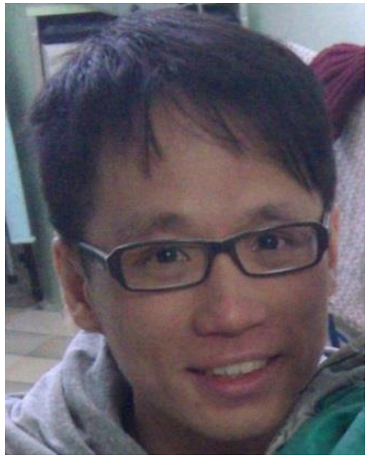
Leveraging Parallel Data Processing Frameworks with Verified Lifting



Maaz Ahmad

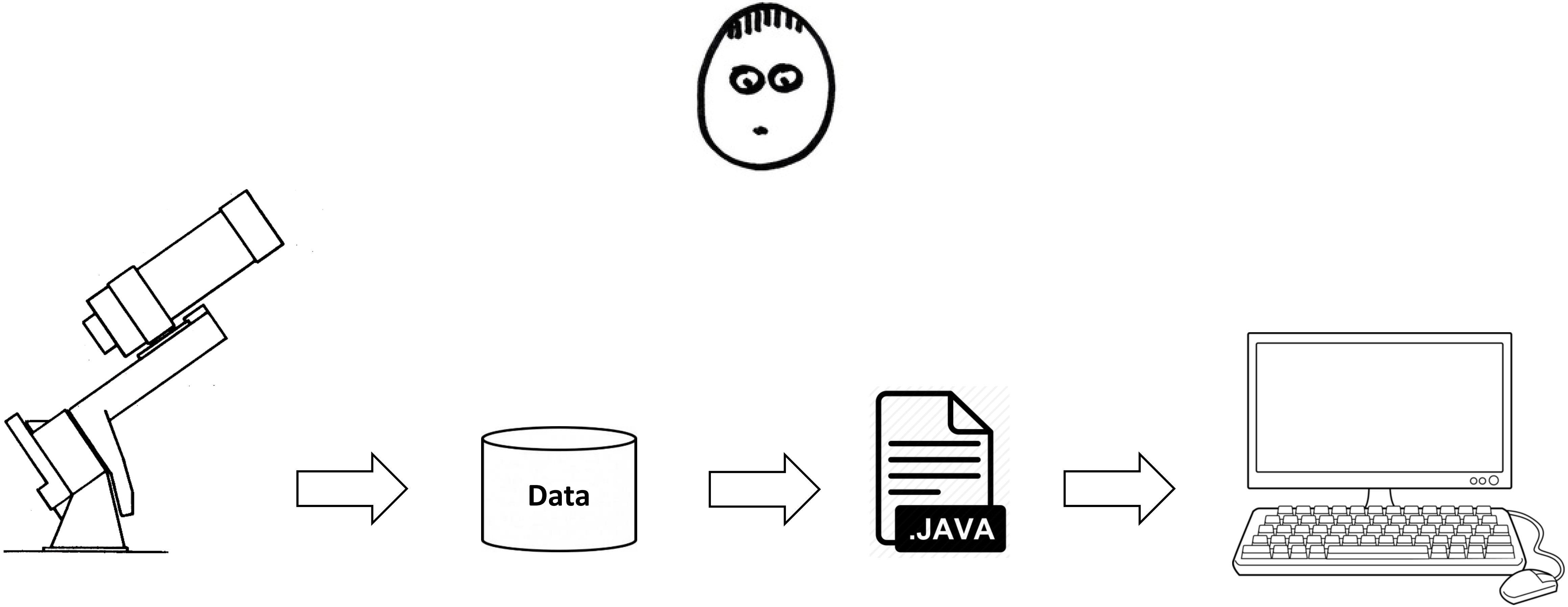
Alvin Cheung

PLSE

UW DB

UNIVERSITY of WASHINGTON

