Characterizing Java Streams in the Wild

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JAVA STREAMS

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- **Stream API** (package java.util.stream)
  - Introduced since Java 8
  - Data processing
    - Functional programming
      - MapReduce style transformations
  - Two key abstractions:
    - **Stream**
    - **Stream pipeline**

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Stream – Java Code Example

```
transactionList.stream()
        .parallel()
        .filter(t -> t.getStatus() == Transaction.VALID)
        .map(Transaction::getID)
        .collect(Collectors.toSet());
```

Stream

```
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        .parallel()
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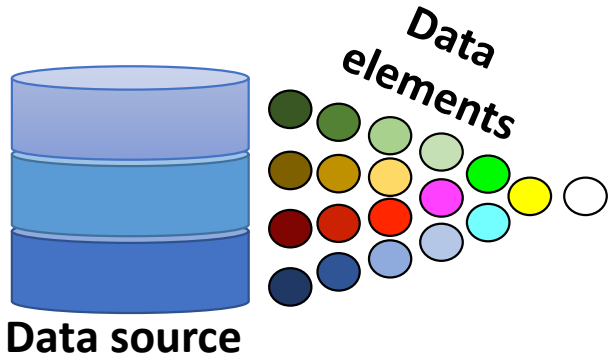
```



- A **stream** represents a sequence of **data elements** that comes from a **data source**

Data Source

```
transactionList.stream()
    .parallel()
    .filter(t -> t.getStatus() == Transaction.VALID)
    .map(Transaction::getID)
    .collect(Collectors.toSet());
```

Data source

Data source

`List`: transactionList

transactionList is a Collection

- Other data sources from which a stream can be created:
  - Arrays
  - Files
  - Strings
  - …

Source Collection Type

```
transactionList.stream()
        .parallel()
        .filter(t -> t.getStatus() == Transaction.VALID)
        .map(Transaction::getID)
        .collect(Collectors.toSet());
```

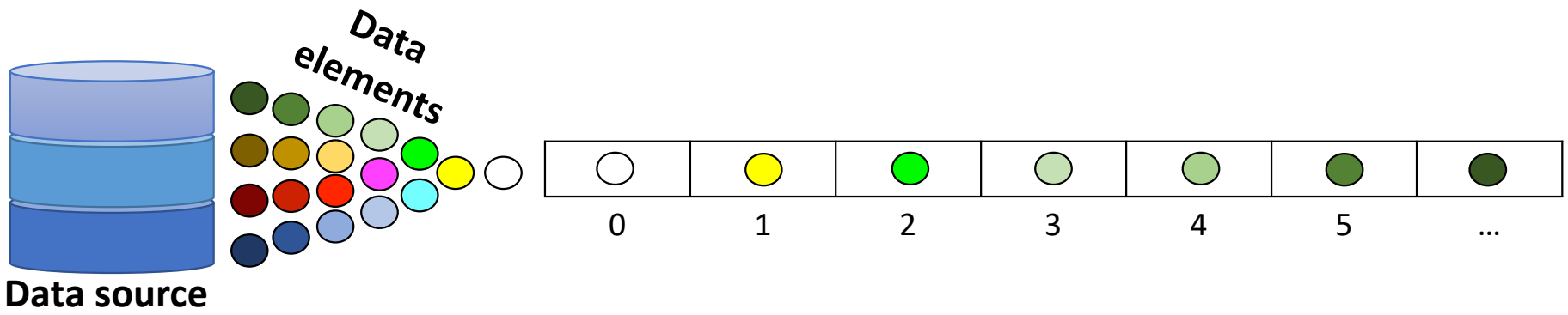
Data source

`List`:
transactionList

Source collection type:
e.g., `java.util.ArrayList`

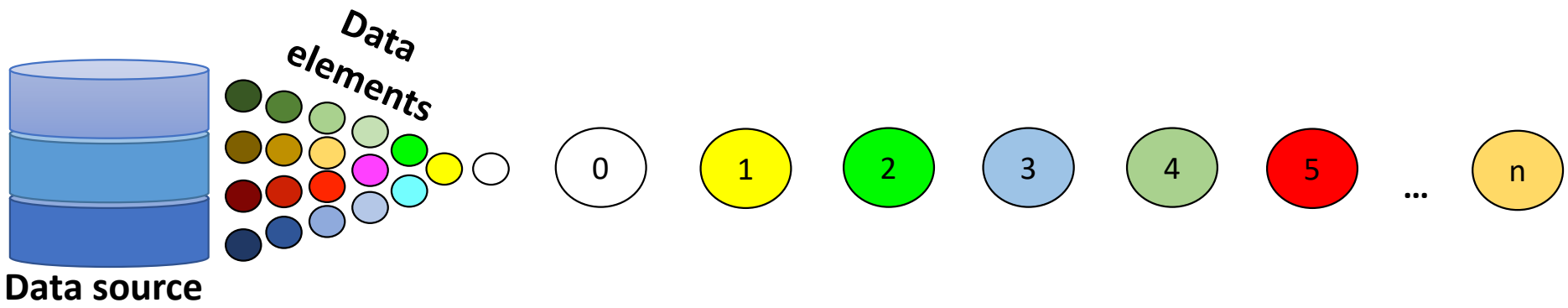
Characteristics of the Data Source - Encounter Order

- **Encounter Order:** whether the data source makes its elements available in a defined order (i.e., index order)



Characteristics of the Data Source - Sort Order

- **Sort Order:** whether the data source makes its elements available in a sort order



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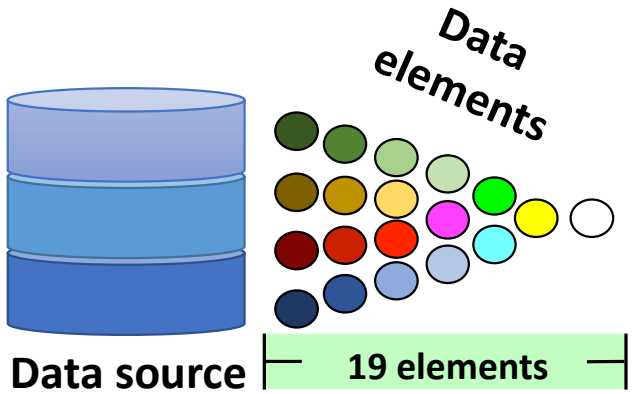
Characteristics of the Data Source

- **Concurrent:** whether the data source allows concurrent modification
- **Distinct:** whether the data source allows duplicates
- **Immutable:** whether the elements in the data source can be modified

Characteristics of the Data Source – Data-Source Size

- **Data-source size:** the total number of elements in the data source



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Stream Types

```
transactionList.stream()
        .parallel()
        .filter(t -> t.getStatus() == Transaction.VALID)
        .map(Transaction::getID)
        .collect(Collectors.toSet());
```

Stream type:
`java.util.stream.Stream`

- Other stream types include:
  - `java.util.stream.IntStream`
  - `java.util.stream.LongStream`
  - `java.util.stream.DoubleStream`

Source Method

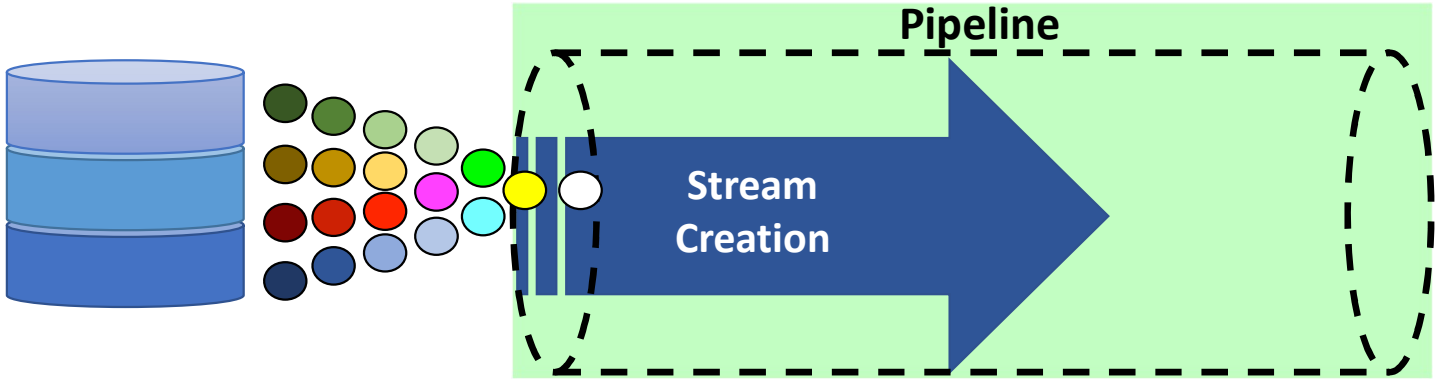
Source method:
`java.util.Collection.stream`

```
transactionList.stream()
        .parallel()
        .filter(t -> t.getStatus() == Transaction.VALID)
        .map(Transaction::getID)
        .collect(Collectors.toSet());
```

Pipeline

```
transactionList.stream()
    .parallel()
    .filter(t -> t.getStatus() == Transaction.VALID)
    .map(Transaction::getID)
    .collect(Collectors.toSet());
```

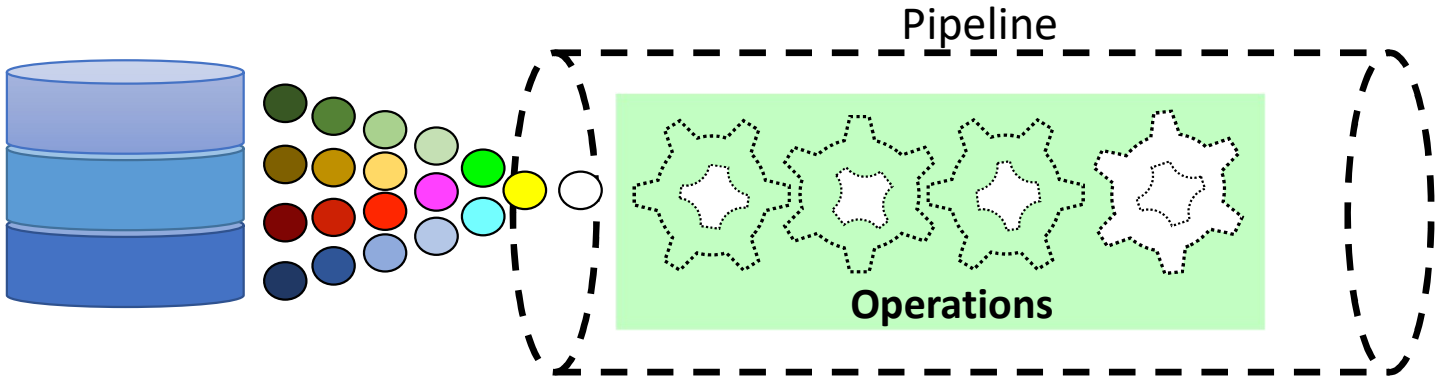
Stream creation



Operations

```
transactionList.stream()
        .parallel()
        .filter(t -> t.getStatus() == Transaction.VALID)
        .map(Transaction::getID)
        .collect(Collectors.toSet());
```

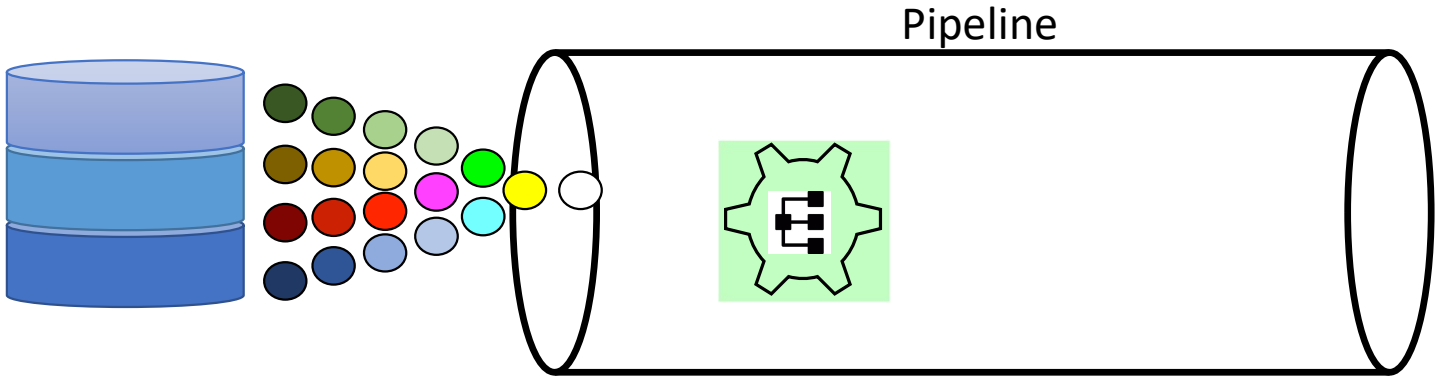
- The stream pipeline contains **operations**



Operation Appending

```
transactionList.stream()
    .parallel()
    .filter(t -> t.getStatus() == Transaction.VALID)
    .map(Transaction::getID)
    .collect(Collectors.toSet());
```

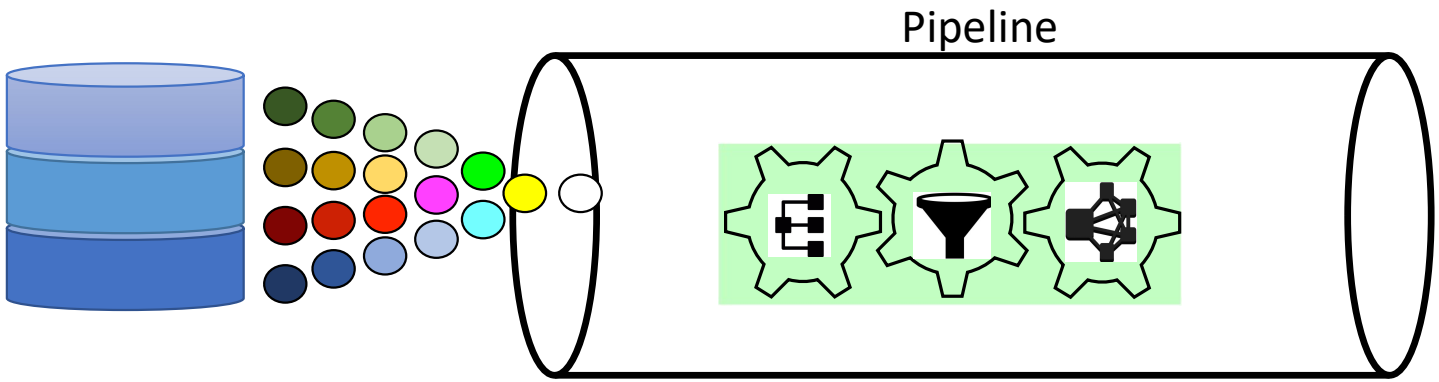
The operation is **appended** to the pipeline



