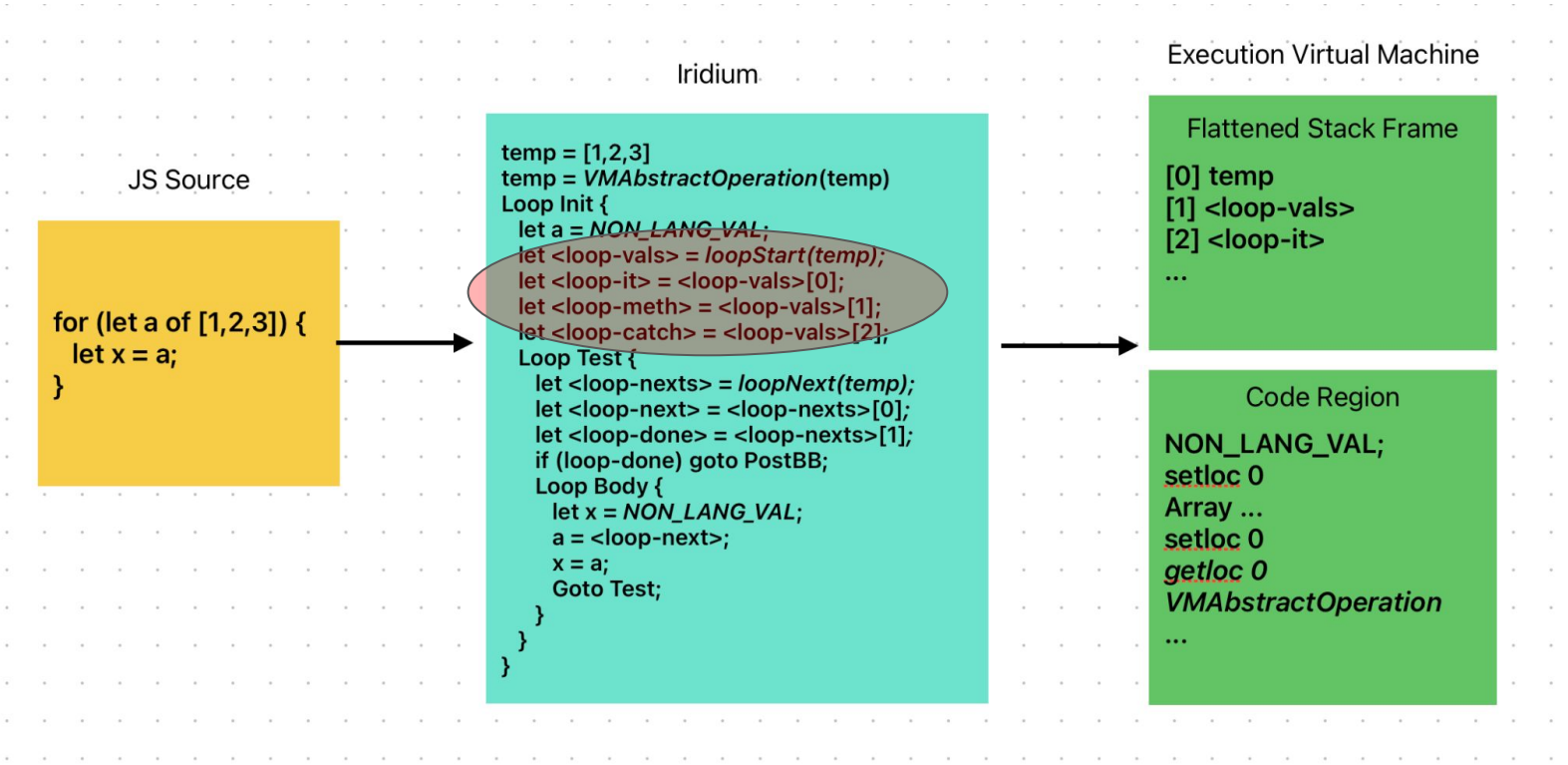
Just a loop right?