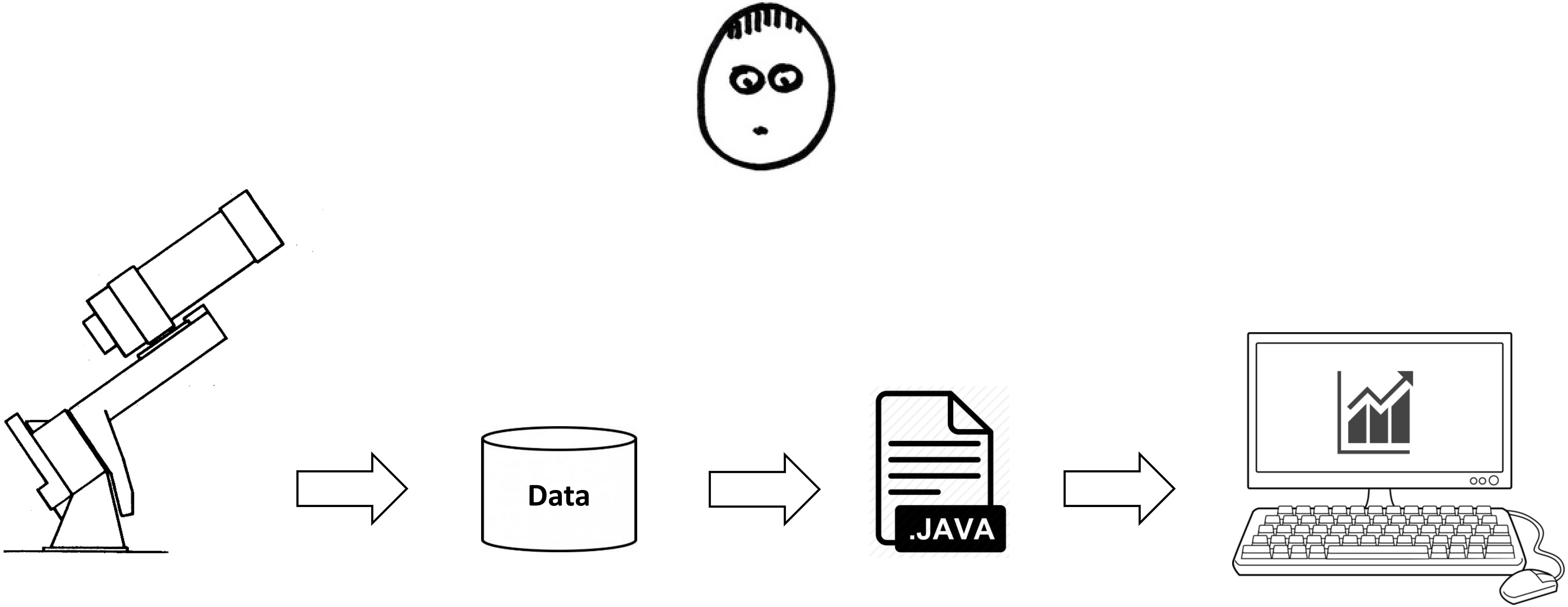
Motivation



Data Collection Tool

Data Analytics Application
(Sequential Java)

Motivation



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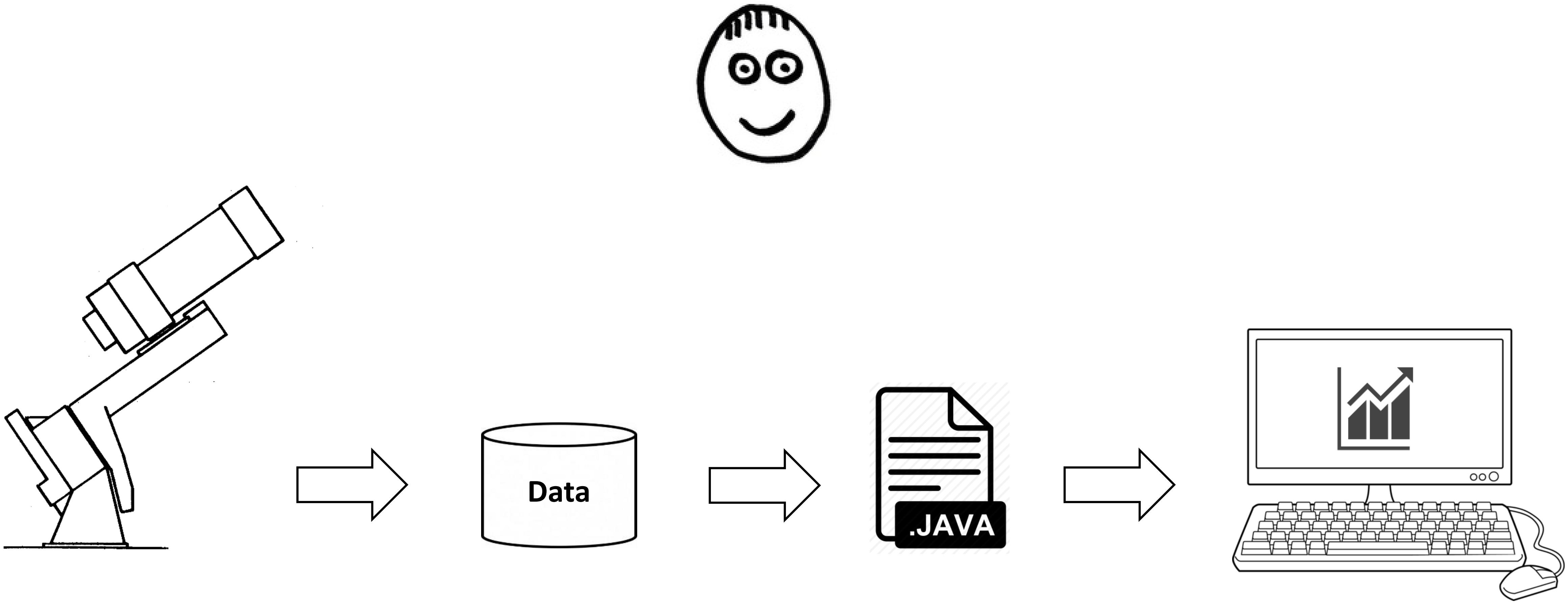