Intermediate Operations

```
transactionList.stream()
      .parallel()
      .filter(t -> t.getStatus() == Transaction.VALID)
      .map(Transaction::getID)
      .collect(Collectors.toSet());
```

Intermediate operations



Terminal Operation

```
transactionList.stream()
        .parallel()
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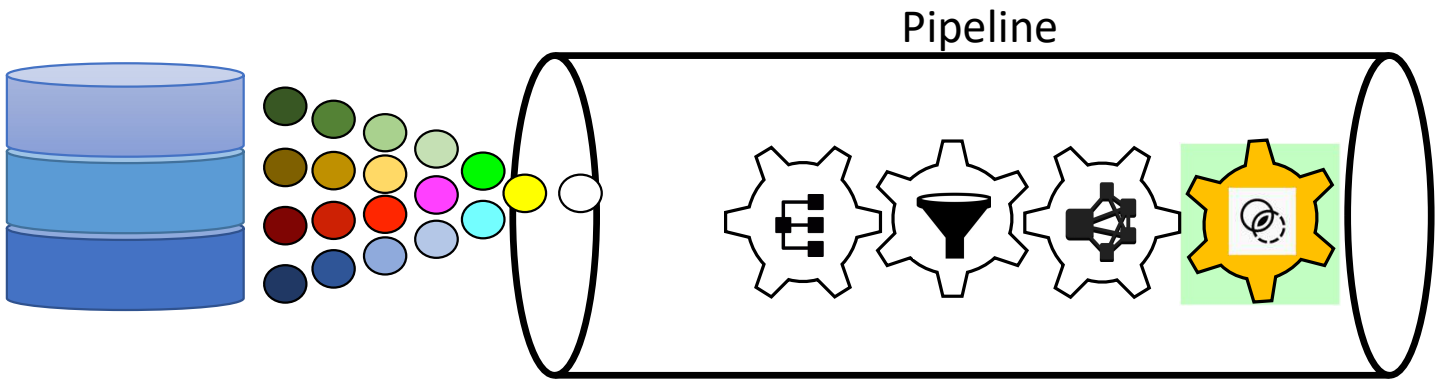
        .collect(Collectors.toSet());
```

Terminal operation



Terminal Operation

```
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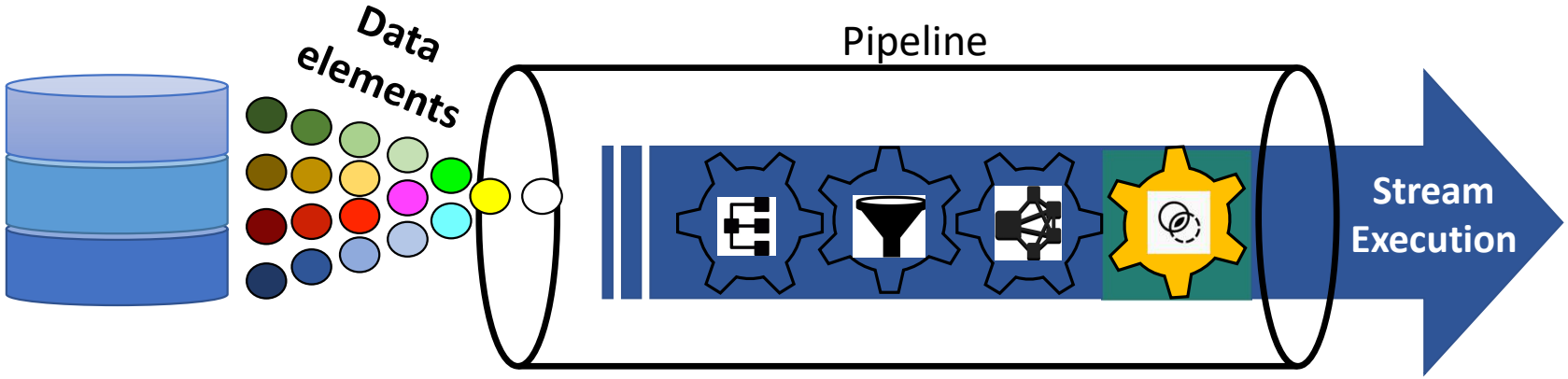
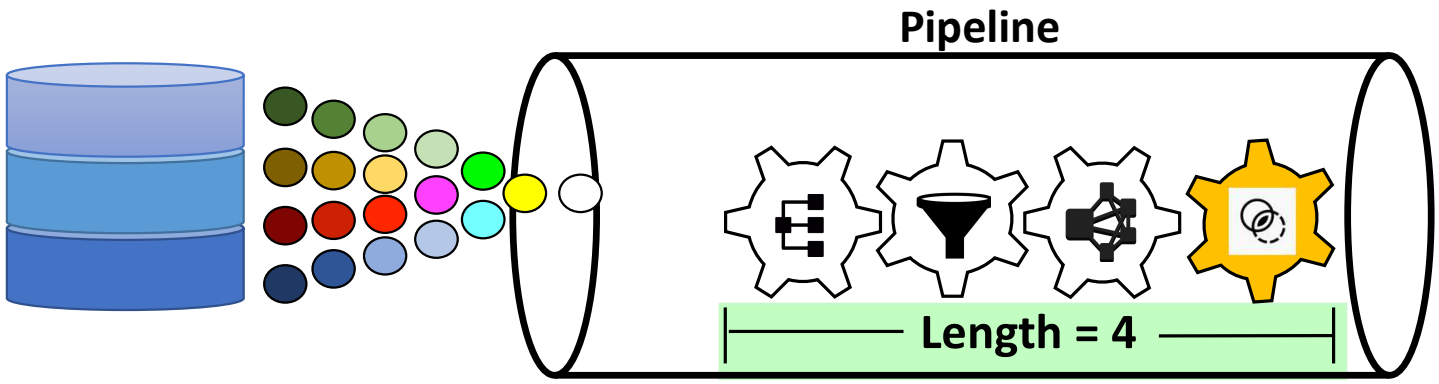
Terminal operation



Pipeline Length

```
transactionList.stream()
        .parallel()
        .filter(t -> t.getStatus() == Transaction.VALID)
        .map(Transaction::getID)
        .collect(Collectors.toSet());
```

There are 4 operations in the pipeline

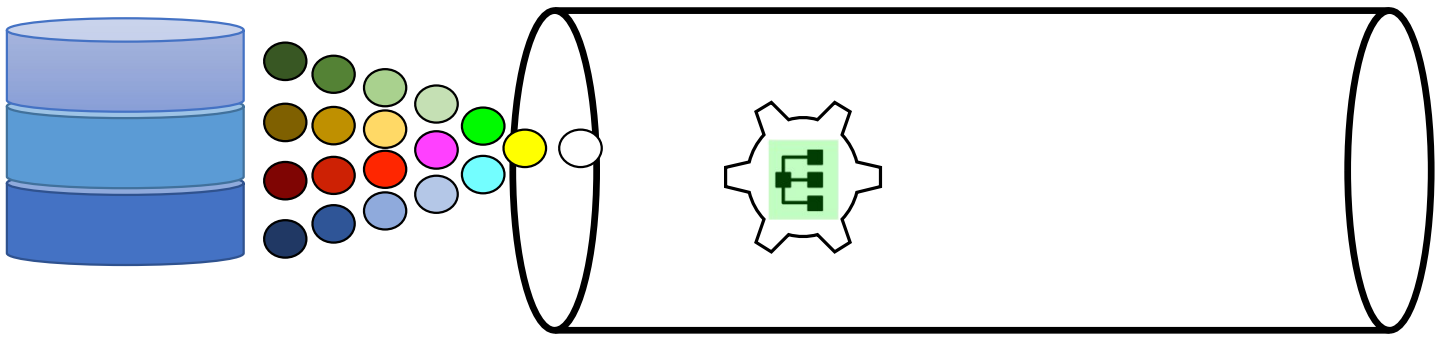


Execution Mode

```
transactionList.stream()
    .parallel()
    .filter(t -> t.getStatus() == Transaction.VALID)
    .map(Transaction::getID)
    .collect(Collectors.toSet());
```

Switches the **execution mode**

Execution Mode	
Sequential	Parallel



Intermediate Operations

```
transactionList.stream()
        .parallel()
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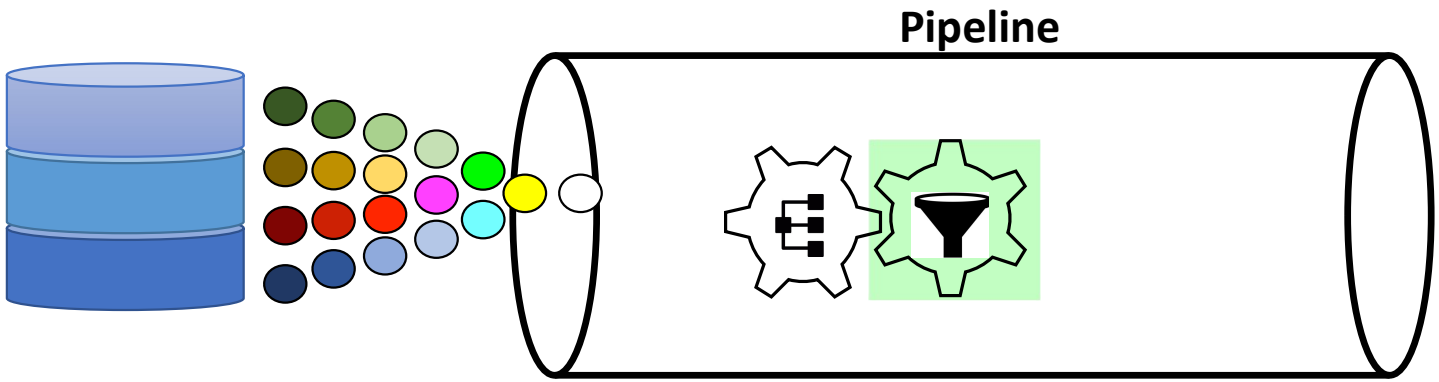
        .map(Transaction::getID)
        .collect(Collectors.toSet());
```

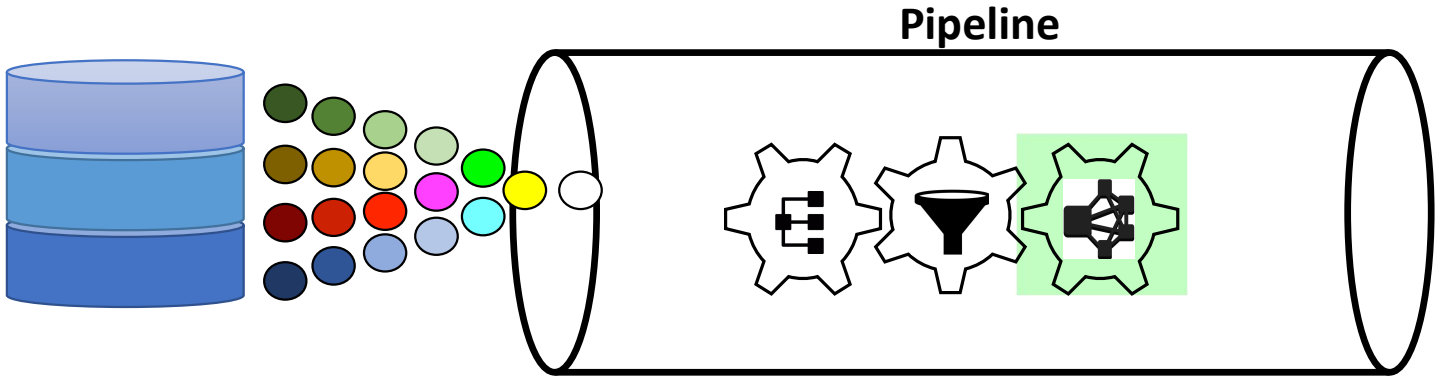
Filters valid transactions



Intermediate Operations

```
transactionList.stream()
        .parallel()
        .filter(t -> t.getStatus() == Transaction.VALID)
        .map(Transaction::getID)
        .collect(Collectors.toSet());
```

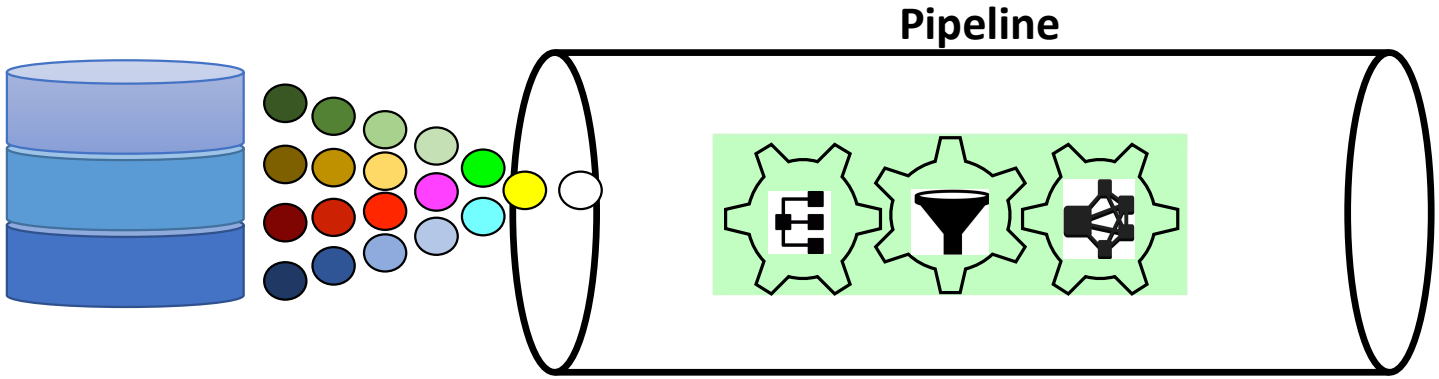
Extracts the IDs of valid transactions



Stateless Intermediate Operations