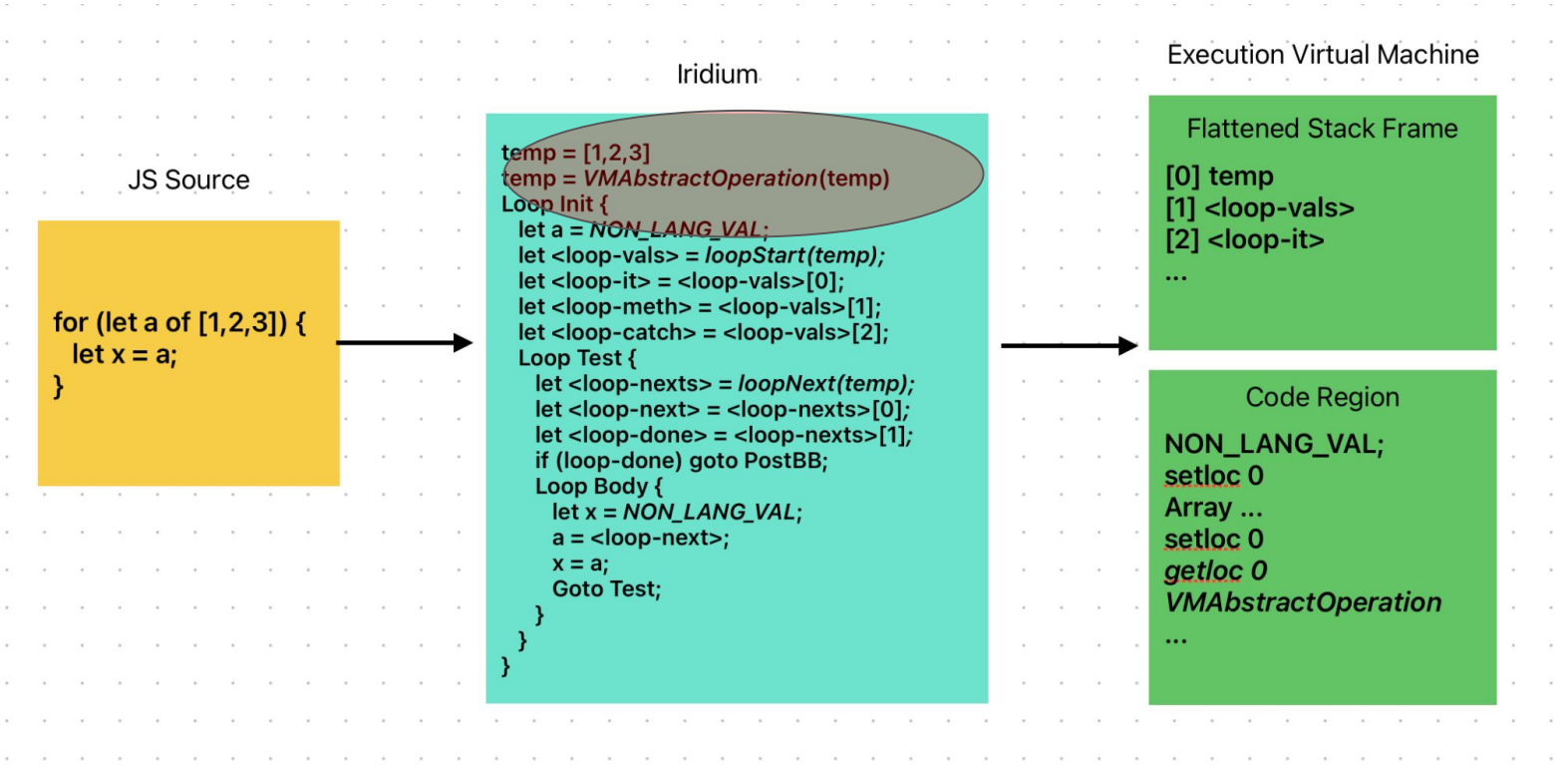
Just a loop right? **Wrong**



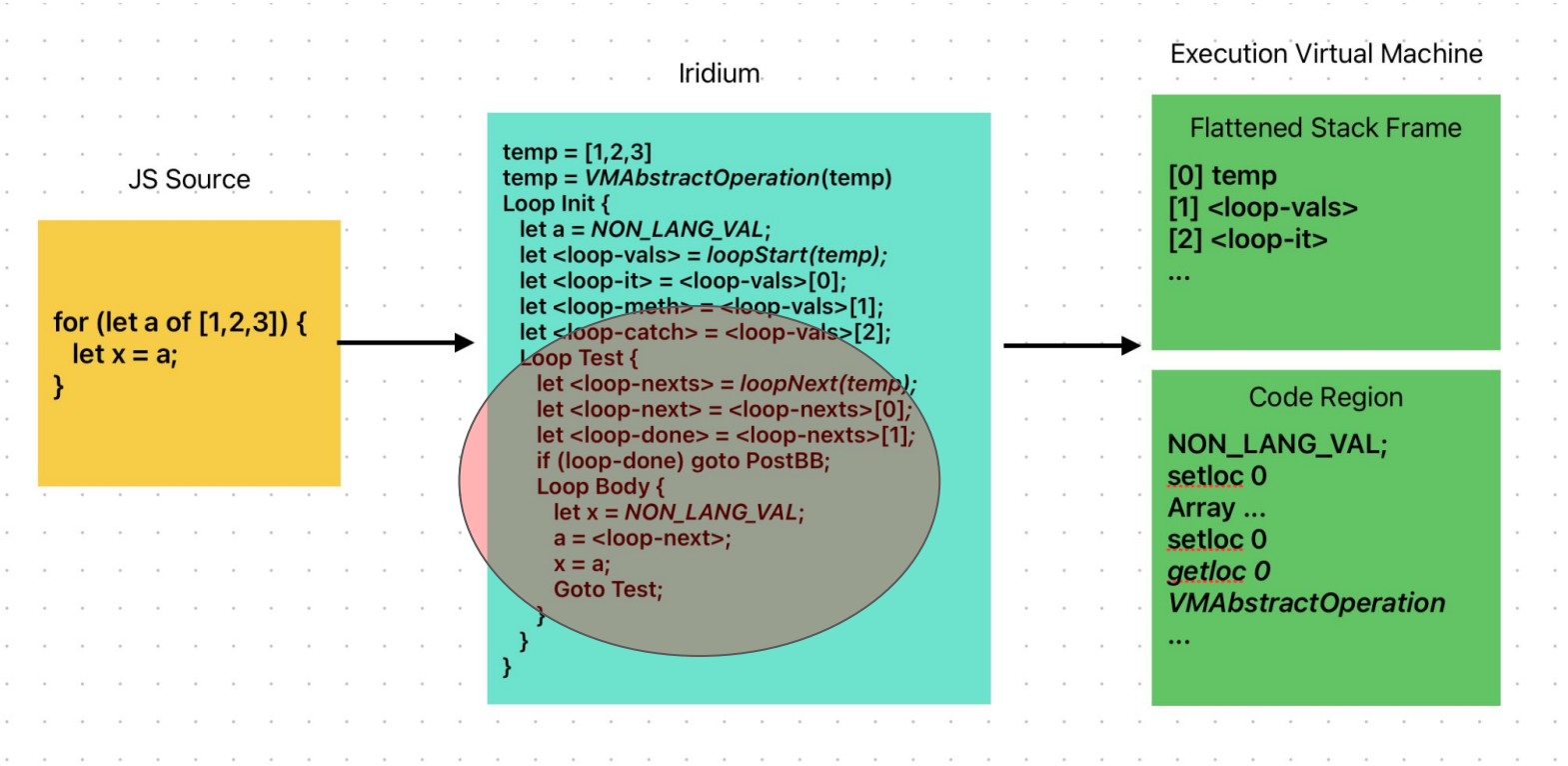
Try Catch Block, Implicit Abstract Operations and new evaluation scopes



Try Catch Block, **Implicit Abstract Operations** and new evaluation scopes



Try Catch Block, Implicit Abstract Operations and **new evaluation scopes**



Iridium SEXP Format

```
IridiumSEXP
```

```
String : IridiumPrimitive
```

```
Args
```

A generic S-Expression has this format.

Tag : Denotes the SEXP kind
Flags: Quirks on the SEXP
Args: The children of the node

Iridium Primitives

```
number | boolean | string | null;
```

```
a = 10;
```

```
[
 "EnvWrite",
 [
   [
     "EnvBinding",
     [],
     [["NAME",”a”]...]
   ],
   [
     "Number",
     [],
     [["IridiumPrimitive", 10.0]...]
   ],
 ],
 [...]
]
```

```
a = 10;
```

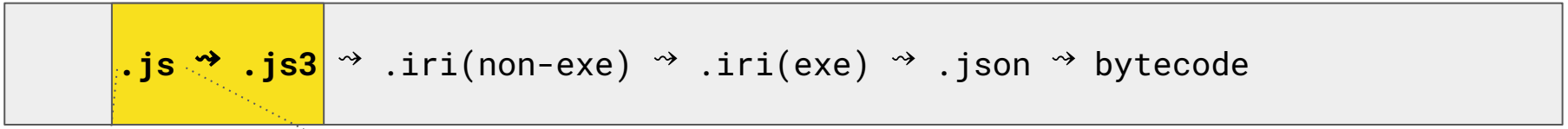
```
[
 "EnvWrite",
 [
   [
     "EnvBinding",
     [],
     [["NAME",”a”]...]
   ],
   [
     "Number",
     [],
     [["IridiumPrimitive", 10.0]...]
   ],
 ],
 [...]
]
```

```
a = 10;
```

```
[
 "EnvWrite",
 [
   [
     "EnvBinding",
     [],
     [["NAME","a"]...]
   ],
   [
     "Number",
     [],
     [["IridiumPrimitive", 10.0]...]
   ],
 ],
 [...]
]
```

```
a = 10;
```

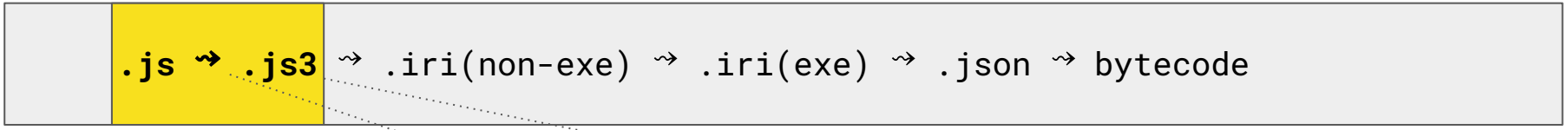
```
[
 "EnvWrite",
 [
   [
     "EnvBinding",
     [],
     [["NAME",”a”]...]
   ],
   [
     "Number",
     [],
     [["IridiumPrimitive", 10.0]...]
   ],
 ],
 [...]
]
```




```
let a = 12;
{
 console.log(a);
 let a = 13;
}
```

What's the output?

Running Example




```
let a = 12;
{
 console.log(a);
 let a = 13;
}
```

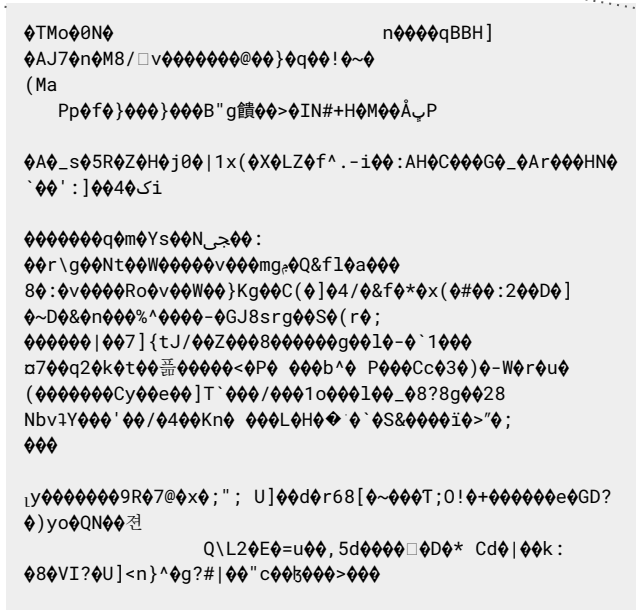
```
let a = 12;
{
 let js3$1 = console.log(a);
 let a = 13;
}
```

```
./iridium js3 --tout tests/basic/ex1.mjs
```