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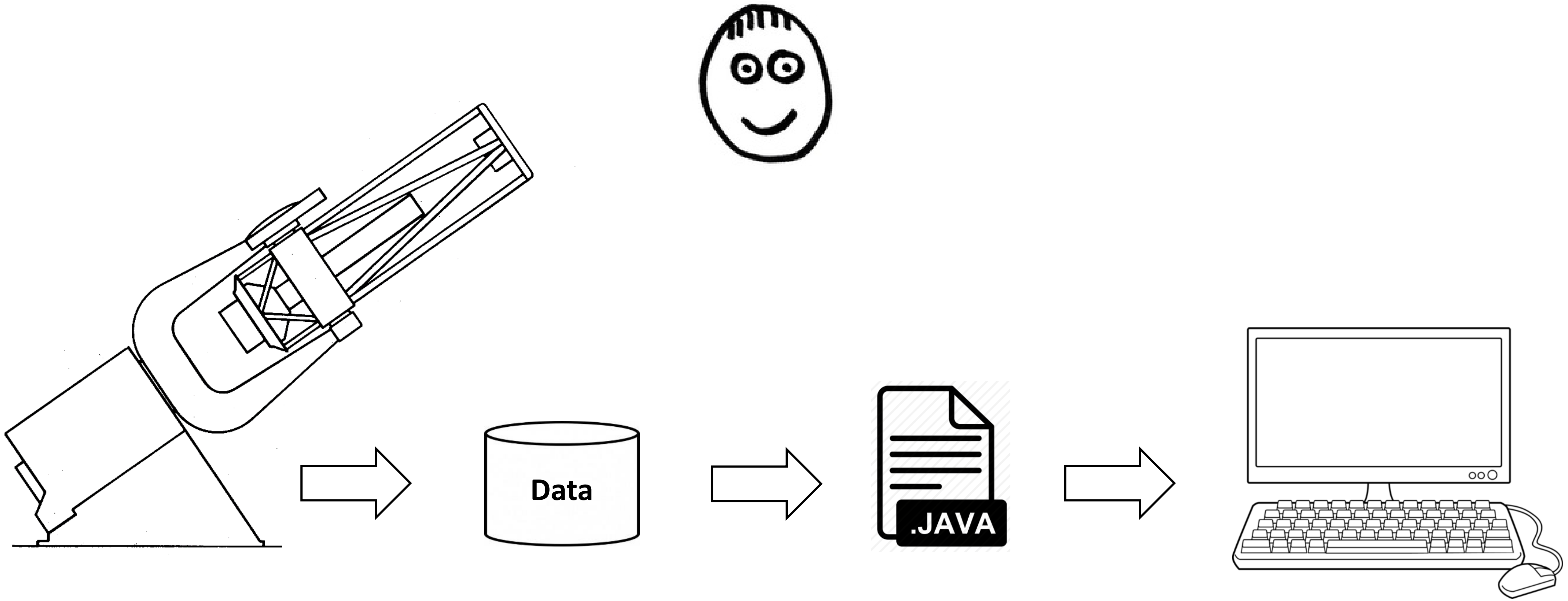

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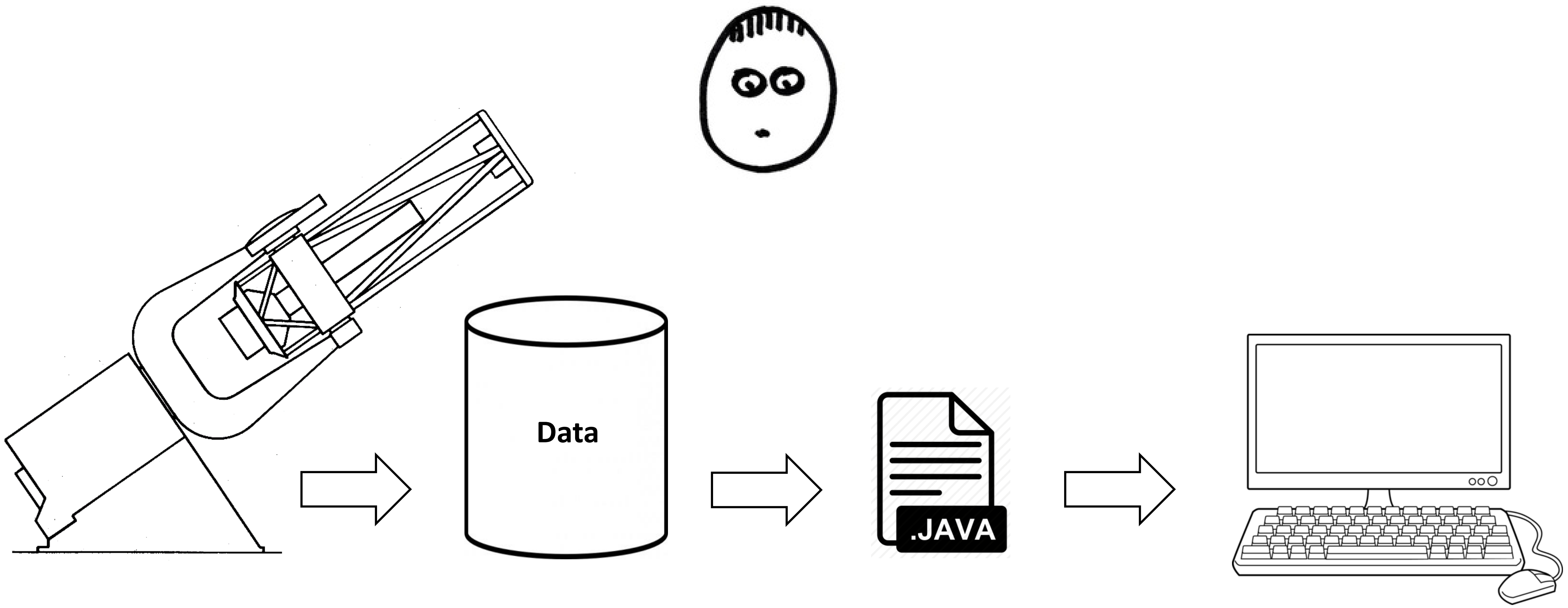