```
transactionList.stream()
    .parallel()
    .filter(t -> t.getStatus() == Transaction.VALID)
    .map(Transaction::getID)
    .collect(Collectors.toSet());
```

Stateless intermediate operations

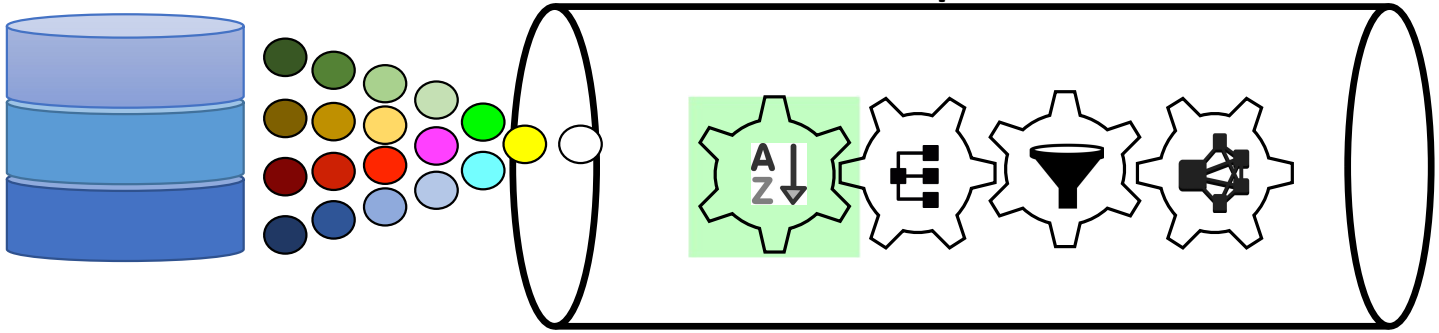


Stateful Intermediate Operations

```
transactionList.stream()
      .sorted()
      .parallel()
      .filter(t -> t.getStatus() == Transaction.VALID)
      .map(Transaction::getID)
      .collect(Collectors.toSet());
```

Stateful operation sorting the elements in the pipeline

Pipeline



Stateful Intermediate Operations

```
transactionList.stream()
      .sorted()
      .parallel()
      .filter(t -> t.getStatus() == Transaction.VALID)
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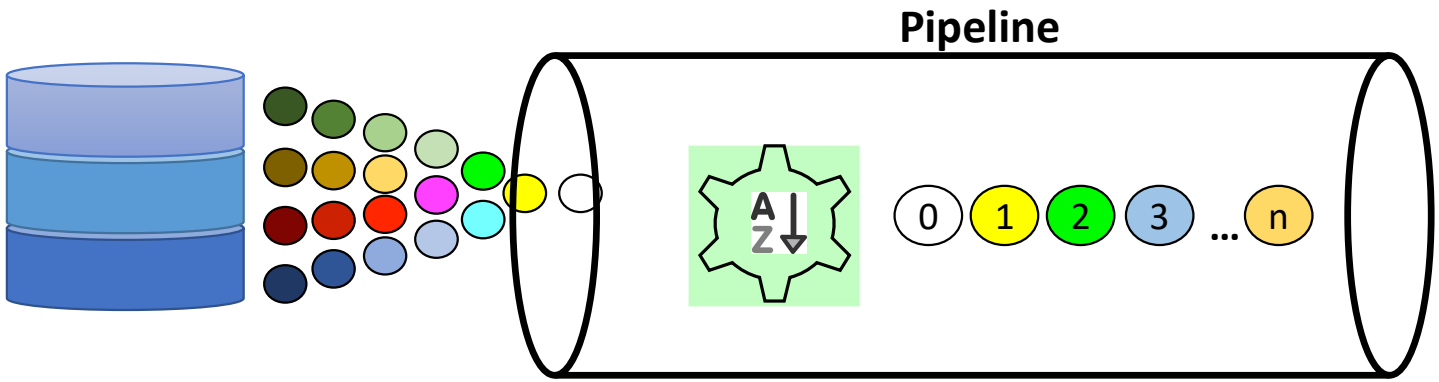
      .collect(Collectors.toSet());
```

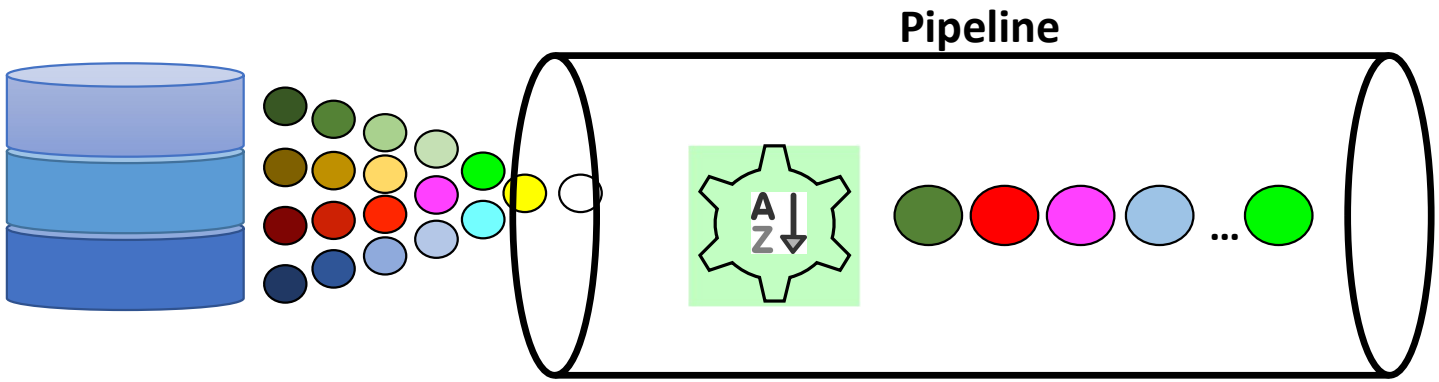
Stateful operations and ordering constraints may impair parallel performance



Stateful Intermediate Operations

De-orders the stream, which may improve parallel performance

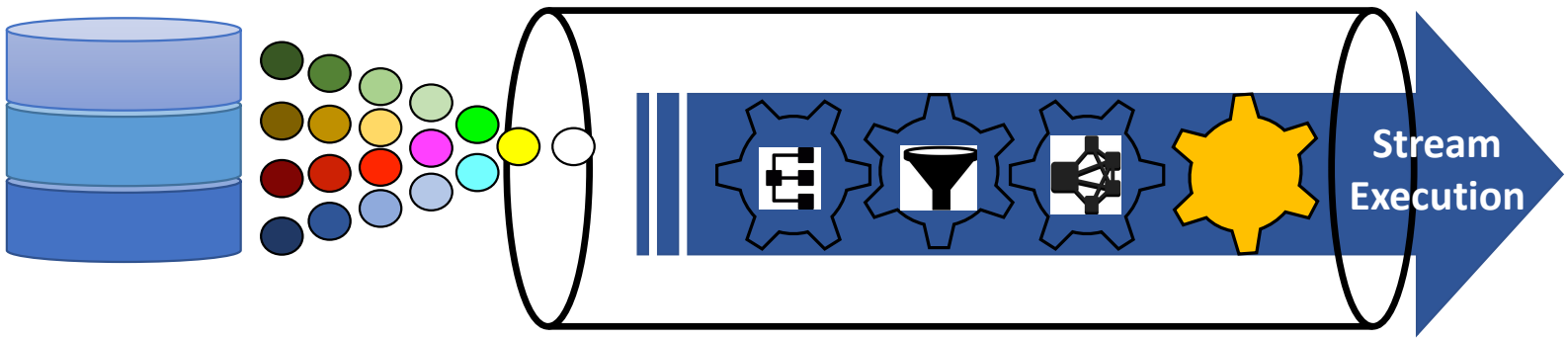
```
transactionList.stream()
      .unorderded()
      .parallel()
      .filter(t -> t.getStatus() == Transaction.VALID)
      .map(Transaction::getID)
      .collect(Collectors.toSet());
```



Stream Execution

```
transactionList.stream()
        .parallel()
        .filter(t -> t.getStatus() == Transaction.VALID)
        .map(Transaction::getID)
        .collect(Collectors.toSet());
```

Stream execution



Stream Execution

```
transactionList.stream()
        .parallel()
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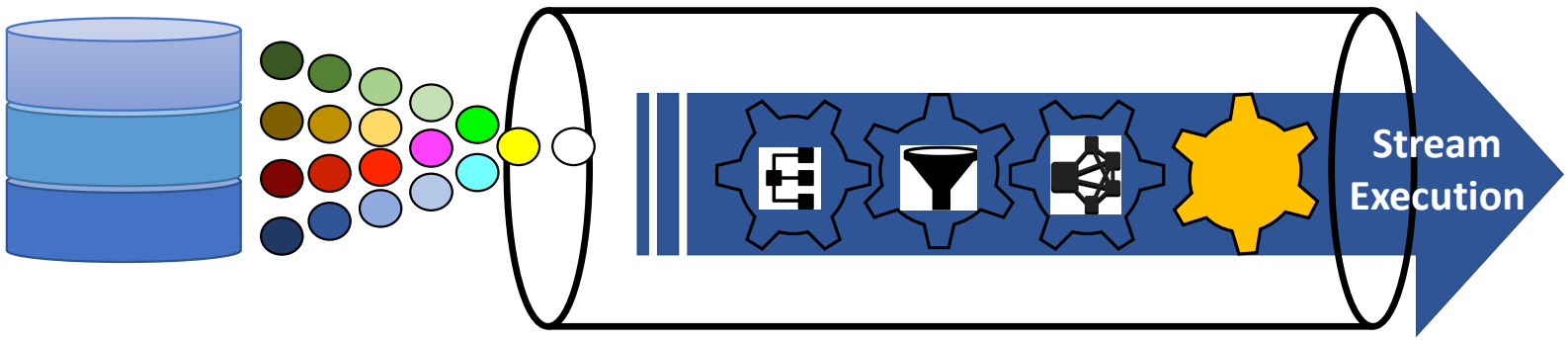
        .map(Transaction::getID)
        .collect(Collectors.toSet());
```

Performs a mutable reduction



Collector

```
transactionList.stream()
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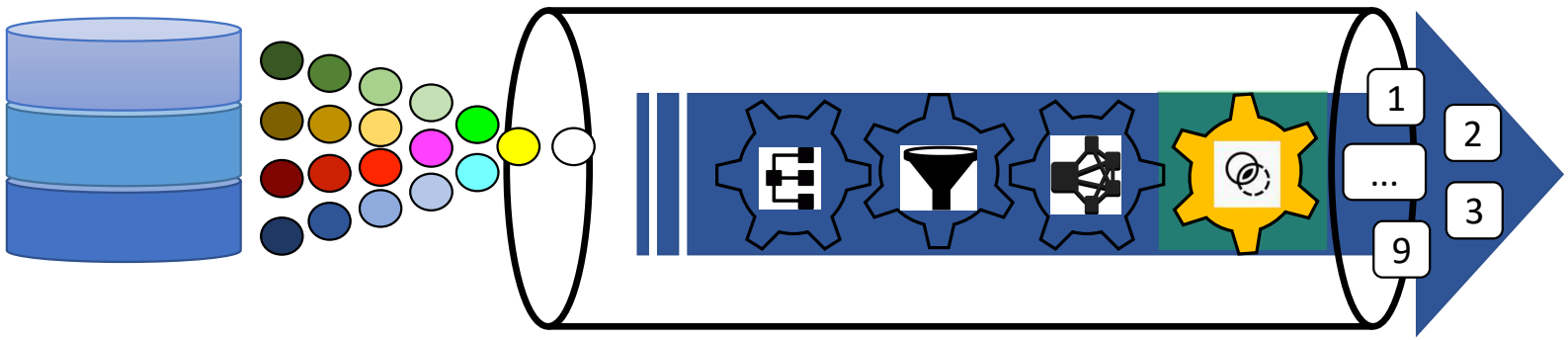
```

Collector



Collector

```
transactionList.stream()
        .parallel()
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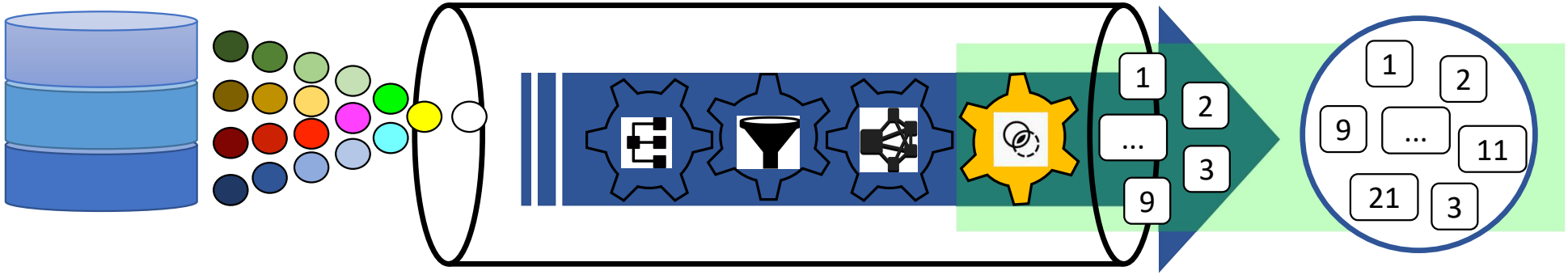
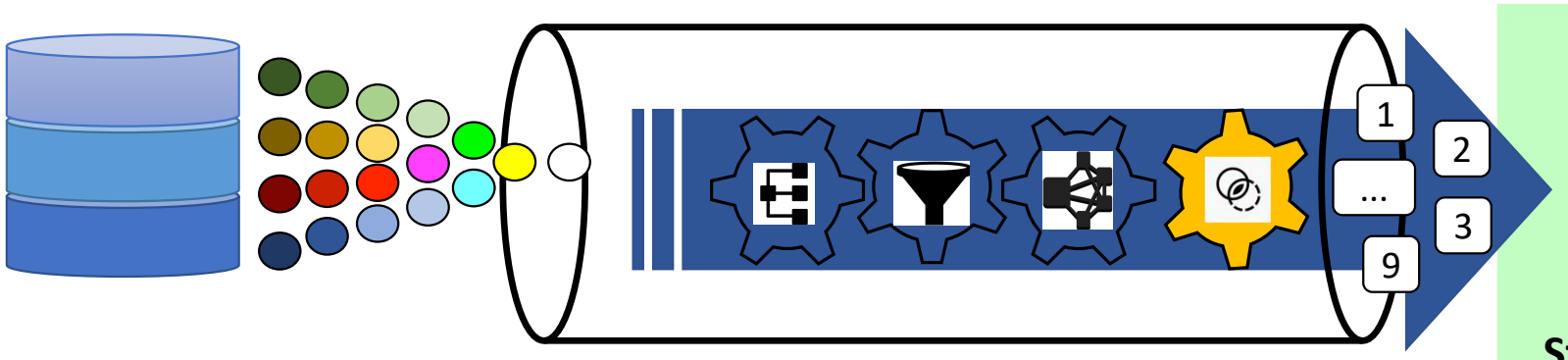
        .map(Transaction::getID)
        .collect(Collectors.toSet());
```

Acumulates the IDs into a Set



Stream Result Type