Running Example

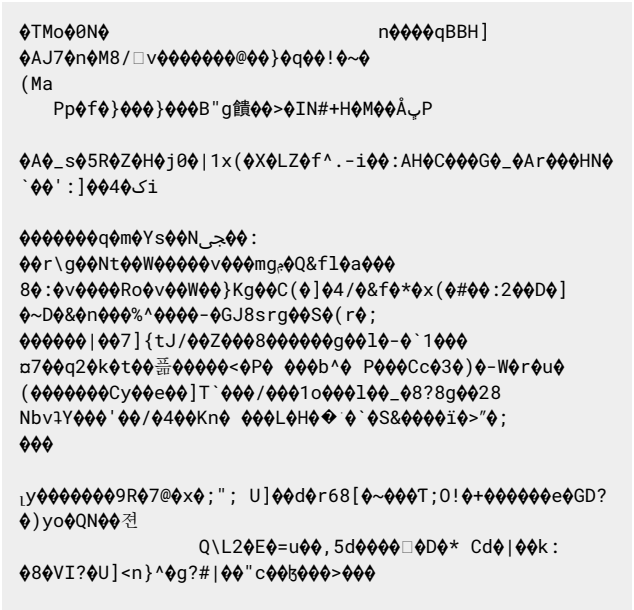
.js ⇝ **.js3 ⇝ .iri(non-exe)** ⇝ .iri(exe) ⇝ .json ⇝ bytecode

```
let a = 12;
{
 let js3$1 = console.log(a);
 let a = 13;
}
```



```
./iridium iri --debugIri . ./tests/basic/test1.mjs
```

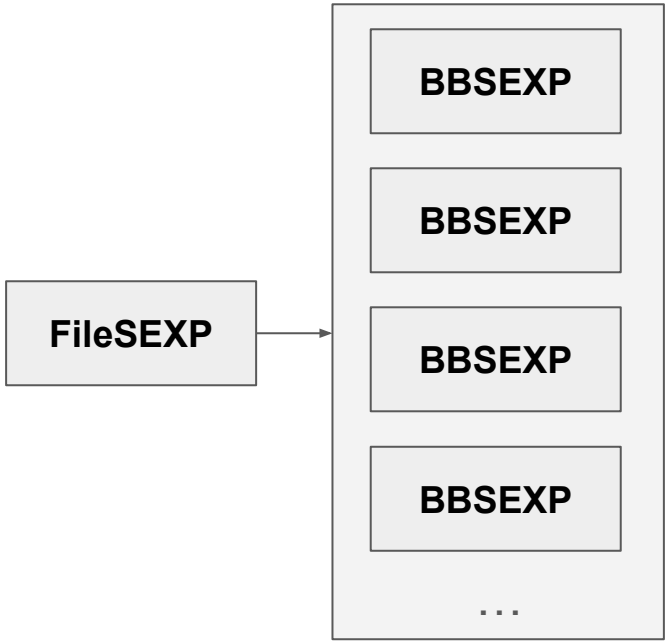
Running Example



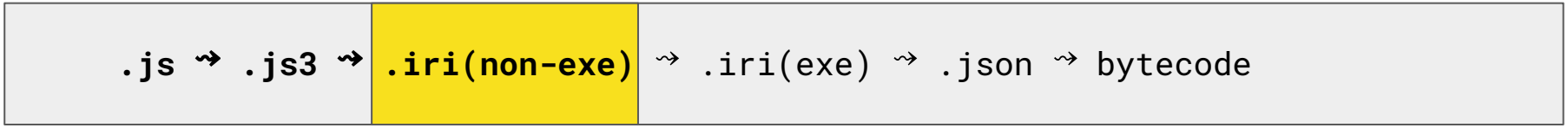
```
File[JSModule=null] {
 BB[IDX=0, ScopeIDX=0, TopLevel=null]
  JSImplicitBindingDeclaration[NAME="this"...]
   ResolveEnvBinding[NAME="this"]
   List
  IfElseJump[TRUE=1, FALSE=2]
   EnvRead(ResolveEnvBinding[NAME="this"]))

 BB[IDX=1, ScopeIDX=1, Lexical=null]
  Return[ModuleEarlyReturn=null]
   ...
 BB[IDX=2, ScopeIDX=0, Lexical=null]
  JSImplicitBindingDeclaration
   ResolveEnvBinding[NAME="<module_meta>"]
...
```

Running Example

.js ⇝ .js3 ⇝	**.iri(non-exe)**	⇝ .iri(exe) ⇝ .json ⇝ bytecode



Running Example




```
BB0:
 {this, VSYSCALL(9)}
 goto (this) ? 1 : 2

BB1:
 Return undefined

BB2:
 {<module_meta>, VSYSCALL(6)}
 {a, 12}
 goto 3
```

```
BB3:
 {ccallCallee$2, console.log}
 CallSite({console}, {ccallCallee$2},{a})
 {a, 13}
 goto 4

BB4:
 AsyncReturn undefined
```

Running Example

.js ⇝ .js3 ⇝	**.iri(non-exe)**	⇝ .iri(exe) ⇝ .json ⇝ bytecode

```
BB0:
 {this, VSYSCALL(9)}
 goto (this) ? 1 : 2

BB1:
 Return undefined

BB2:
 {<module_meta>, VSYSCALL(6)}
 {a, 12}
 goto 3
```

```
BB3:
 {ccallCallee$2, console.log}
 CallSite({console}, {ccallCallee$2},{a})
 {a, 13}
 goto 4

BB4:
 AsyncReturn undefined
```

Running Example

.js ⇝ .js3 ⇝ **.iri(non-exe)** ⇝ .iri(exe) ⇝ .json ⇝ bytecode

```
BB0:
 {this, VSYSCALL(9)}
 goto (this) ? 1 : 2

BB1:
 Return undefined

BB2:
 {<module_meta>, VSYSCA
 {a, 12}
 goto 3
```

JSImplicitBinding
DeclarationSEXP

```
BB3:
 llee$2, cor
 sole},
 fir
```

Running Example

.js ⇝ .js3 ⇝	**.iri(non-exe)**	⇝ .iri(exe) ⇝ .json ⇝ bytecode

```
BB0:
 {this, VSYSCALL(9)}
 goto (this) ? 1 : 2

BB1:
 Return undefined

BB2:
 {<module_meta>, VSYSCALL(6)}
 {a, 12}
 goto 3
```

```
BB3:
 {ccallCallee$2, console.log}
 CallSite({console}, {ccallCallee$2},{a})
 {a, 13}
 goto 4

BB4:
 AsyncReturn undefined
```

Running Example

.js ⇝ .js3 ⇝ **.iri(non-exe)** ⇝ .iri(exe) ⇝ .json ⇝ bytecode

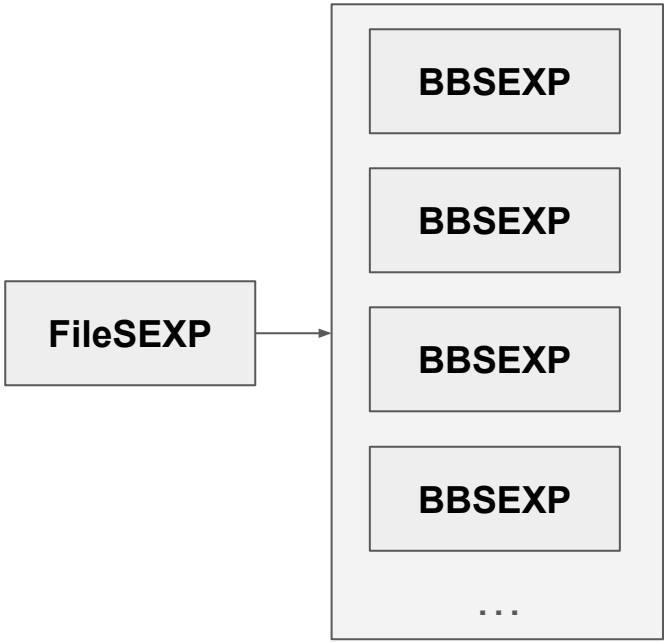
```
BB0:
 {this, VSYSCALL(9)}
 goto (this) ? 1 : 2

BB1:
 Return undefined

BB2:
 {<module_meta>, VSYSCA
 {a, 12}
 goto 3
```