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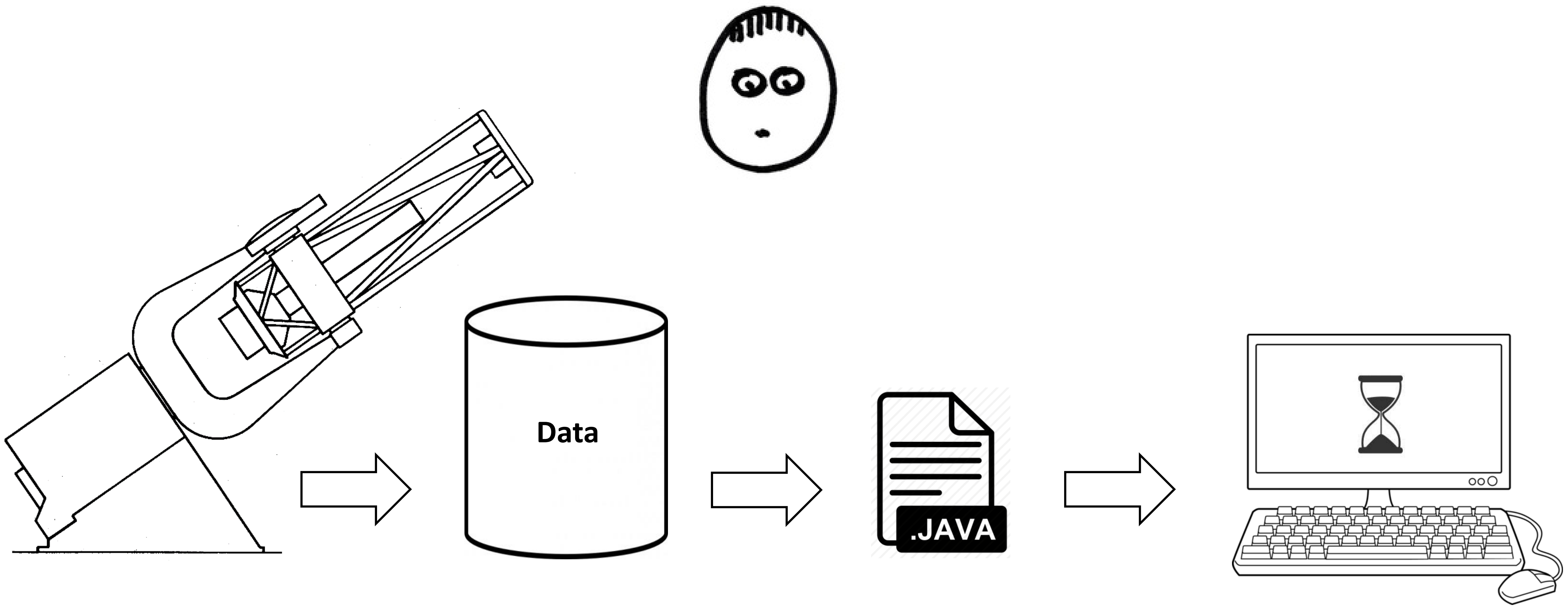