```
transactionList.stream()
        .parallel()
        .filter(t -> t.getStatus() == Transaction.VALID)
        .map(Transaction::getID)
        .collect(Collectors.toSet());
```

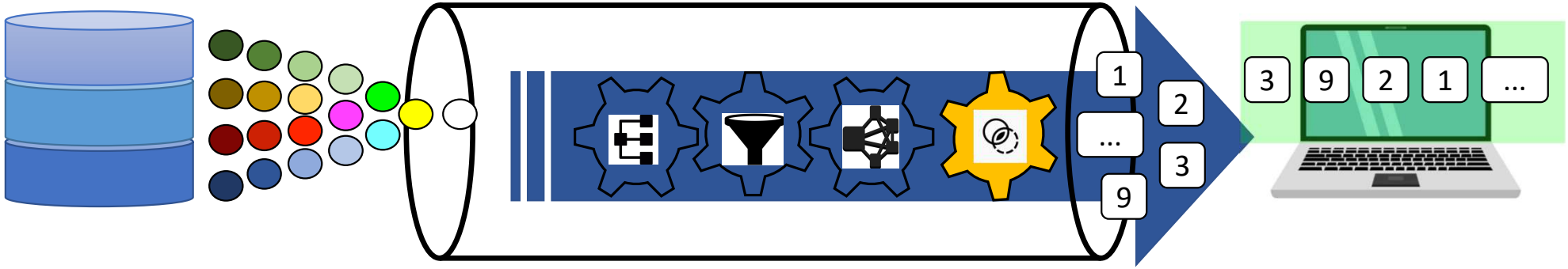


Stream result type
e.g., java.util.HashSet

Side Effects

```
transactionList.stream()
        .parallel()
        .filter(t -> t.getStatus() == Transaction.VALID)
        .map(Transaction::getID)
        .forEach(System.out::print);
```

Prints the IDs of valid transactions



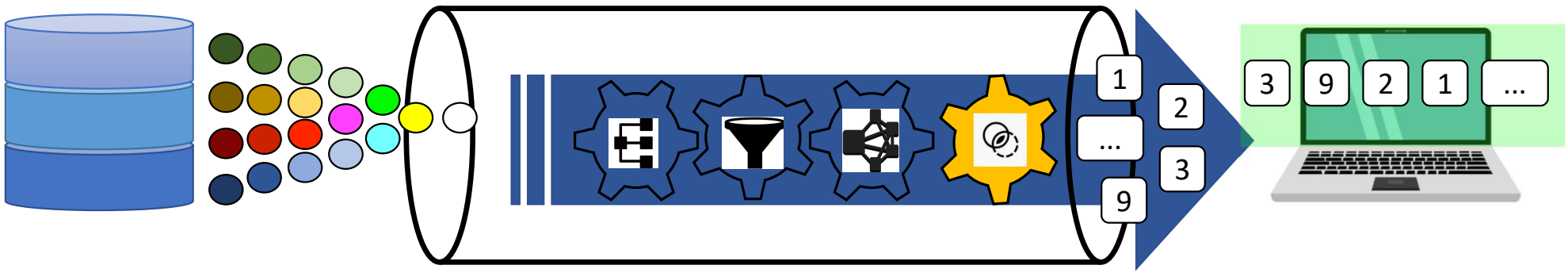
Side Effects