JSExplicitBinding
DeclarationSEXP

```
BB3:
 llee$2, console.log}
 sole},
 fine
```

Running Example

.js ⇝ .js3 ⇝	**.iri(non-exe)**	⇝ .iri(exe) ⇝ .json ⇝ bytecode



- Explicit control flow
- Transitional Nodes

- No logical stack frames
- No closure grouping
- Incomplete semantics
  - Decorators
  - Stack Balancing

Running Example

Our Pipeline

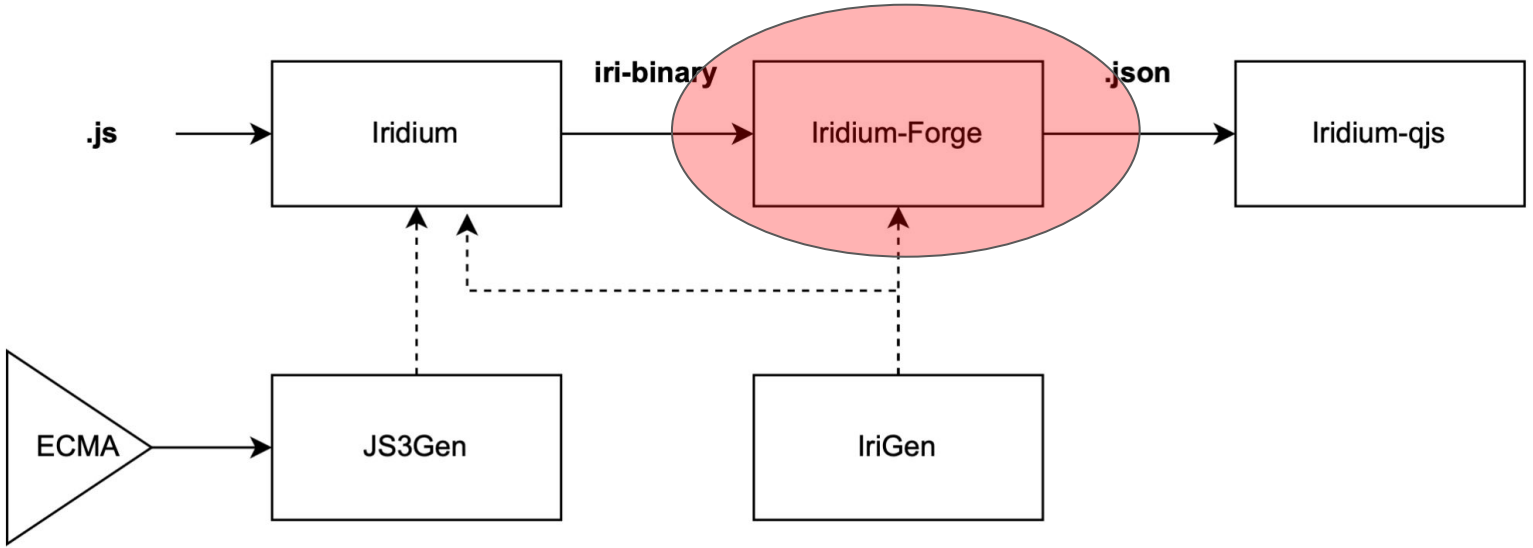
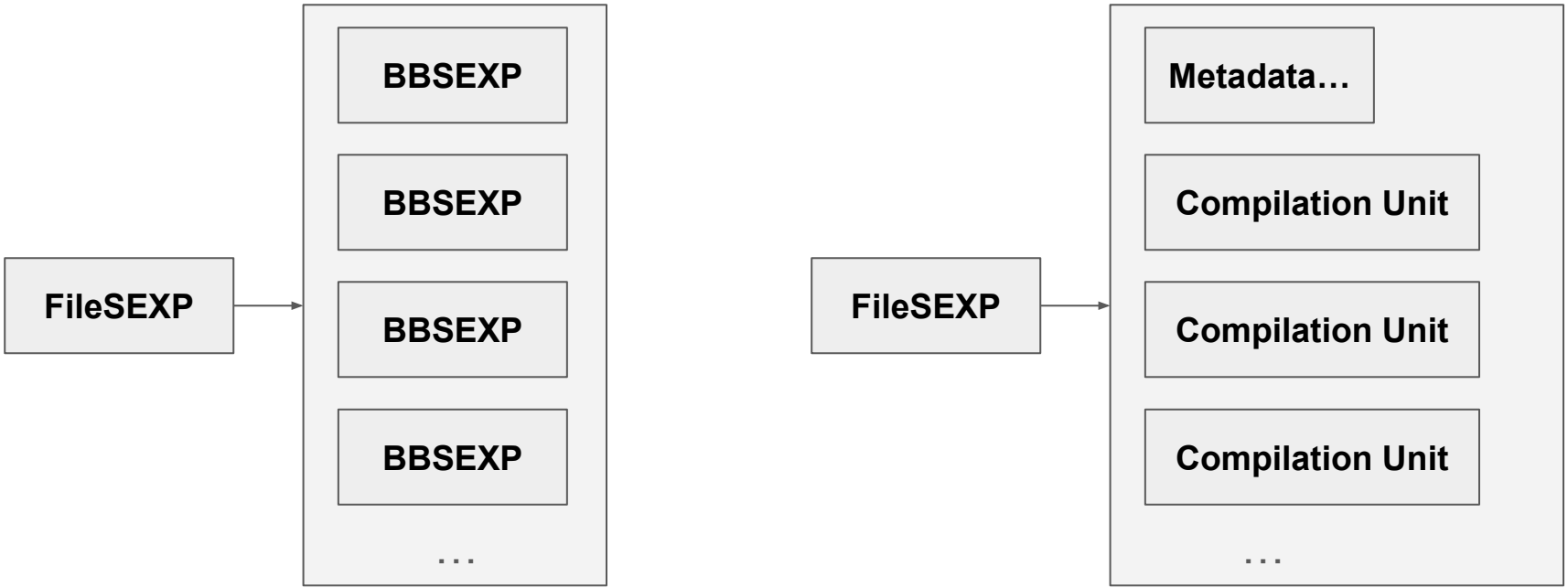


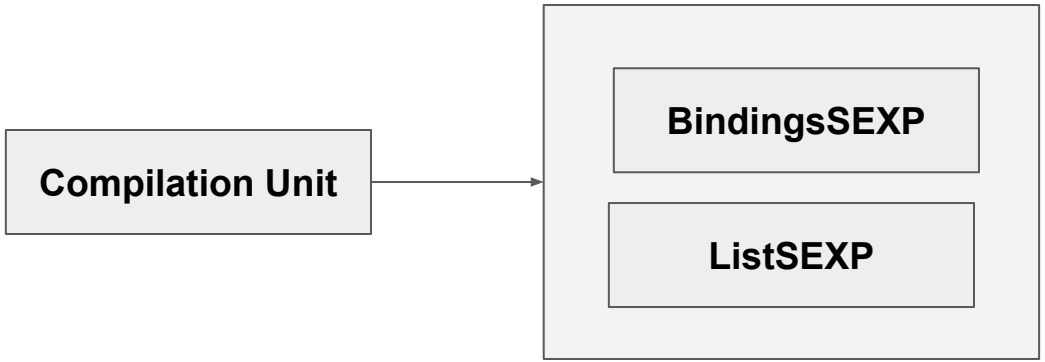
Figure 3.1: Overview of the Iridium architecture.

Forge.