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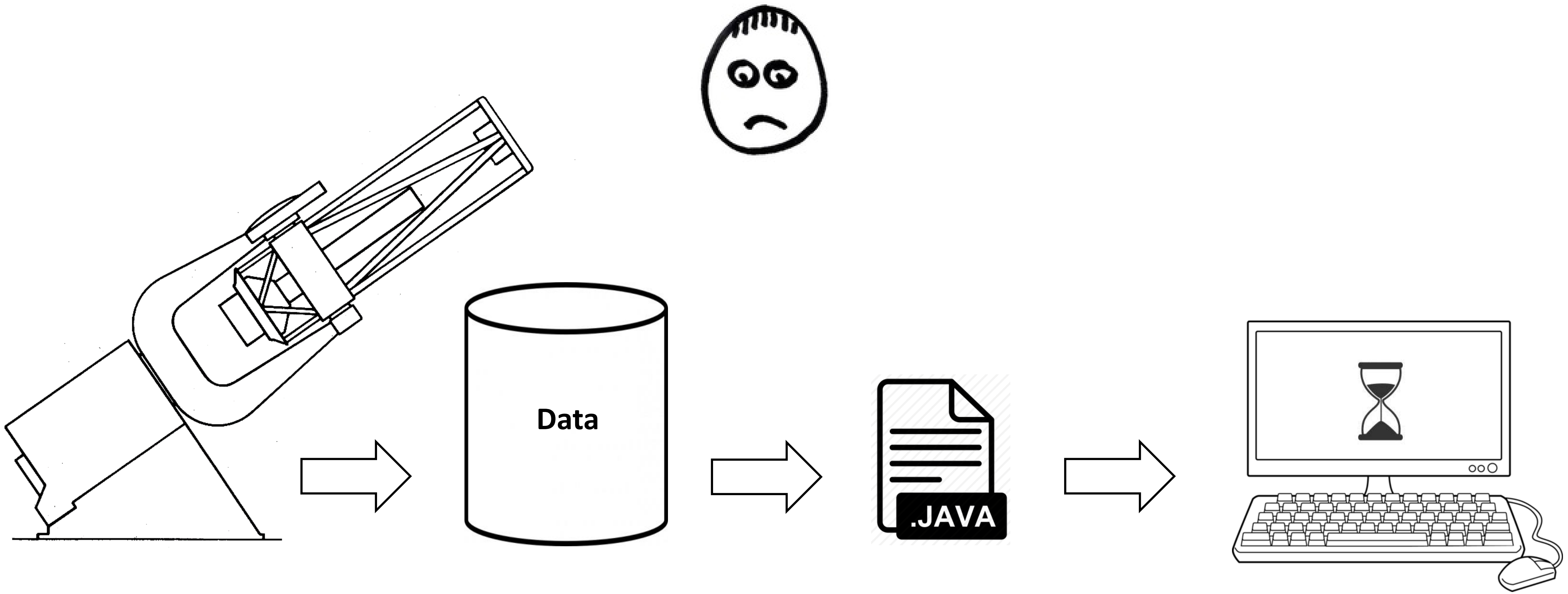

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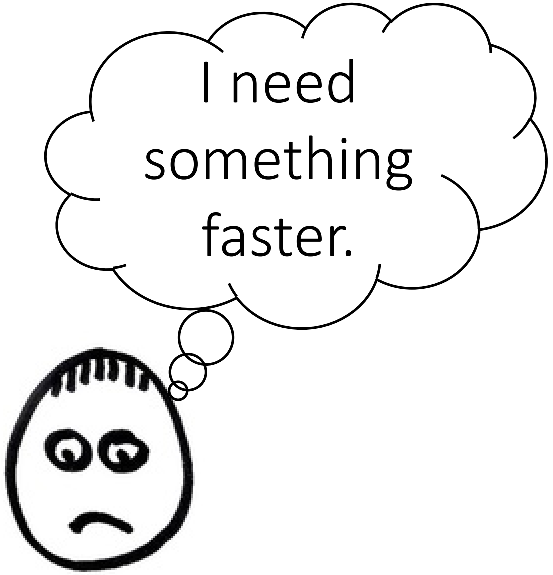