```
transactionList.stream()
        .parallel()
        .filter(t -> t.getStatus() == Transaction.VALID)
        .map(Transaction::getID)
        .forEach(System.out::print);
```

Non-deterministic

3 9 2 1 ...

Prints the IDs of valid transactions



THE PROBLEM

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The Problem

- Recent studies focused on the popularity of streams:
  - Tanaka et al. [1] mine 100 repositories to study the use of lambdas, streams, and the `java.util.Optional` class
  - Khatchadourian et al. [2] examine 34 projects to study the use of the Stream API
  - Nostas et al. [3] study 610 projects to do a partial replication of the study of Khatchadourian et al. at a larger scale

[1] Tanaka et al. *A Study on the Current Status of Functional Idioms in Java*. IEICE Trans. on Info. and Sys. 2019
[2] Khatchadourian et al. *An Empirical Study on the Use and Misuse of Java 8 Streams*. FASE'20.
[3] Nostas et al. *How Do Developers Use the Java Stream API*. ICCSA'21.

The Problem

- **Limitations:**
  - They consider only a small number of projects
  - They rely on manual code inspection and static analysis techniques
    - Disregarding the analysis of dynamic metrics unique to streams

There is yet limited evidence to make conclusions on how the Stream API is used

CONTRIBUTIONS

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Contributions

- We present *Stream-Analyzer*, a novel tool specifically designed for the characterization of dynamic metrics specific to streams
  - Detects all forms of stream creation and execution as well as all operations available in the Stream API
  - Targets dynamic information and metrics that enable fine-grained characterization of stream processing
    - The selected metrics are suitable to be massively collected in the wild

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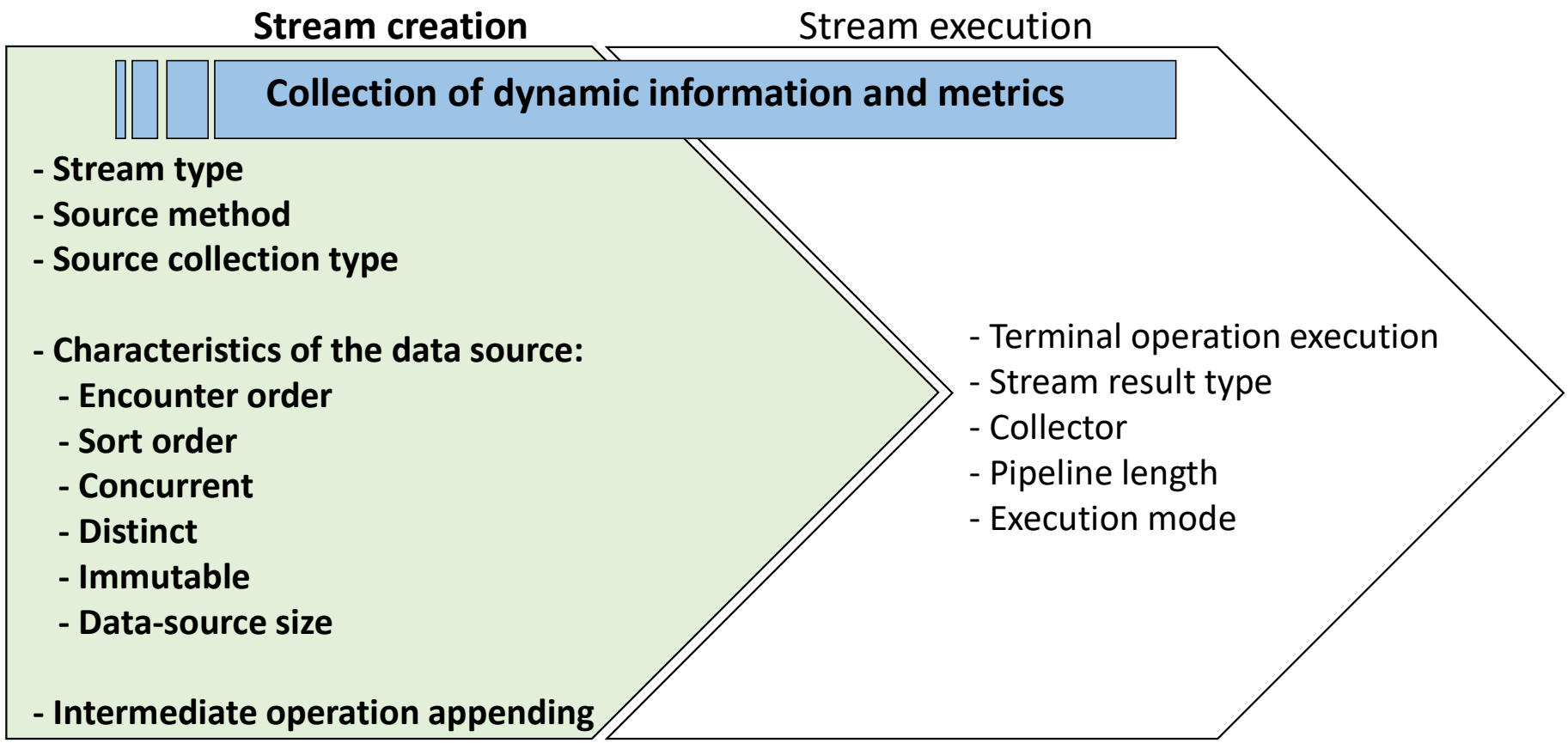
Contributions

- We use Stream-Analyzer to conduct the first large-scale empirical study on the use of Java streams
  - Stream-Analyzer runs on top of *NAB* [4], to enable a fully automated approach (no manual intervention, no manual code inspection)
- We target 1'8M open-source projects available in GitHub, of which 132K use the Stream API
  - Our study analyzes a total of 620M streams
- We confirm the findings of previous studies and report new dynamic information and metrics that related work overlooks

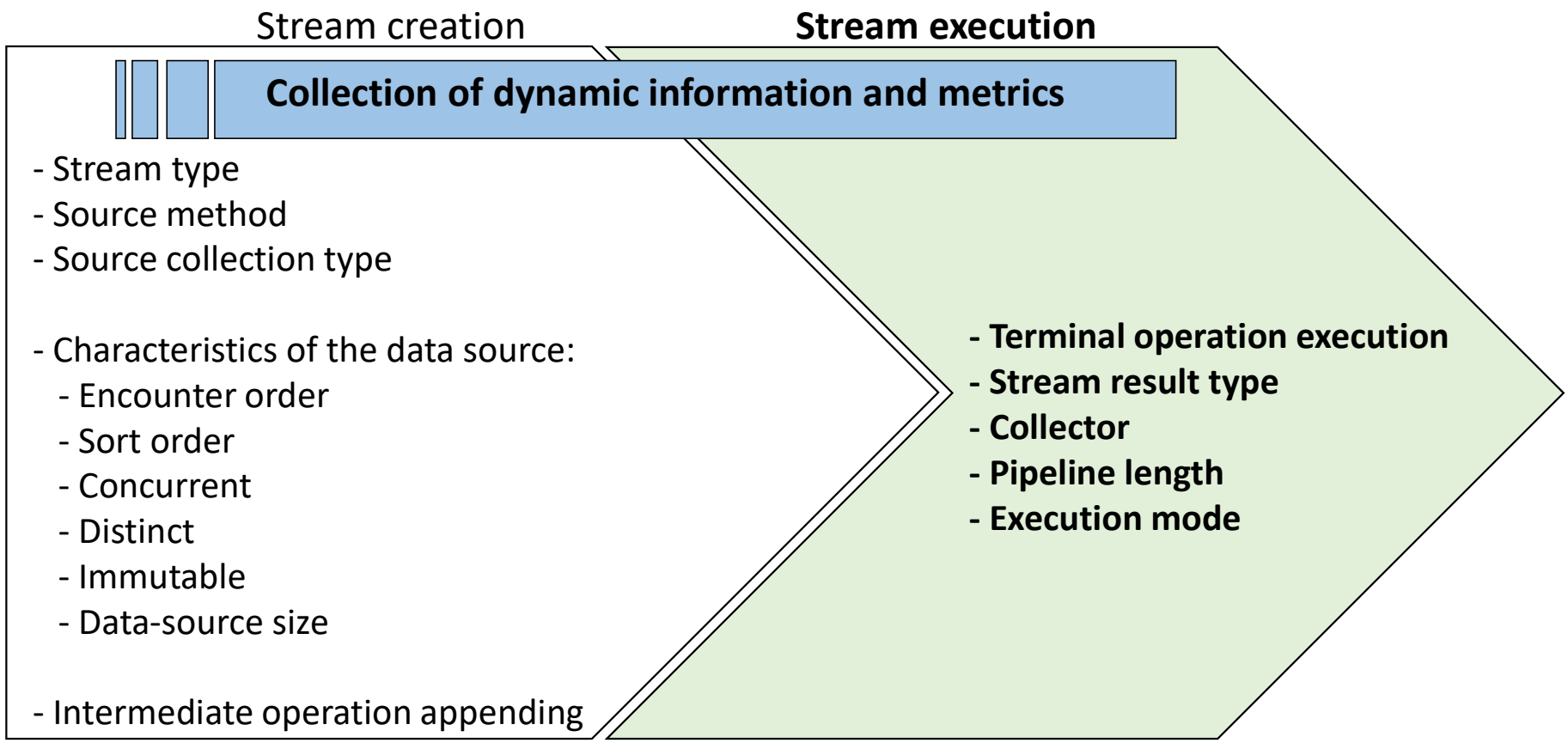
[4] Villazón et al. *Automated Large-Scale Multi-Language Dynamic Program Analysis in the Wild*. ECOOP'19.

Stream-Analyzer

Stream-Analyzer

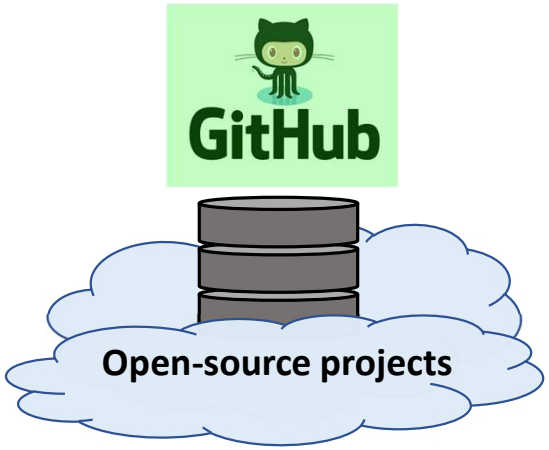


Stream-Analyzer

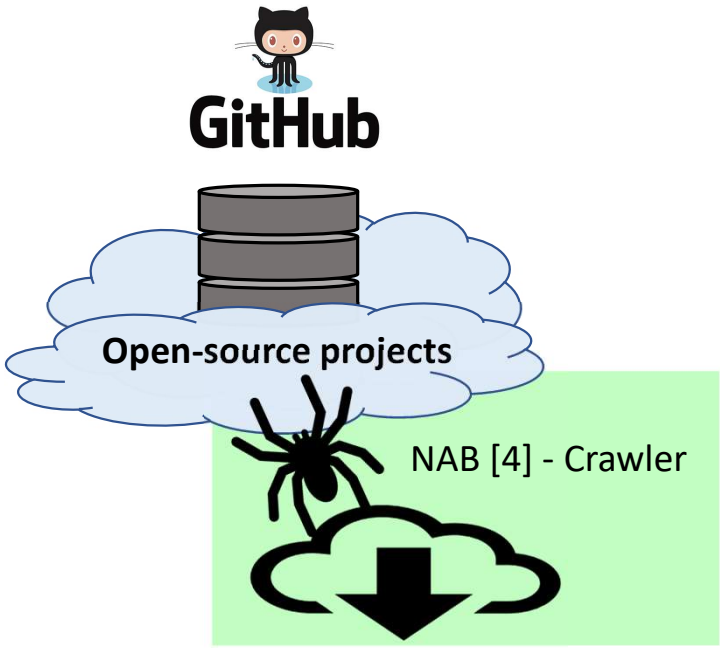


LARGE SCALE ANALYSIS

Stream-Analyzer + NAB



Stream-Analyzer + NAB



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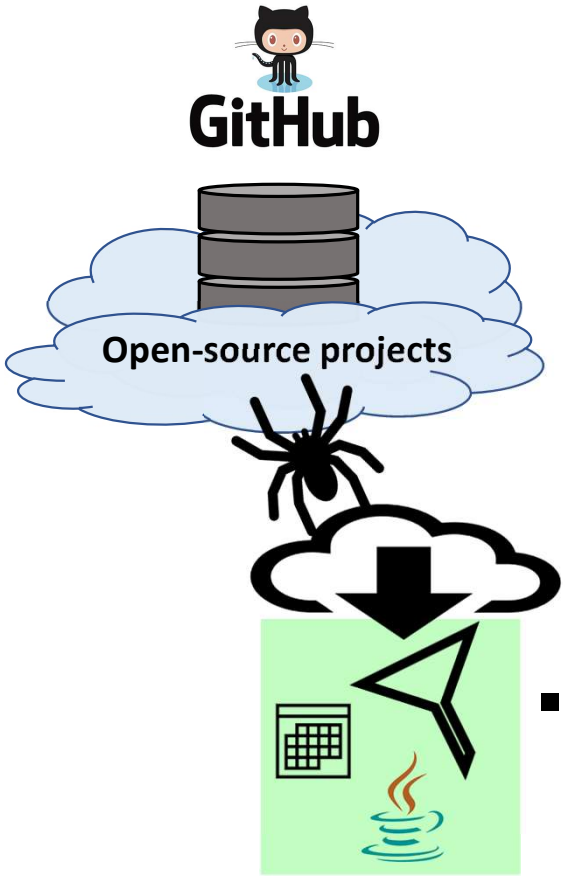
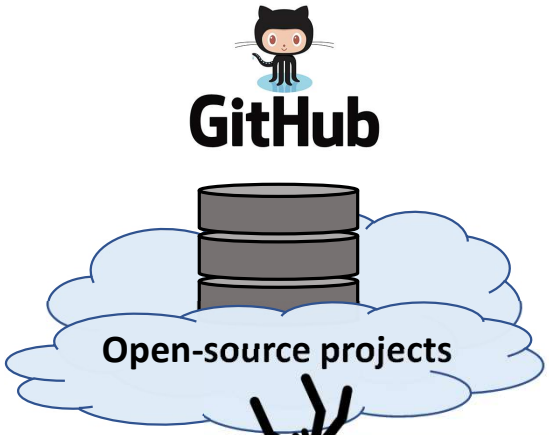
Stream-Analyzer + NAB

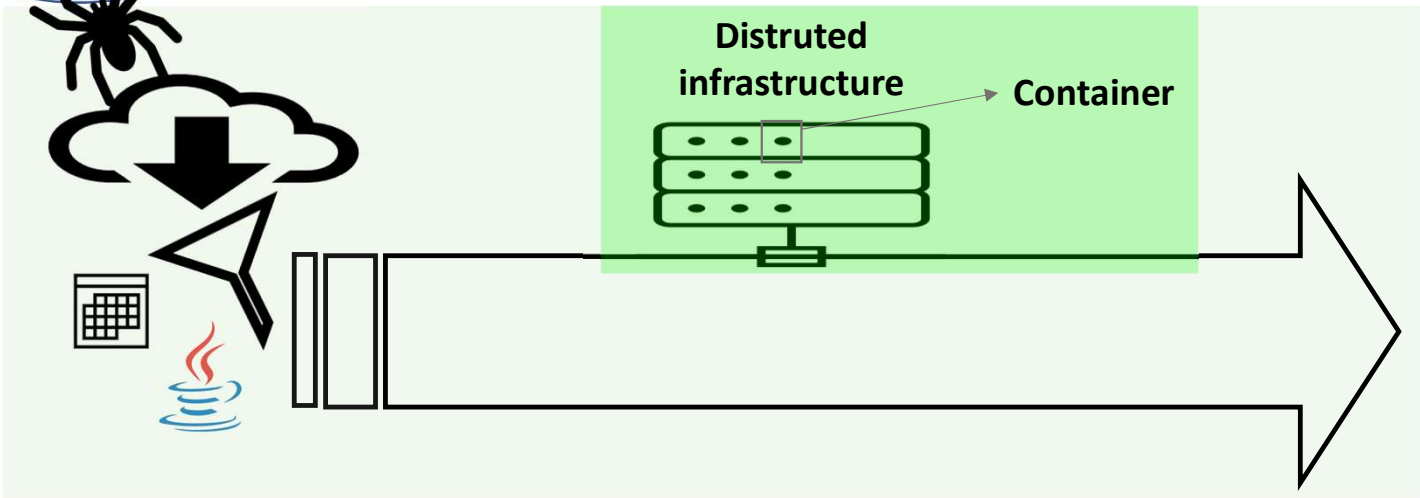


- **Timeframe:**
  - Java projects with at least one commit in year 2020

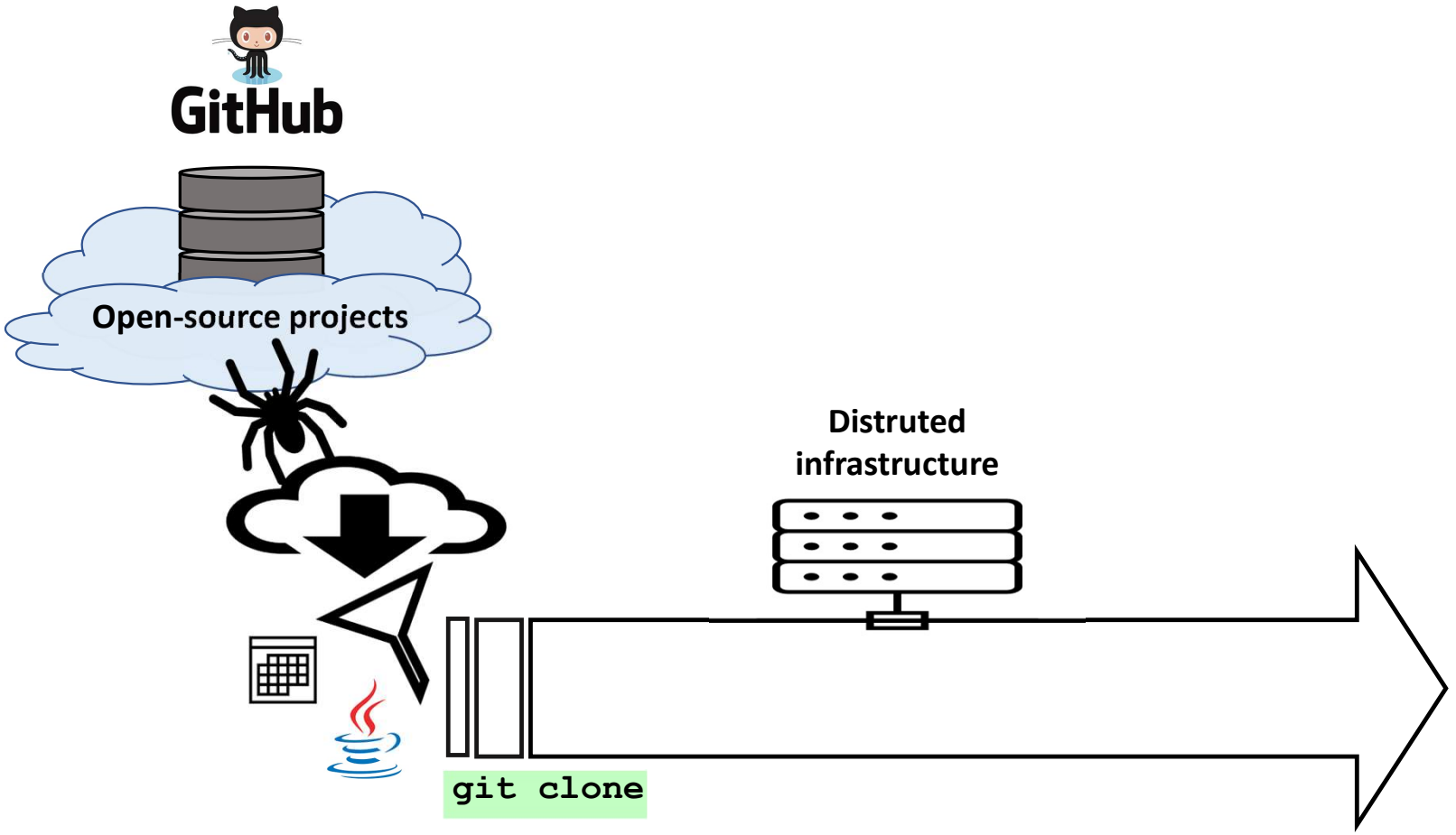
Stream-Analyzer + NAB



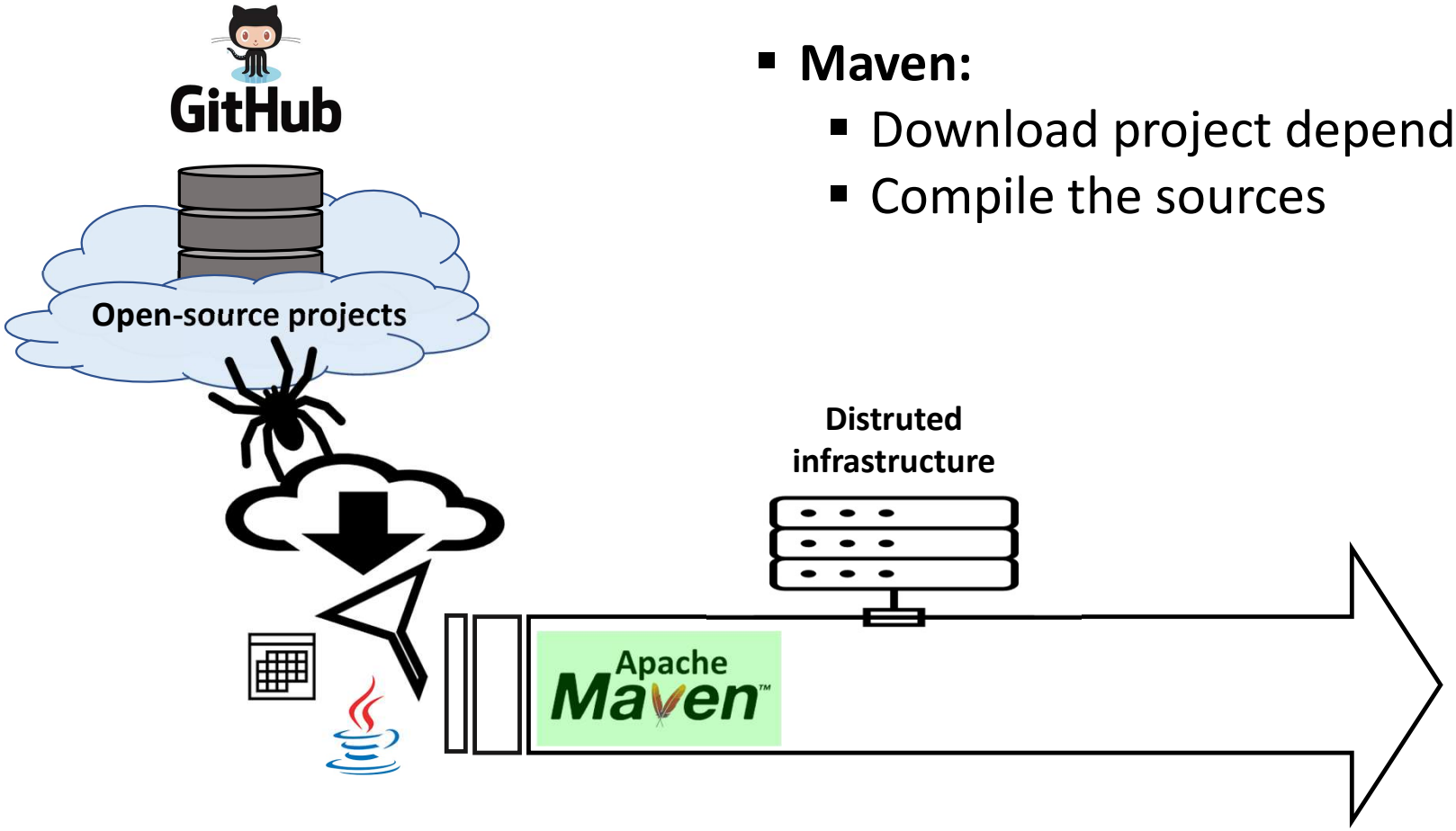
- **Containerization:**
  - Security: enables isolation
  - Performance: eases parallelization



Stream-Analyzer + NAB

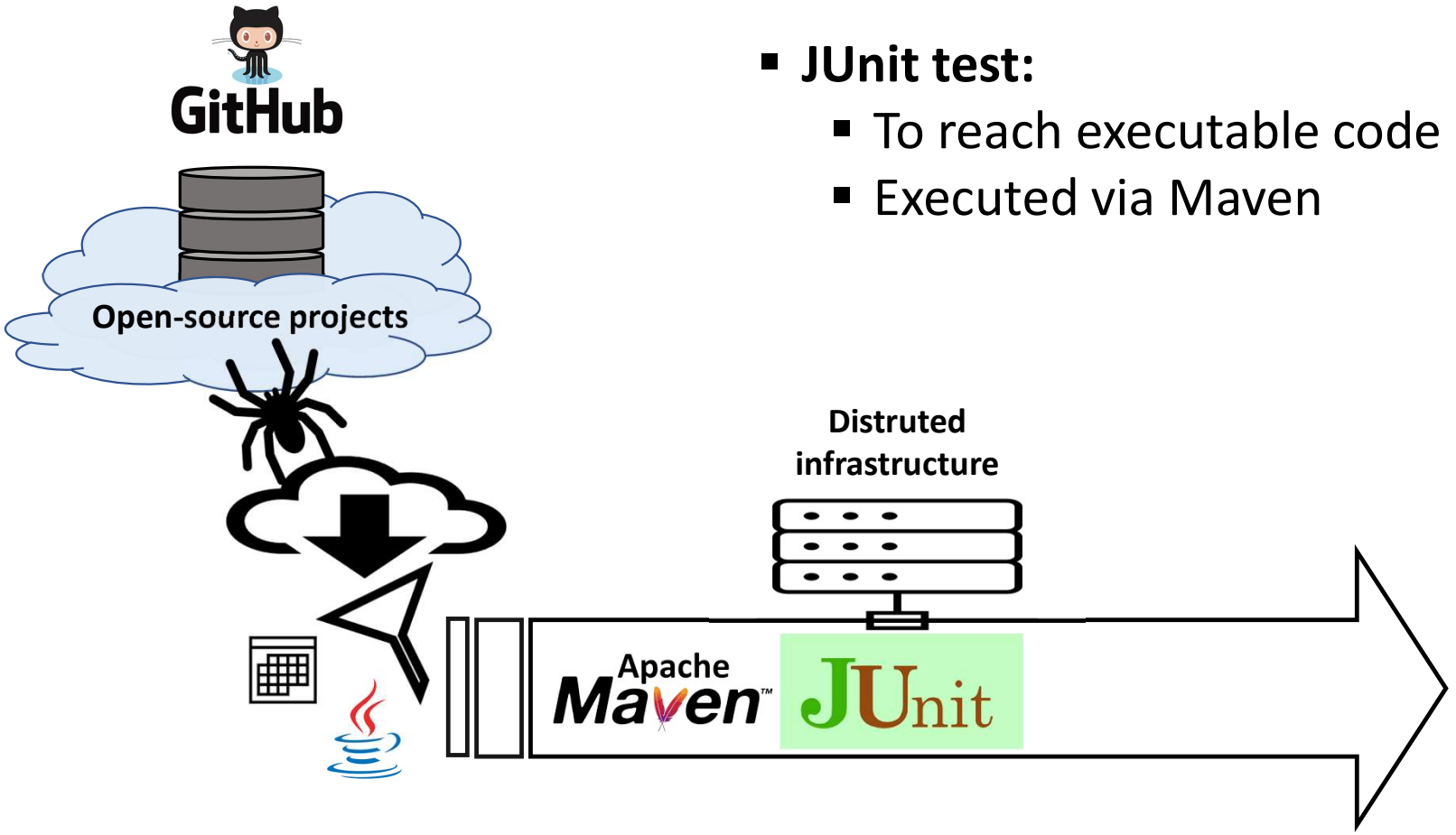


Stream-Analyzer + NAB



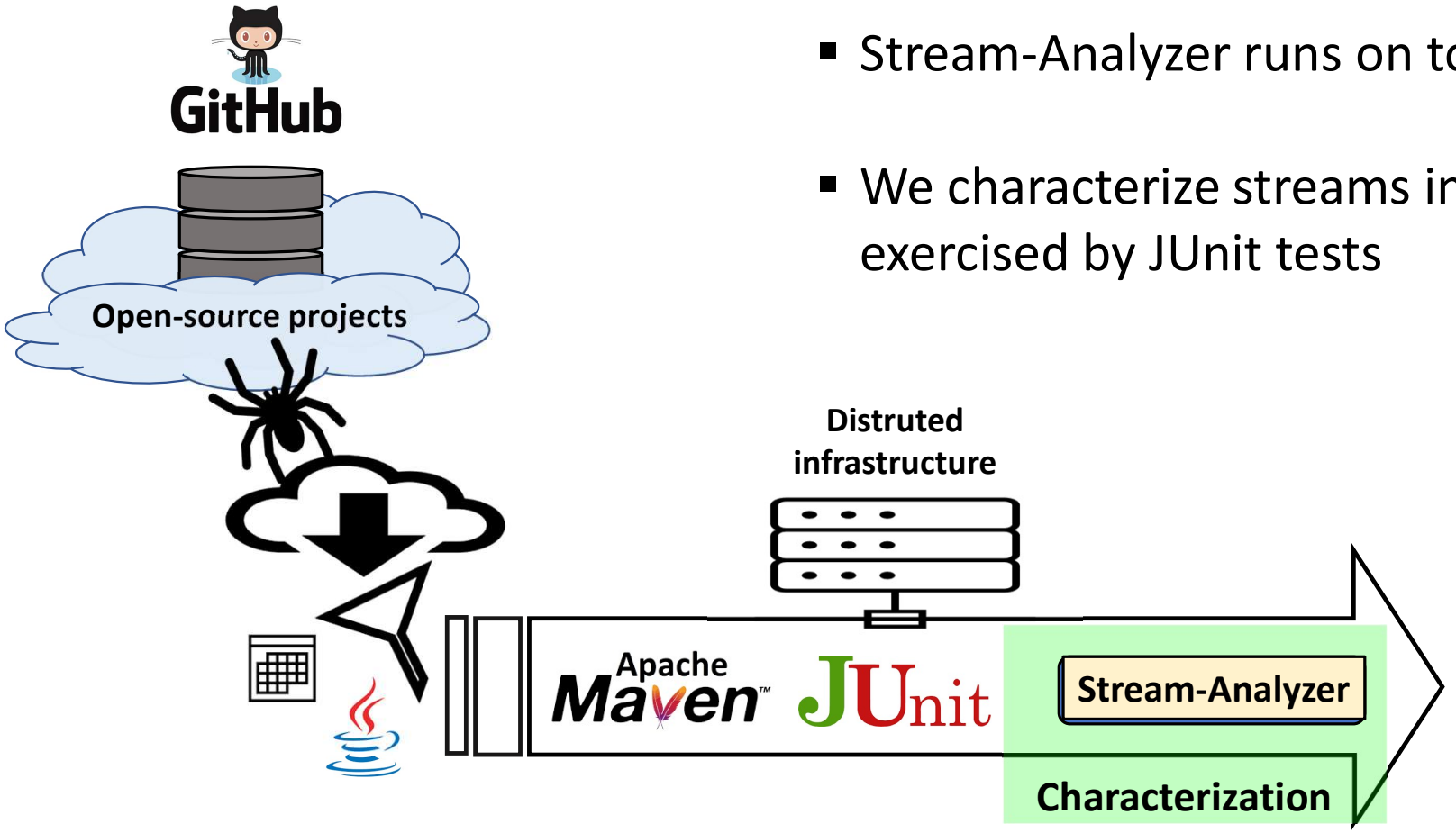
- **Maven:**
  - Download project dependencies
  - Compile the sources

Stream-Analyzer + NAB



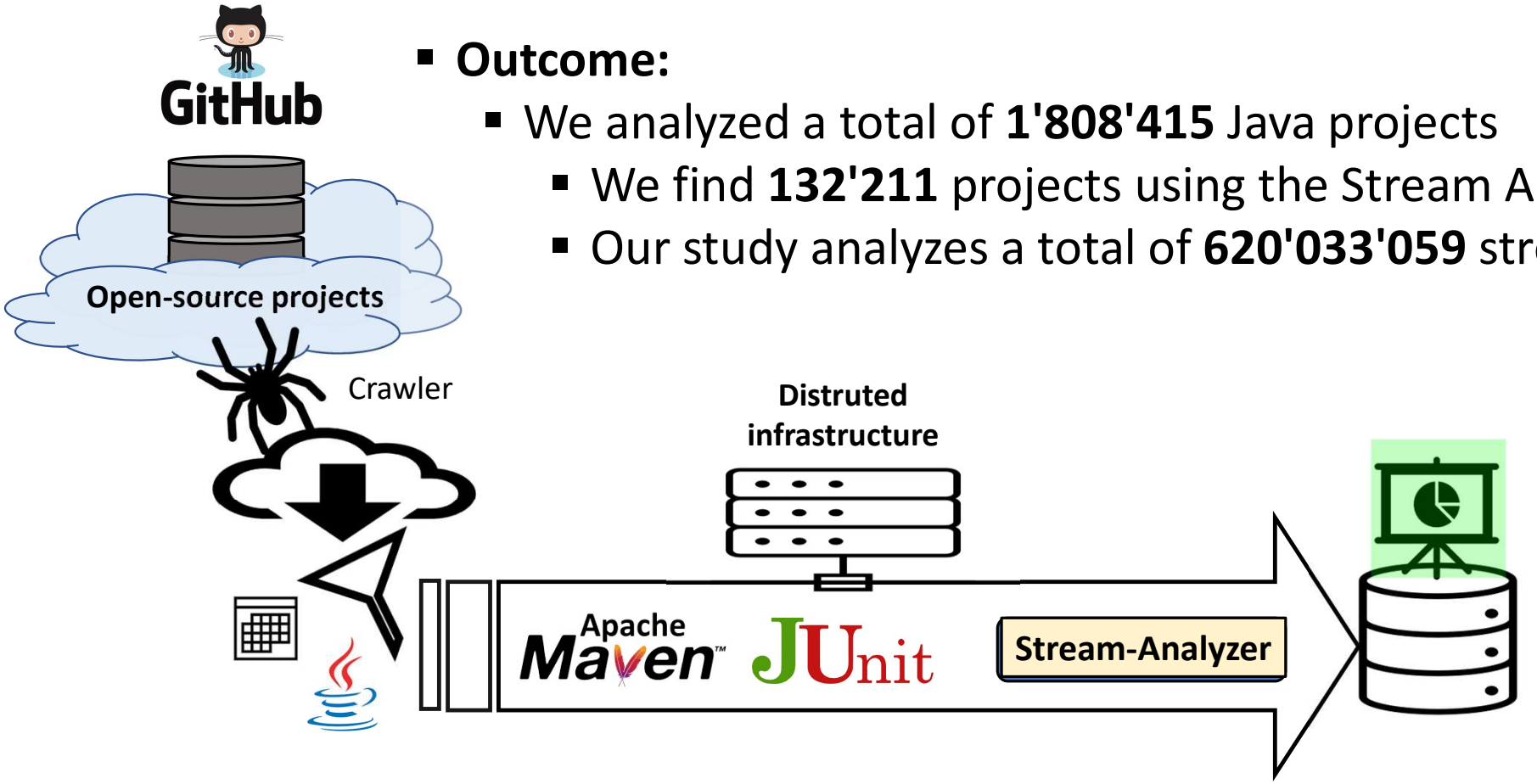
- **JUnit test:**
  - To reach executable code