Structural Separation happens in this phase



Structural Separation happens in this phase



BindingsSEXP is the logical stack frame

ListSEXP is a homogenous list of BBs

Structural Separation happens in this phase

```
let bar = () => {
 console.log(foo);
}
let foo = 12;
bar()
```

```
foo = NUBD
bar = NUBD
bar = Lambda@0
foo = 12;
bar()
```

```
Locals:
  [0]bar
  [1]foo
Remote:
```

```
console.log(foo)
```

```
Locals:
Remote:
  [0][1]foo
```

Structural Separation happens in this phase

```
let bar = () => {
 console.log(foo);
}
let foo = 12;
bar()
```

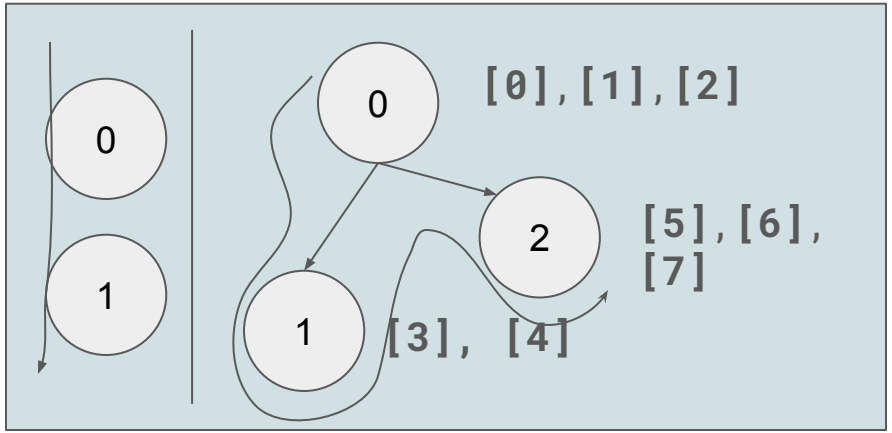
```
foo = NUBD
bar = NUBD
bar = Lambda@0
foo = 12;
bar()
```

```
Locals:
  [0]bar
  [1]foo
Remote:
```

```
console.log(foo)
```

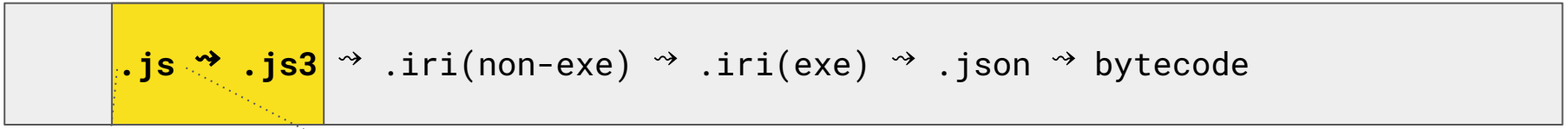
```
Locals:
Remote:
  [0][1]foo
```

Logical Stack Frames - Flattening



Preorder traversal of the scope tree

```
[0] b1 [-1]
[1] b2 [0]
[2] b3 [1]

[3] b7 [2]
[4] b8 [3]

[5] b4 [2]
[6] b5 [5]
[7] b6 [6]

[0] loc|remote [IDX]
[1] loc|remote [IDX]
```




```
let a = 12;
{
 console.log(a);
 let a = 13;
}
```

What's the output?

Running Example

.js ⇝ .js3 ⇝ .iri(non-exe) ⇝	**.iri(exe)**	⇝ .json ⇝ bytecode

```
BB0:
 [0]-[0]              = NBUD
 [0]                  = VSYSCALL(9)   // this
 If (this) goto 1
 [1]                  = VSYSCALL(9) //<module_meta>
 [0]-[0]              = 12
 [2]                  = NUBD
 [3]                  = NUBD
 [4]                  = NUBD
 [2]                  = console.log
 [3]                  = call (console, [2], [4])
 [4]                  = 13
 AsyncReturn undefined
```

```
BB1:
 Return undefined
```

Running Example


```
BB0:
 [0]-[0]              = NBUD // remote a
 [0]                  = VSYSCALL(9)   // this
 If (this) goto 1
 [1]                  = VSYSCALL(9) //<module_meta>
 [0]-[0]              = 12 // remote a = 12
 [2]                  = NUBD
 [3]                  = NUBD
 [4]                  = NUBD // local a
 [2]                  = console.log
 [3]                  = call (console, [2], [4])
 [4]                  = 13 // local a = 12
 AsyncReturn undefined
```

```
BB1:
 Return undefined
```

```
[0] this              [-1]
[1] <module_meta>     [0]
[2] ccallCallee$2     [1]
[3] js3$1             [2]
[4] a                 [3]

[0] a:loc [0]
```

Running Example


```
BB0:
 [0]-[0]              = NBUD // remote a
 [0]                  = VSYSCALL(9)   // this
 If (this) goto 1
 [1]                  = VSYSCALL(9) //<module_meta>
 [0]-[0]              = 12 // remote a = 12
 [2]                  = NUBD
 [3]                  = NUBD
 [4]                  = NUBD // local a
 [2]                  = console.log
 [3]                  = call (console, [2], [4])
 [4]                  = 13 // local a = 12
 AsyncReturn undefined
```

```
BB1:
 Return undefined
```

```
[0] this              [-1]
[1] <module_meta>     [0]
[2] ccallCallee$2     [1]
[3] js3$1             [2]
[4] a                 [3]

[0] a:loc [0]
```