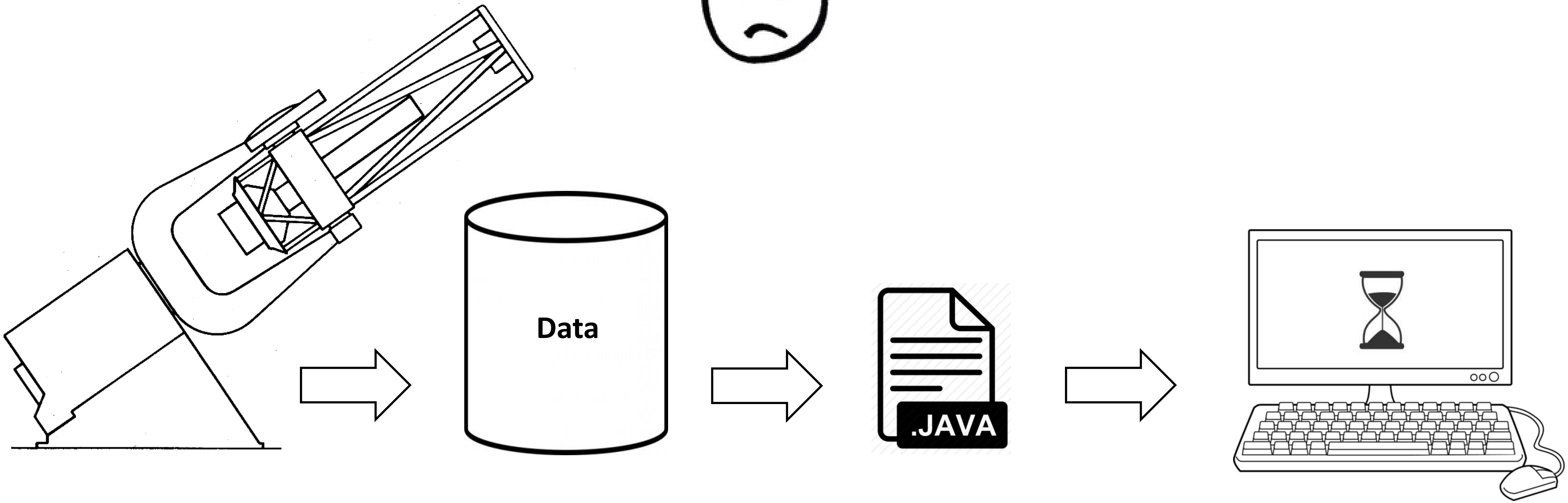

Data Collection Tool

Data Analytics Application
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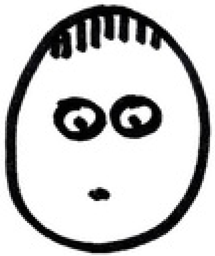
Parallel Processing Frameworks

Spark

GraphLab

hadoop

APACHE STORM™



OpenMP®

Flink

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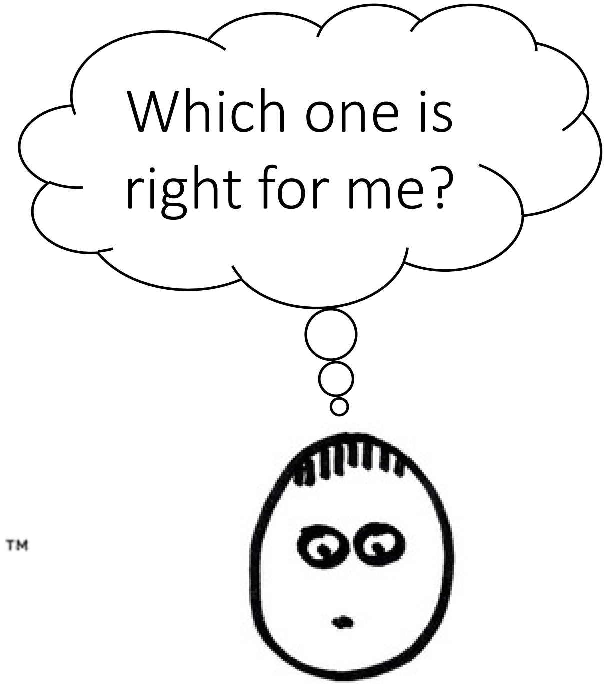

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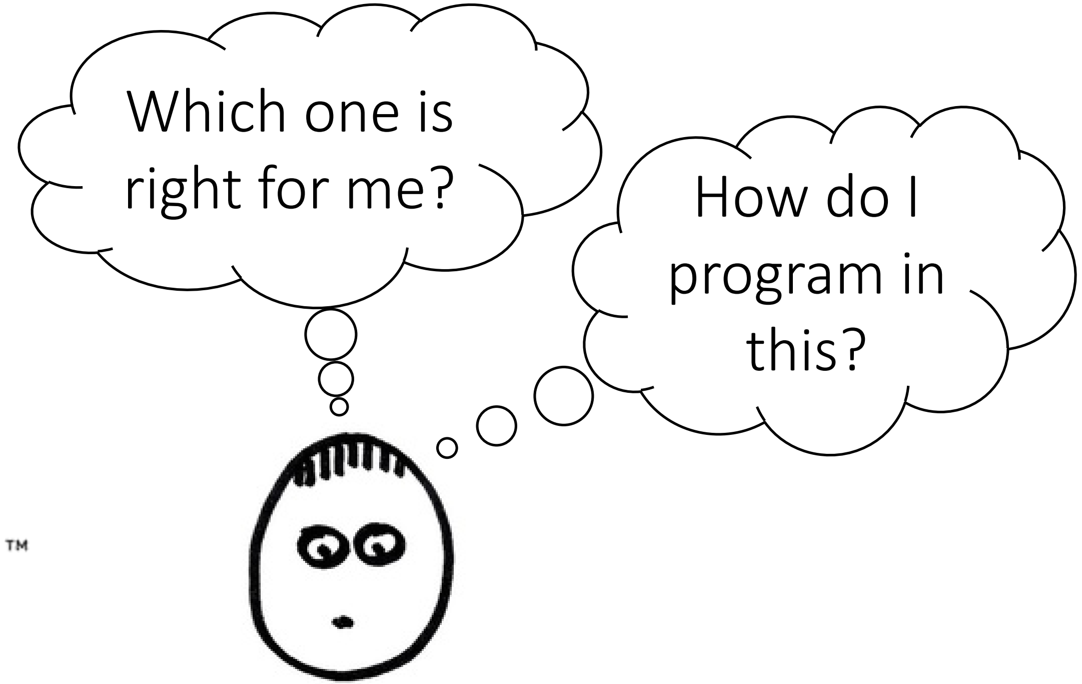