  - Executed via Maven

Stream-Analyzer + NAB



- Stream-Analyzer runs on top of NAB
- We characterize streams in code exercised by JUnit tests

Stream-Analyzer + NAB



- **Outcome:**
  - We analyzed a total of **1'808'415** Java projects
    - We find **132'211** projects using the Stream API
    - Our study analyzes a total of **620'033'059** streams

RESULTS

Source Methods

- **Source methods:** the method used to create the stream

Source Method	Occurrences	%
java.util.Collection.stream	349'303'956	56.33
java.util.stream.IntStream.range	87'677'566	14.14
java.util.Arrays.stream	58'690'188	9.46
java.util.Collections$SynchronizedCollection.stream	27'069'317	4.37
java.util.stream.Stream.of	26'565'005	4.28
java.util.stream.Stream.concat	22'869'945	3.69
java.util.Random.ints	12'020'051	1.94
java.util.Collections$UnmodifiableCollection.stream	11'795'112	1.90
java.util.stream.Stream.empty	7'397'430	1.19
java.lang.CharSequence.chars	5'001'524	0.81

Finding 1: Streams are mainly created from collections, generators of integers, and arrays

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Source Collection Type

- **Source collection type:** the type of the collection from which a stream is created, if any

Source Collection Type	Occurrences	%
java.util.ArrayList	258'713'462	41.72
java.util.HashSet	29'330'326	4.73
java.util.Collections$SynchronizedSet	25'569'216	4.12
java.util.LinkedList	12'246'909	1.98
java.util.LinkedHashSet	7'730'718	1.25
java.util.Arrays$ArrayList	7'480'889	1.21
java.util.Collections$EmptyList	5'759'041	0.93
java.util.HashMap$EntrySet	5'687'645	0.92
java.util.Collections$UnmodifiableCollection	5'466'774	0.88
java.util.Collections$UnmodifiableRandomAccessList	4'806'994	0.78

Finding 2: Streams generated from collections are mostly created from list and sets

Stream Types

- **Stream types:** the type of the stream

Stream Types	Occurrences	%
java.util.Stream	504'832'673	81.41
java.util.IntStream	114'970'830	18.54
java.util.LongStream	284'473	0.05
java.util.DoubleStream	5'627	0.001

Finding 3: Object-based stream types are far more popular than primitive-based types

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Characteristics of the Data Source

- **Data source:** the source of data from which the stream is created

Data-source Characteristics	Occurrences	%
Encounter order	543'905'362	87.71
Sorted order	91'226'771	14.71
Concurrent	873'955	0.14
Distinct	197'900'117	31.91
Immutable	172'796'006	27.87

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Finding 4: Stream data sources often allow duplicates, have ordering constraints, are mutable, and do not support concurrent modification

Data-source Size

- **Data-source size:** the total number of elements in the data source upon stream creation

Size Range	Occurrences	%
0	51'585'754	13.02
$[10^0, 10^1)$	310'352'326	78.33
$[10^1, 10^2)$	29'085'769	7.34
$[10^2, 10^3)$	4'620'480	1.17
$[10^3, 10^4)$	557'893	0.14
$[10^4, 10^5)$	1692	$4 \cdot 10^{-4}$
$[10^5, 10^6)$	34	$1 \cdot 10^{-5}$
$[10^6, 10^7)$	5	$1 \cdot 10^{-6}$

Finding 5: Stream data sources typically have few elements

Intermediate Operations

- **Intermediate operations:** operations that produce other streams that can be further processed

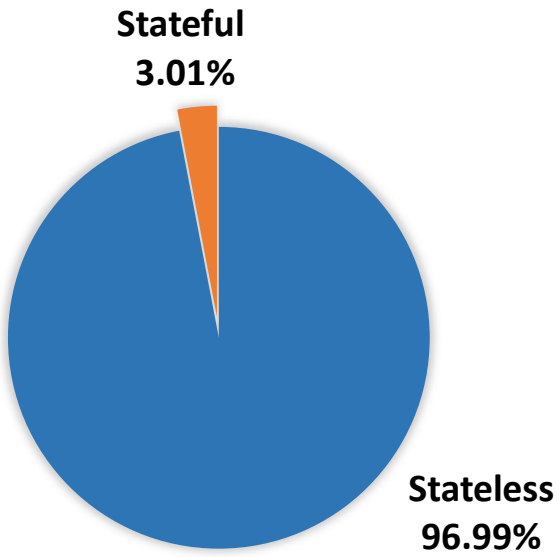
Intermediate Operation	Occurrences	%
map	427'009'693	51.57
filter	227'938'406	27.53
mapToObj	77'898'391	9.41
flatMap	34'512'362	4.17
mapToInt	27'327'892	3.30
limit	12'697'146	1.53
mapToLong	6'264'703	0.76
sorted	5'275'399	0.64
skip	4'041'440	0.49
distinct	2'877'764	0.35

- 827'977'847 intermediate operations detected