Running Example

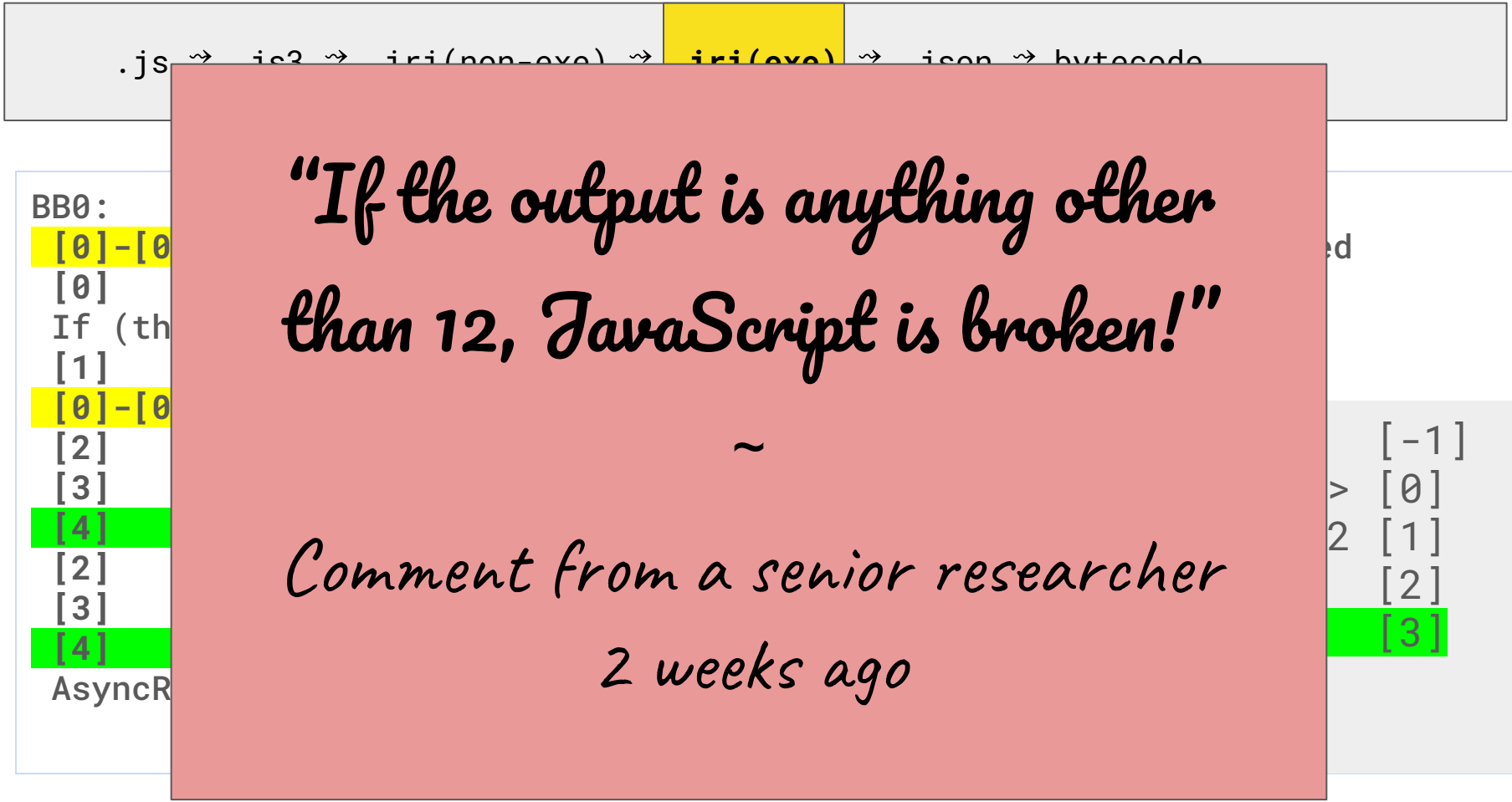
NUBD = No Use Before Def

This will cause a runtime error

```
BB0:
 [0]-[0]                                          ned
 [0]
 If (this)
 [1]
 [0]-[0]
 [2]                = NUBD
 [3]                = NUBD
 [4]                = NUBD // local a
 [2]                = console.log
 [3]                = call (console, [2], [4])
 [4]                = 13 // local a = 12
 AsyncReturn undefined
```

```
[0] this              [-1]
[1] <module_meta>     [0]
[2] ccallCallee$2     [1]
[3] js3$1             [2]
[4] a                 [3]

[0] a:loc [0]
```

Running Example



Running Example

Our Pipeline

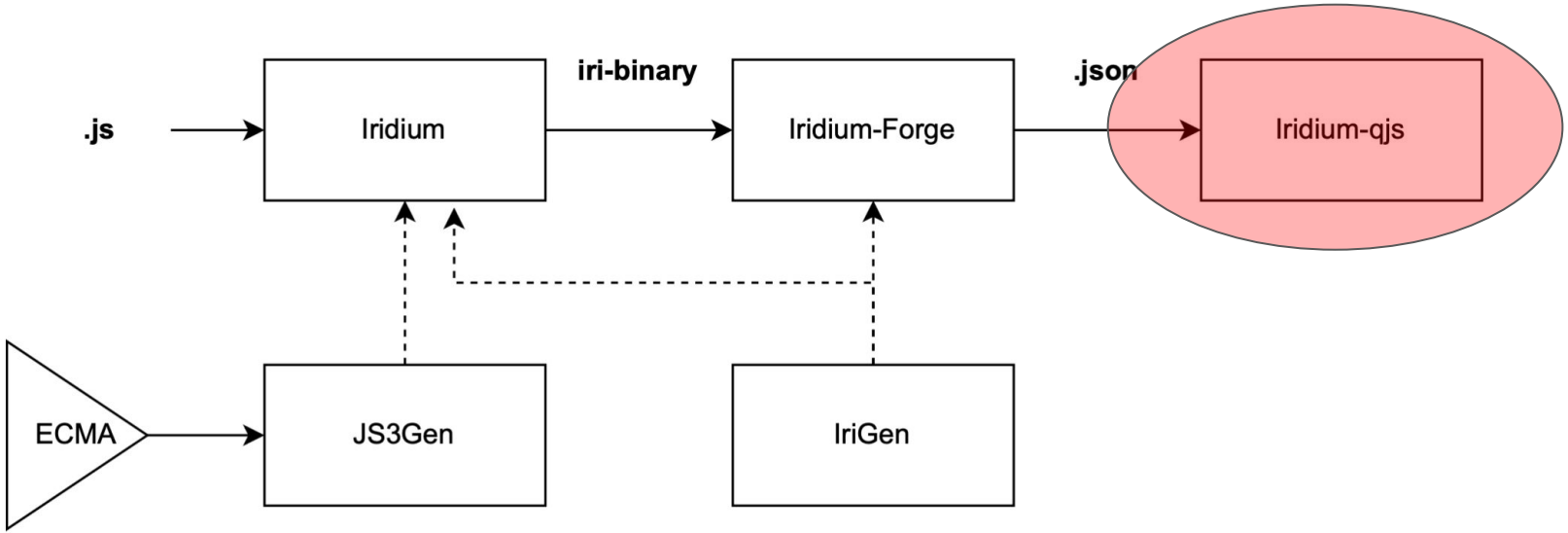


Figure 3.1: Overview of the Iridium architecture.

Backend.

.js ⇝ .js3 ⇝ .iri(non-exe) ⇝ .iri(exe) ⇝ **.json** ⇝ bytecode


```
{
 "version": "0.9a",
 "absoluteFilePath": "/home/meetesh/wd/Iridium/tests/basic/ex1.mjs",
 "iridium": [
   "File",
   [
     [
       "List",
       [],
       [
         [
           "TYPE",
           "ModuleRequest"
         ]
       ]
     ],
     ...
```


Running Example

Parsing

- Load and parse the Iridium code
- **cJSON library** is used to load the Iridium code into memory
- We haven’t set a binary format (yet).
- Empirical results say that this part is not very costly (yet), so its low priority currently.

Instruction Selection

- We have a very basic instruction selection currently.
  - **Lot of room for improvement.**
- Independent problem from Iridium analysis/optimization.
  - We are considering introducing new intrinsics for **special cases**.

.js ⇝ .js3 ⇝ .iri(non-exe) ⇝ .iri(exe) ⇝ .json ⇝ **bytecode**

```
ex1.mjs:1:1: function: <null>
  mode: strict
  locals:
    0: const this
    1: const <module_meta>
    2: var ccallCallee$2 [level:2 next:1]
    3: var js3$1 [level:2 next:2]
    4: var a [level:2 next:3]
  closure vars:
    0: a local:loc0 var
  stack_size: 3
  byte_code_len: 93
  opcodes: 30
```

Running Example

.js ⇝ .js3 ⇝ .iri(non-exe) ⇝ .iri(exe) ⇝ .json ⇝ **bytecode**

```
        push_const      0    ; uninitialized
        put_var_ref     0    ; a
        push_this
        put_loc         0    ; this
        get_loc_check   0    ; this
        if_true         91
        special_object  6
        put_loc         1    ; "<module_meta>"
        push_i8         12
        put_var_ref     0    ; a
        push_const      1    ; uninitialized
        put_loc         2    ; ccallCallee$2
        push_const      2    ; uninitialized
        put_loc         3    ; js3$1
...
```

Running Example

.js ⇝ .js3 ⇝ .iri(non-exe) ⇝ .iri(exe) ⇝ .json ⇝ **bytecode**

```
        push_const      0    ; uninitialized
        put_var_ref     0    ; a
```

```
Possibly unhandled promise rejection: ReferenceError: a is not initialized
    at <anonymous> (/home/meetesh/wd/Iridium/tests/basic/ex1.mjs:1:1)
```

```
        push_const      2    ; uninitialized
        put_loc         3    ; js3$1
...
```