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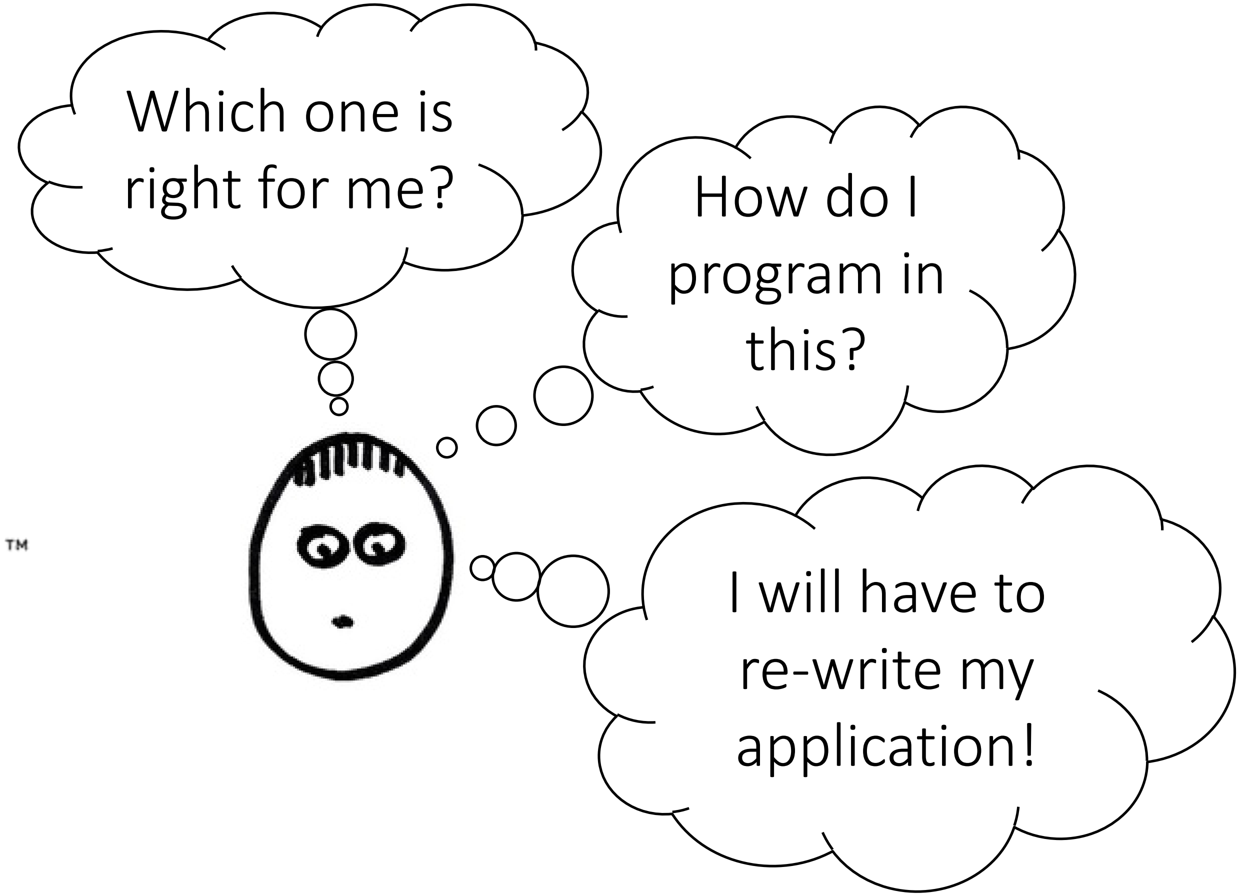