- `Unordered()` is not popular (less than 0.001%)

Finding 6: Mapping and filtering are by far the most popular intermediate operations

Intermediate Operations

- **Intermediate operations:** operations that produce other streams that can be further processed



- Pipelines containing only stateless operations can be processed in a single pass, potentially improving performance

Finding 7: Stateful intermediate operations are barely used

Terminal Operations

- **Terminal operations:** operations that trigger stream execution

Terminal Operation	Occurrences	%
collect	197'338'242	31.83
forEach	145'774'791	23.51
allMatch	68'072'088	10.98
findFirst	51'274'578	8.27
anyMatch	43'892'114	7.08
sum	38'716'266	6.24
findAny	38'505'248	6.21
reduce	9'720'348	1.57
toArray	7'555'733	1.22
count	6'033'536	0.97

- 620'033'509 terminal operations detected

Finding 8: Map-reduce-like data reductions via `collect` and iterative-style processing via `forEach` are the most common terminal operations

Terminal Operations

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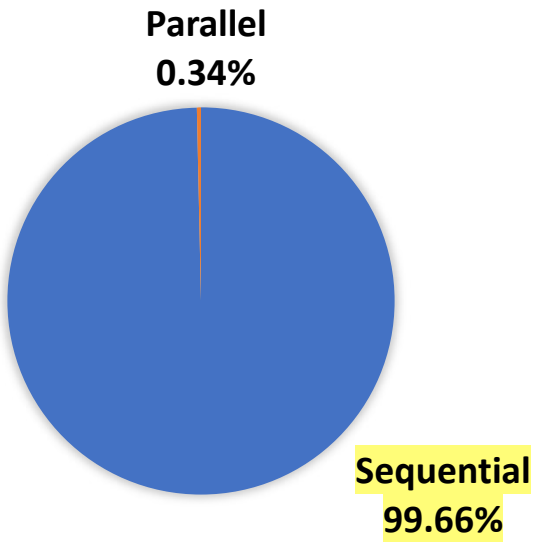
- Deterministic terminal operations are the most used (70.28%)

Finding 9: Deterministic terminal operations are more popular than nondeterministic ones

Execution Mode

- **Execution mode:** whether the stream is executed sequentially or in parallel



- 620'033'509 streams were executed
- 60'094 streams lack a terminal operation

Finding 10: Parallel streams are not popular

Pipeline Length

- **Length:** the total number of operations in the pipeline

Length	Occurrences	%
2	293'021'334	47.25
1	123'683'254	19.95
3	119'522'688	19.27
5	44'258'049	7.14
4	39'501'712	6.37
0	46'102	$7 \cdot 10^{-3}$
7	40'050	$6 \cdot 10^{-3}$
6	15'448	$2 \cdot 10^{-3}$
8	2'468	$4 \cdot 10^{-4}$
11	2'447	$4 \cdot 10^{-4}$
10	34	$5 \cdot 10^{-6}$
14	17	$3 \cdot 10^{-6}$

- The average pipeline length is only 2.34
- 46'102 streams have no operations in their pipelines.

Finding 11: Stream pipelines are typically composed of few operations

Collectors

- **Collector:** the collector to perform a mutable reduction

Collector	Occurrences	%
N/A	422'695'267	68.17
Collectors.toList	146'091'282	23.56
Collectors.toSet	15'855'229	2.56
Collectors.toCollection	15'550'665	2.51
Collectors.toMap	6'819'658	1.10
Collectors.joining	5'830'648	0.94
Collectors.collectingAndThen	5'495'747	0.89
Collectors.groupingBy	987'487	0.16
Collectors.counting	553'012	0.09
Collectors.reducing	121'687	0.02

- `groupingByConcurrent()` is not widely used (less than 0.001%)

Finding 12: Collectors that collect elements into lists and set are the most used

Stream Result Types

- **Stream Result Type:** the type of the output produced after the stream is executed, if any

Stream Result Type	Occurrences	%
java.util.ArrayList	148'567'911	23.96
void	145'918'994	23.53
boolean	112'159'247	18.09
java.util.Optional	99'032'395	15.97
int	29'961'760	4.83
java.util.HashSet	16'333'376	2.63
java.util.HashMap	15'464'414	2.49
int[]	9'576'981	1.54
java.lang.String	9'506'464	1.53
Object[]	8'745'210	1.41

Finding 13: Lists are the most popular data structure used to store the output of a stream

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Summary

- Streams are mainly used to manipulate lists
- The data sources commonly contain few elements
- Pipelines typically contain few operations
- Lists and sets are widely used to store the result of the stream
- Parallel streams are concurrent reductions are rarely used
- MapReduce-style stream processing is the most popular one