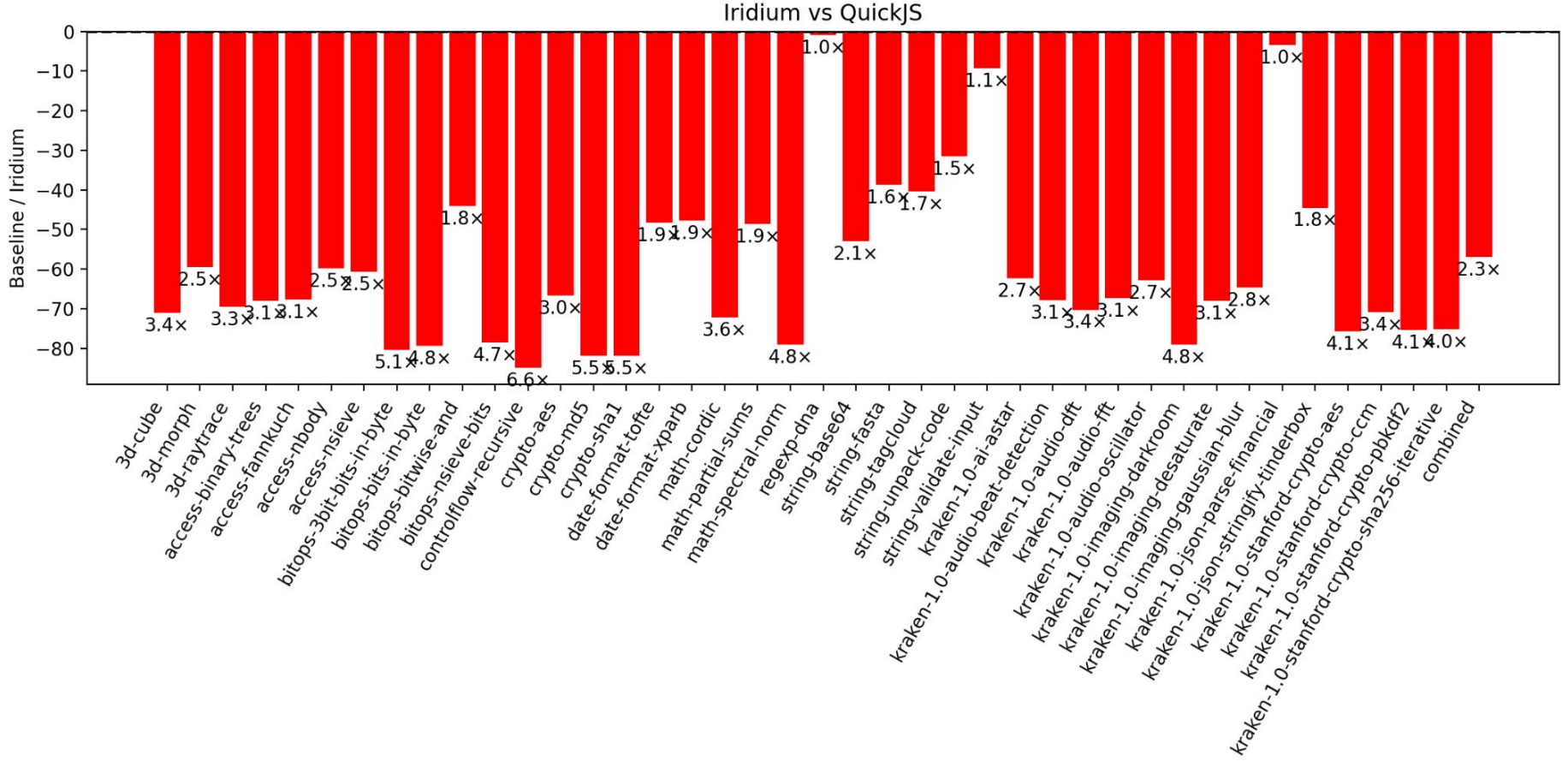
Running Example

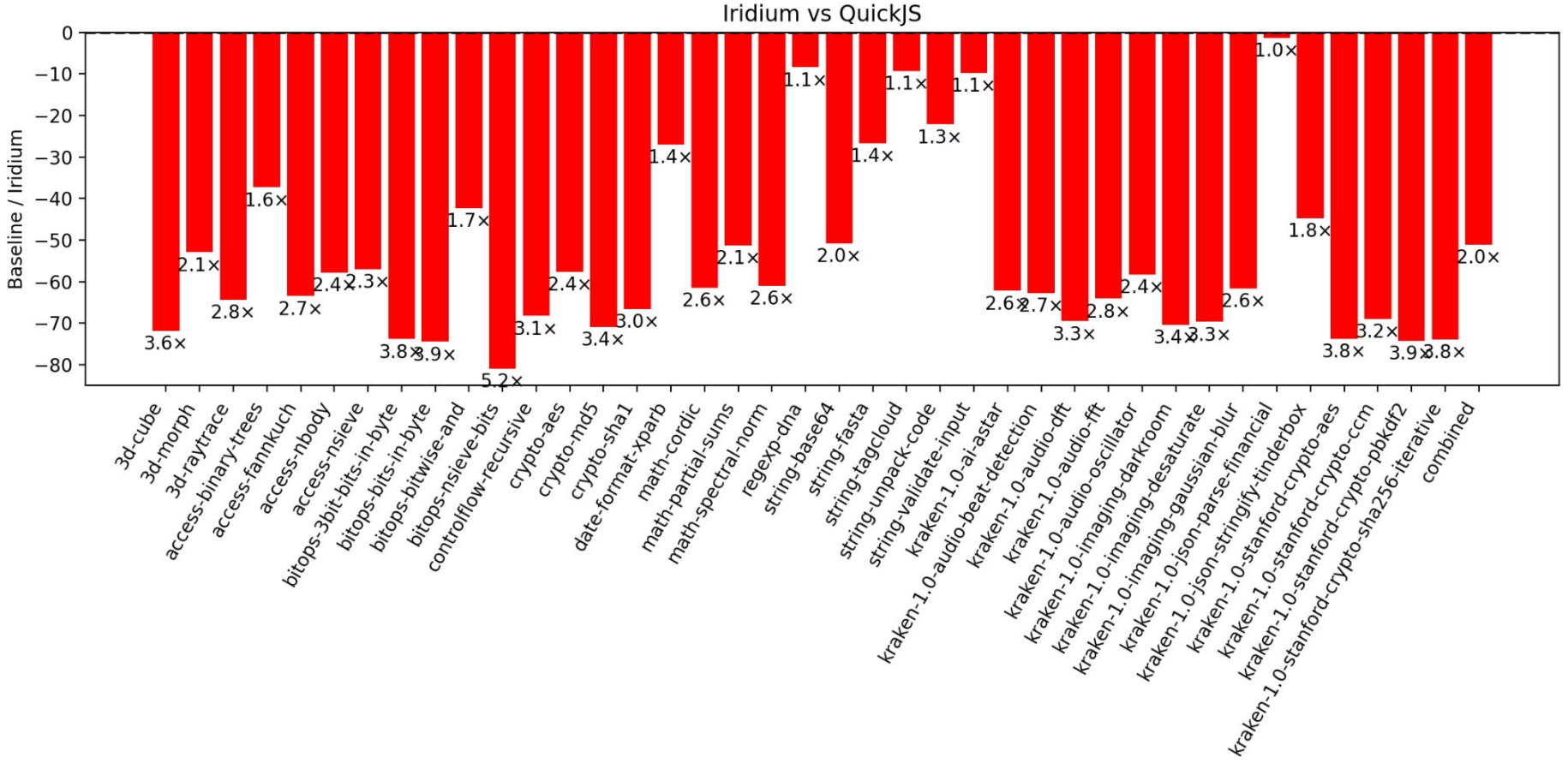
Conclusion.