  - Streams are also widely used for iterative-style collection processing

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Conclusions

- We presented Stream-Analyzer, a novel tool to characterize dynamic metrics specific to streams
- We presented the first large-scale empirical study on the use of streams
  - Fully automated approach
  - 1.8M projects analyzed
    - Find 132K projects that use the Stream API
      - Analyze 620M streams
- Our results confirm the findings of previous studies at a much larger scale, considering runtime metrics previously overlooked

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Future Work

- Consider a newer and longer time frame
- Consider other largest code-hosting facilities (e.g., GitLab, BitBucket)
- Consider other build systems (e.g., Apache Ant, Gradle)
- Find ways to detect and optimize suboptimal stream processing in the wild

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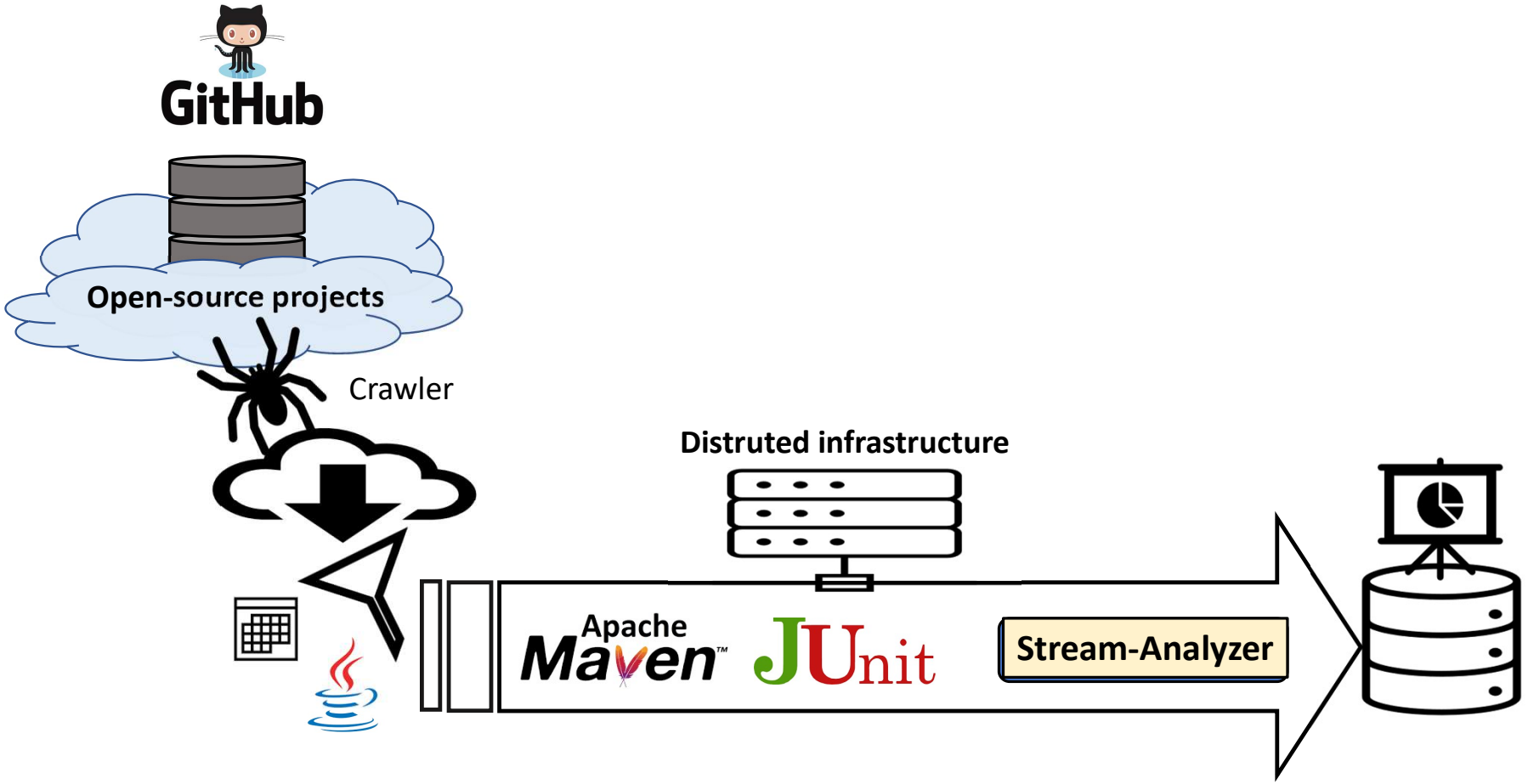
Thanks for your attention

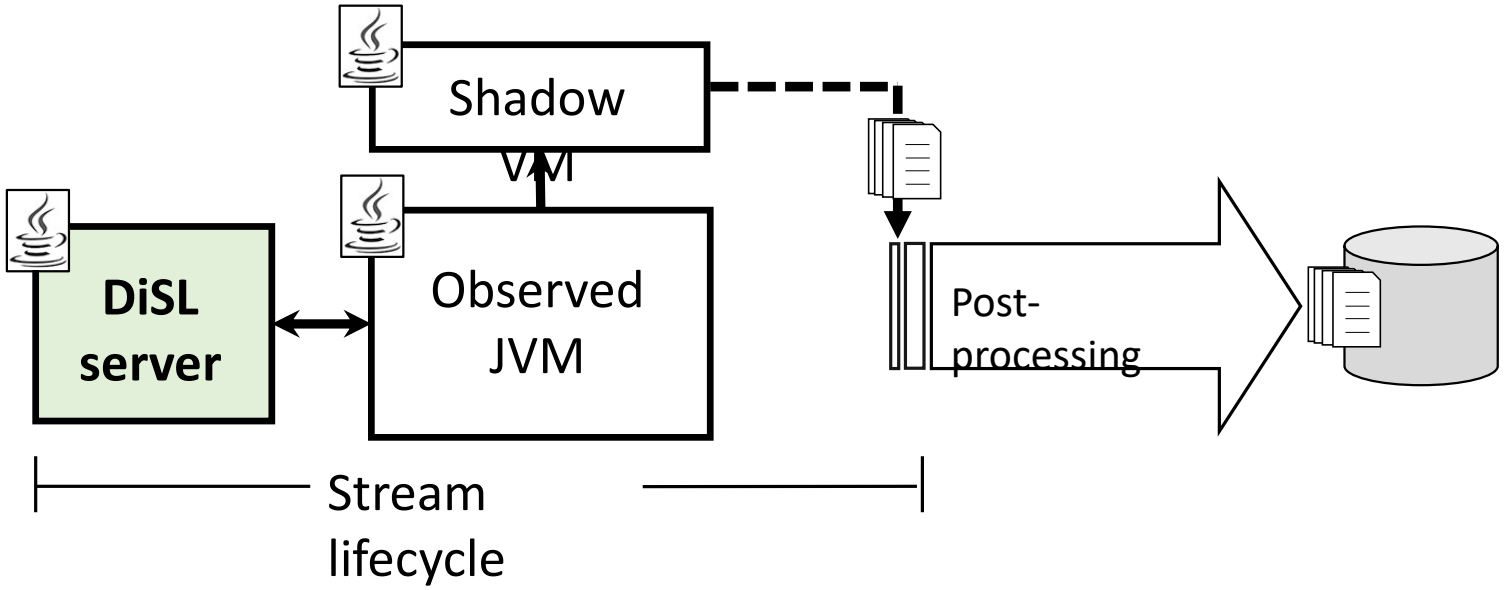
- **Eduardo Rosales:** `rosale@usi.ch`

BACKUP SLIDES

Stream-Analyzer - Implementation



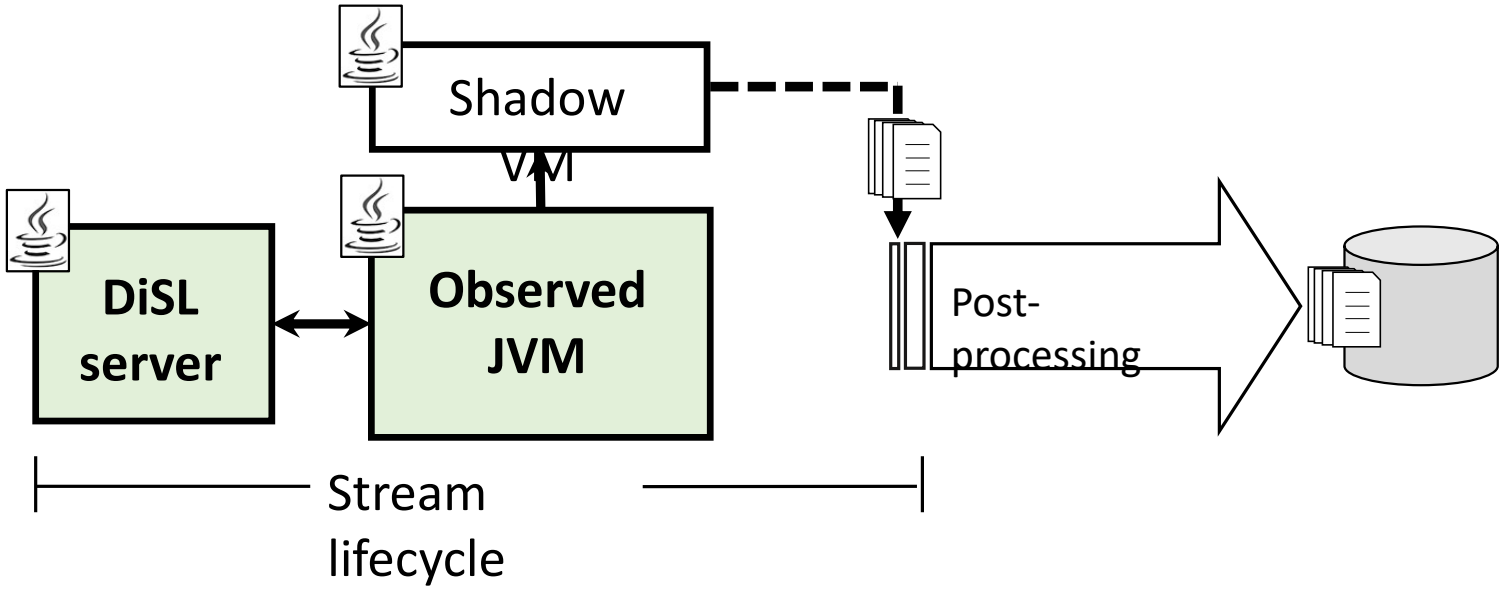
Stream-Analyzer - Implementation



- DiSL server [5]: performs load-time instrumentation
- DiSL offers full bytecode coverage
  - All streams are detected

[5] Marek et al. DiSL: *A Domain-specific Language for Bytecode Instrumentation*. AOSD'12.

Stream-Analyzer - Implementation



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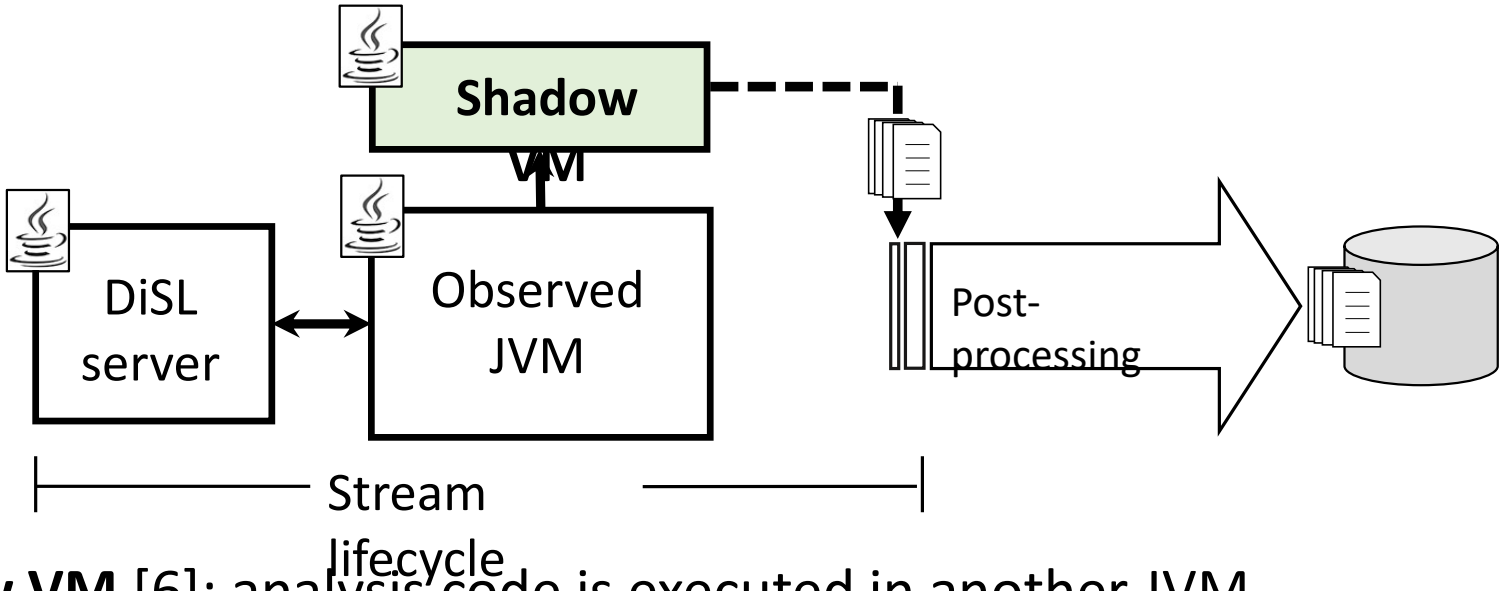
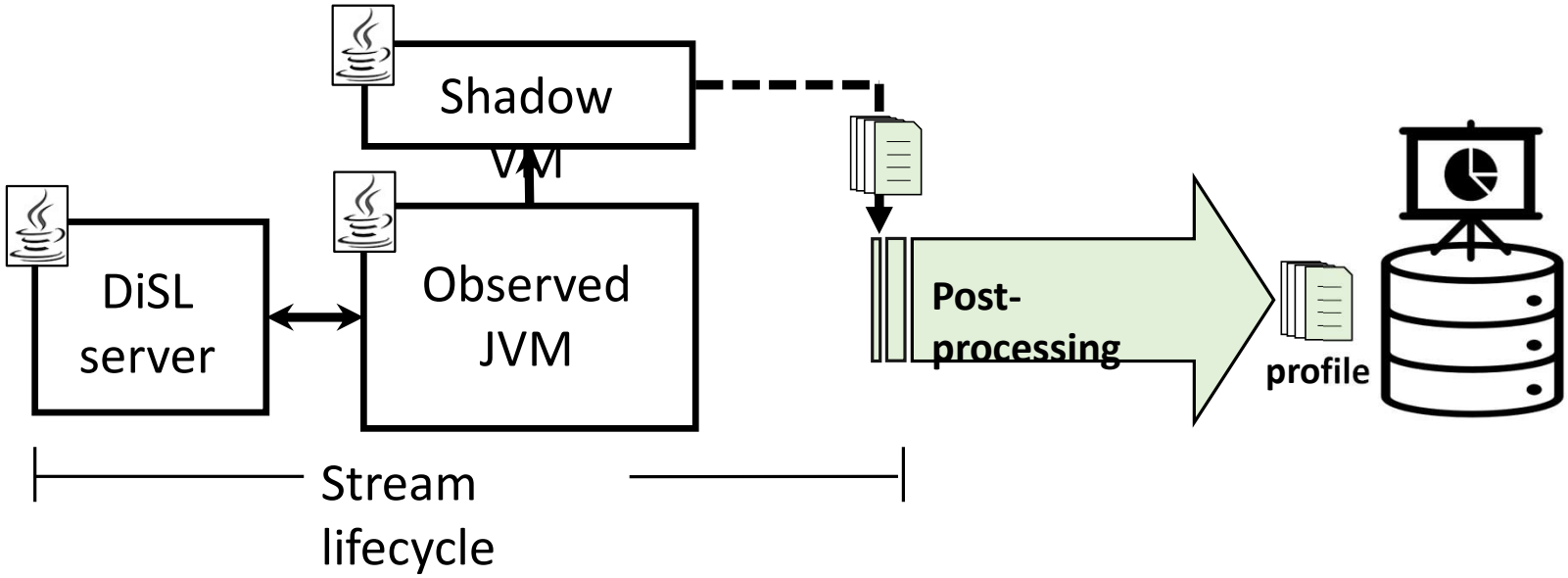
Stream-Analyzer - Implementation



- **Shadow VM** [6]: analysis code is executed in another JVM
  - The profiling logic is deployed in isolation to the observed application

[6] Marek et al. *ShadowVM: Robust and Comprehensive Dynamic Program Analysis for the Java Platform*. GPCE'13.

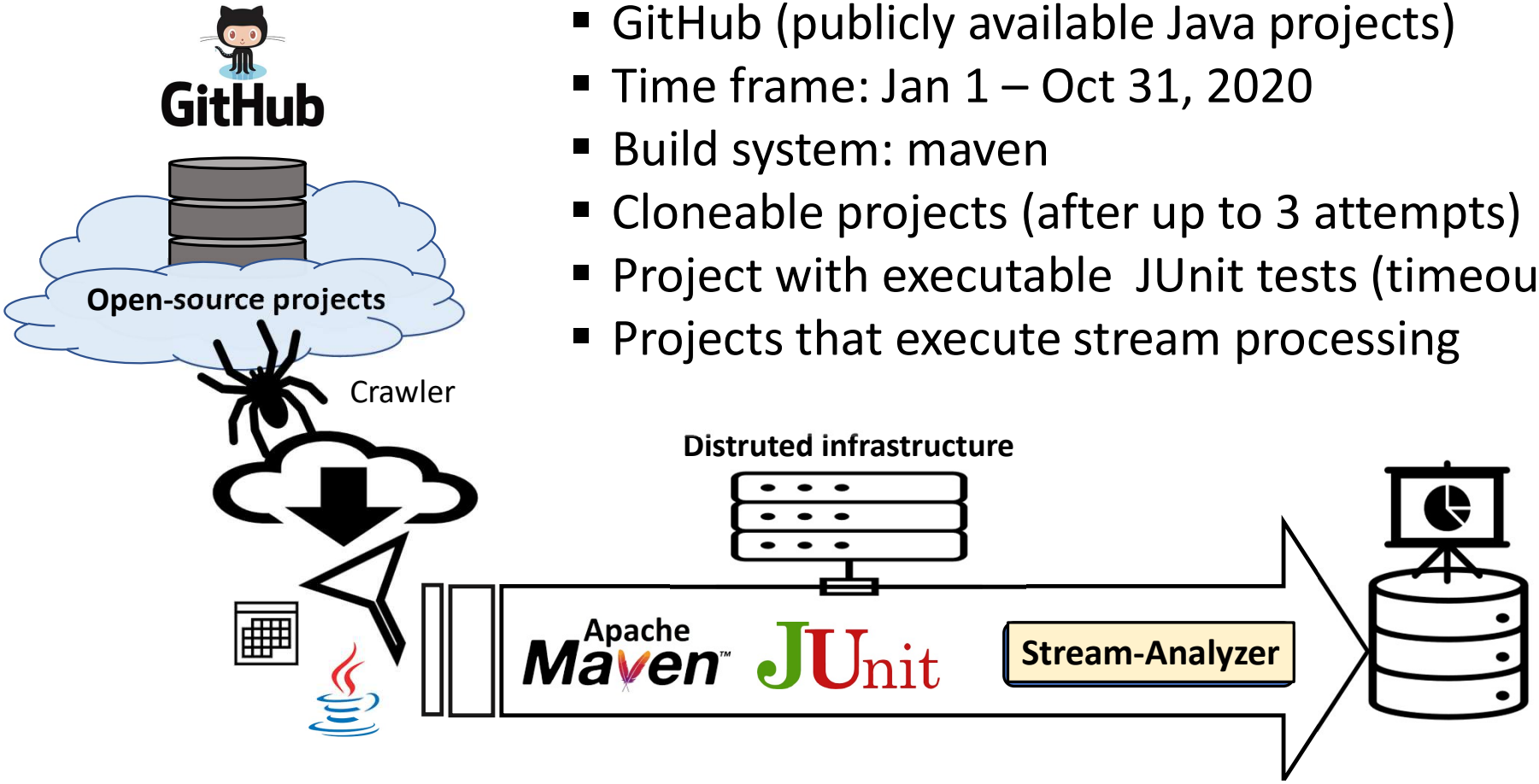
Stream-Analyzer - Implementation



- Offline post-processing produces a single integrated profile
- Profiles are stored on a database for further data analysis

Scope

- **Scope:**
  - GitHub (publicly available Java projects)
  - Time frame: Jan 1 – Oct 31, 2020
  - Build system: maven
  - Cloneable projects (after up to 3 attempts)
  - Project with executable JUnit tests (timeout 1 hour)
  - Projects that execute stream processing



Related Work

Study	Projects analyzed
Our work	620'033’059 projects (132’211 use streams)
Tanaka et al. [1]	100 projects (3 use streams)
Khatchadourian et al. [2]	34 projects using streams
Nostas et al. [3]	10’000 projects (610 use streams)

[1] Tanaka et al. *A Study on the Current Status of Functional Idioms in Java*. IEICE Trans. on Info. and Sys. 2019

[2] Khatchadourian et al. *An Empirical Study on the Use and Misuse of Java 8 Streams*. FASE’20.

[3] Nostas et al. *How Do Developers Use the Java Stream API*. ICCSA’21.

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Related Work

Our study is the first to report the popularity of runtime info:

- Source methods
- Source collection types
- Stream types
- Pipeline lengths
- Stream result types

- Characteristics of stream data sources:
  - Size, ordering constraints, duplicate allowance, mutability, and support for concurrent modification

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Discussion

- Feedback to developers of the Java class library
- Feedback to IDE and tool builders
- Basis to promote the discussion on how developers can better leverage the Stream API
- Feedback to educators training Java developers