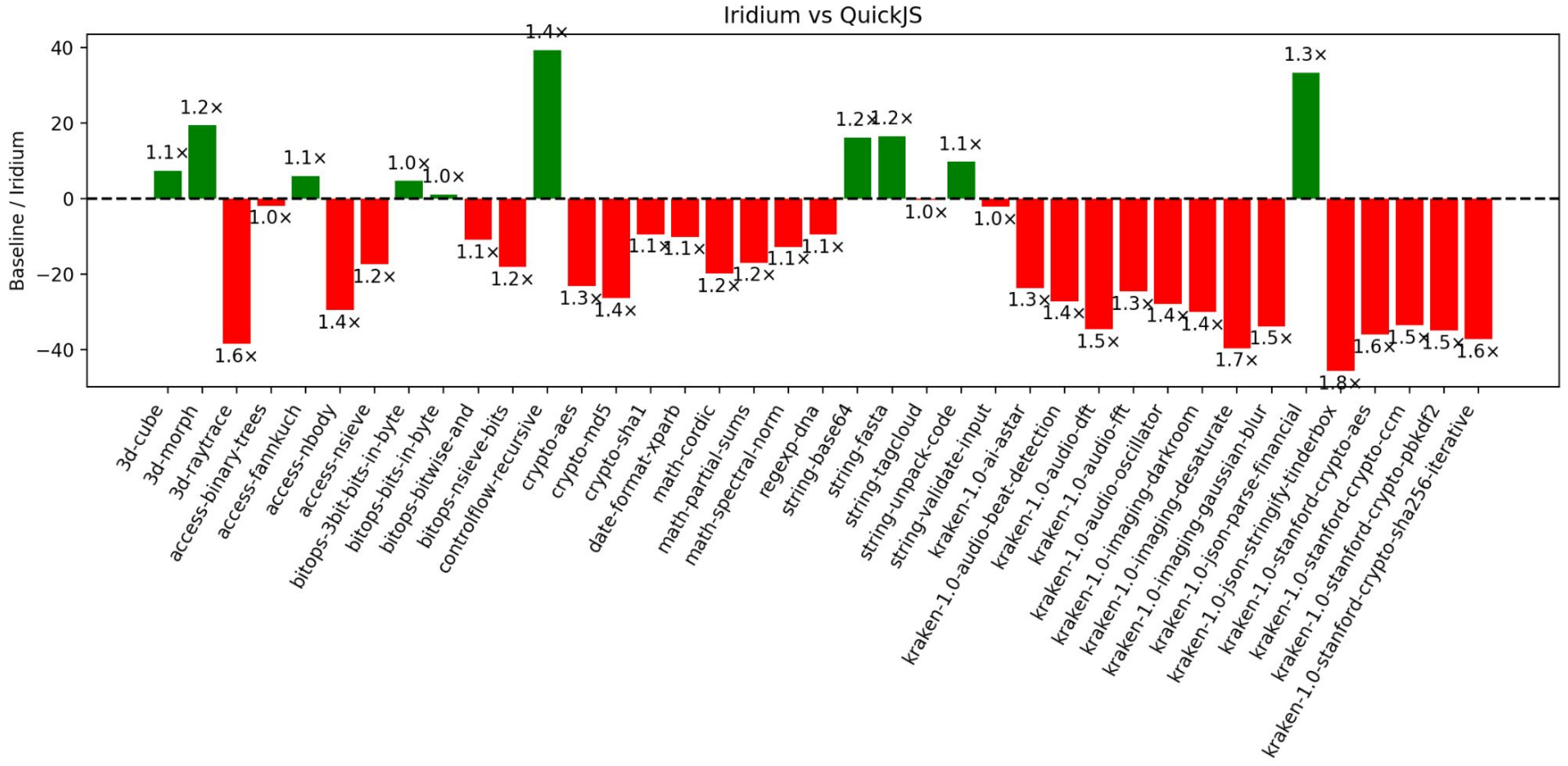
Project Statistics

Project	LOC	Languages	Status
Iridium	~50K	TypeScript	Stable, WIP
JS3Gen	~1K	TypeScript	Mostly Stable
Iridium-Forge	~9K	C++	WIP
IriGen	~200	TypeScript	Mostly Stable
Iridium-qjs (patch)	~5K	C/C++	WIP, one stable release

Table 3.1: Breakdown of Iridium projects by size, language, and stability.


Iridium vs QuickJS
Baseline / Iridium
0
−10
−20
−30
−40
−50
−60
−70
−80
3.4×
2.5×
3.3×
3.1×
3.1×
2.5×
2.5×
5.1×
4.8×
1.8×
4.7×
6.6×
3.0×
5.5×
5.5×
1.9×
1.9×
3.6×
1.9×
4.8×
1.0×
2.1×
1.6×
1.7×
1.5×
1.1×
2.7×
3.1×
3.4×
3.1×
2.7×
4.8×
3.1×
2.8×
1.0×
1.8×
4.1×
3.4×
4.1×
4.0×
2.3×
3d-cube
3d-morph
3d-raytrace
access-binary-trees
access-fannkuch
access-nbody
access-nsieve
bitops-3bit-bits-in-byte
bitops-bits-in-byte
bitops-bitwise-and
bitops-nsieve-bits
controlflow-recursive
crypto-aes
crypto-md5
crypto-sha1
date-format-tofte
date-format-xparb
math-cordic
math-partial-sums
math-spectral-norm
regexp-dna
string-base64
string-fasta
string-tagcloud
string-unpack-code
string-validate-input
kraken-1.0-ai-astar
kraken-1.0-audio-beat-detection
kraken-1.0-audio-dft
kraken-1.0-audio-fft
kraken-1.0-audio-oscillator
kraken-1.0-imaging-darkroom
kraken-1.0-imaging-desaturate
kraken-1.0-imaging-gaussian-blur
kraken-1.0-json-parse-financial
kraken-1.0-json-stringify-tinderbox
kraken-1.0-stanford-crypto-aes
kraken-1.0-stanford-crypto-ccm
kraken-1.0-stanford-crypto-pbkdf2
kraken-1.0-stanford-crypto-sha256-iterative
combined


Iridium vs QuickJS
Baseline / Iridium
0
−10
−20
−30
−40
−50
−60
−70
−80
3.6×
2.1×
2.8×
1.6×
2.7×
2.4×
2.3×
3.8×
3.9×
1.7×
5.2×
3.1×
2.4×
3.4×
3.0×
1.4×
2.6×
2.1×
2.6×
1.1×
2.0×
1.4×
1.1×
1.3×
1.1×
2.6×
2.7×
3.3×
2.8×
2.4×
3.4×
3.3×
2.6×
1.0×
1.8×
3.8×
3.2×
3.9×
3.8×
2.0×
3d-cube
3d-morph
3d-raytrace
access-binary-trees
access-fannkuch
access-nbody
access-nsieve
bitops-3bit-bits-in-byte
bitops-bits-in-byte
bitops-bitwise-and
bitops-nsieve-bits
controlflow-recursive
crypto-aes
crypto-md5
crypto-sha1
date-format-xparb
math-cordic
math-partial-sums
math-spectral-norm
regexp-dna
string-base64
string-fasta
string-tagcloud
string-unpack-code
string-validate-input
kraken-1.0-ai-astar
kraken-1.0-audio-beat-detection
kraken-1.0-audio-dft
kraken-1.0-audio-fft
kraken-1.0-audio-oscillator
kraken-1.0-imaging-darkroom
kraken-1.0-imaging-desaturate
kraken-1.0-imaging-gaussian-blur
kraken-1.0-json-parse-financial
kraken-1.0-json-stringify-tinderbox
kraken-1.0-stanford-crypto-aes
kraken-1.0-stanford-crypto-ccm
kraken-1.0-stanford-crypto-pbkdf2
kraken-1.0-stanford-crypto-sha256-iterative
combined


Iridium vs QuickJS
Baseline / Iridium
40
20
0
−20
−40
1.1×
1.2×
1.6×
1.0×
1.1×
1.4×
1.2×
1.0×
1.0×
1.1×
1.2×
1.4×
1.3×
1.4×
1.1×
1.1×
1.2×
1.2×
1.1×
1.1×
1.2×
1.2×
1.0×
1.1×
1.0×
1.3×
1.4×
1.5×
1.3×
1.4×
1.4×
1.7×
1.5×
1.3×
1.8×
1.6×
1.5×
1.5×
1.6×
3d-cube
3d-morph
3d-raytrace
access-binary-trees
access-fannkuch
access-nbody
access-nsieve
bitops-3bit-bits-in-byte
bitops-bits-in-byte
bitops-bitwise-and
bitops-nsieve-bits
controlflow-recursive
crypto-aes
crypto-md5
crypto-sha1
date-format-xparb
math-cordic
math-partial-sums
math-spectral-norm
regexp-dna
string-base64
string-fasta
string-tagcloud
string-unpack-code
string-validate-input
kraken-1.0-ai-astar
kraken-1.0-audio-beat-detection
kraken-1.0-audio-dft
kraken-1.0-audio-fft
kraken-1.0-audio-oscillator
kraken-1.0-imaging-darkroom
kraken-1.0-imaging-desaturate
kraken-1.0-imaging-gaussian-blur
kraken-1.0-json-parse-financial
kraken-1.0-json-stringify-tinderbox
kraken-1.0-stanford-crypto-aes
kraken-1.0-stanford-crypto-ccm
kraken-1.0-stanford-crypto-pbkdf2
kraken-1.0-stanford-crypto-sha256-iterative

Thank You ✌️

- This sets us in orbit 🛰️
- Now the “real” compiler work starts 🪐
  - Interprocedural PTA
  - async primitives 👬
  - More frontends/backends

PLATO

PLATO @ IITB