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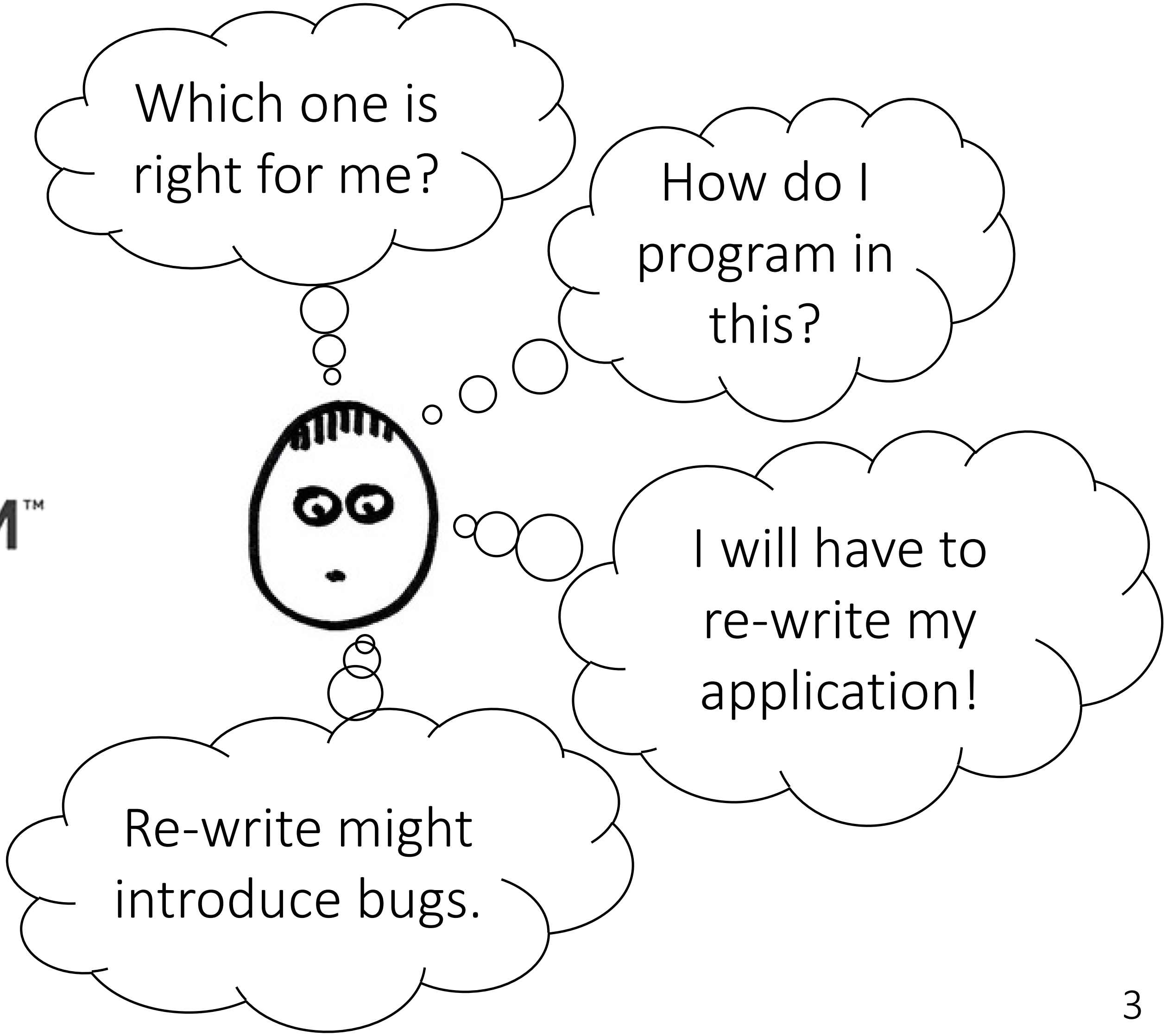

How can we make life easier?

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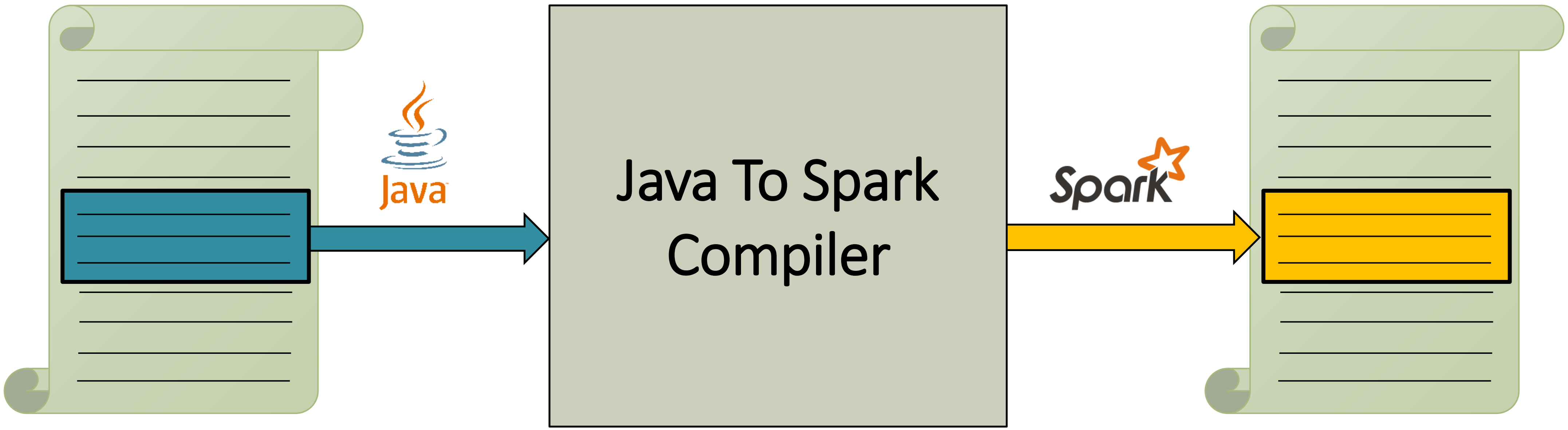

```
for(int i = 0; i < data; i++){
    ...
}
```

Syntax Directed Rules

```
mapper(key, data){
    ...
}
reducer(key, values){
    ...
}
```

Hard to come up with rules

Brittle to code pattern changes

$f_m(val) \rightarrow \boxed{\dots}$

$f_r(val1, val2) \rightarrow \boxed{\dots}$

output = reduce(map(data, f_m), f_r);

Syntax Directed Rules

Java

```
for(int i = 0; i < data; i++){
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Syntax Directed Rules

hadoop

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Hard to come up with rules

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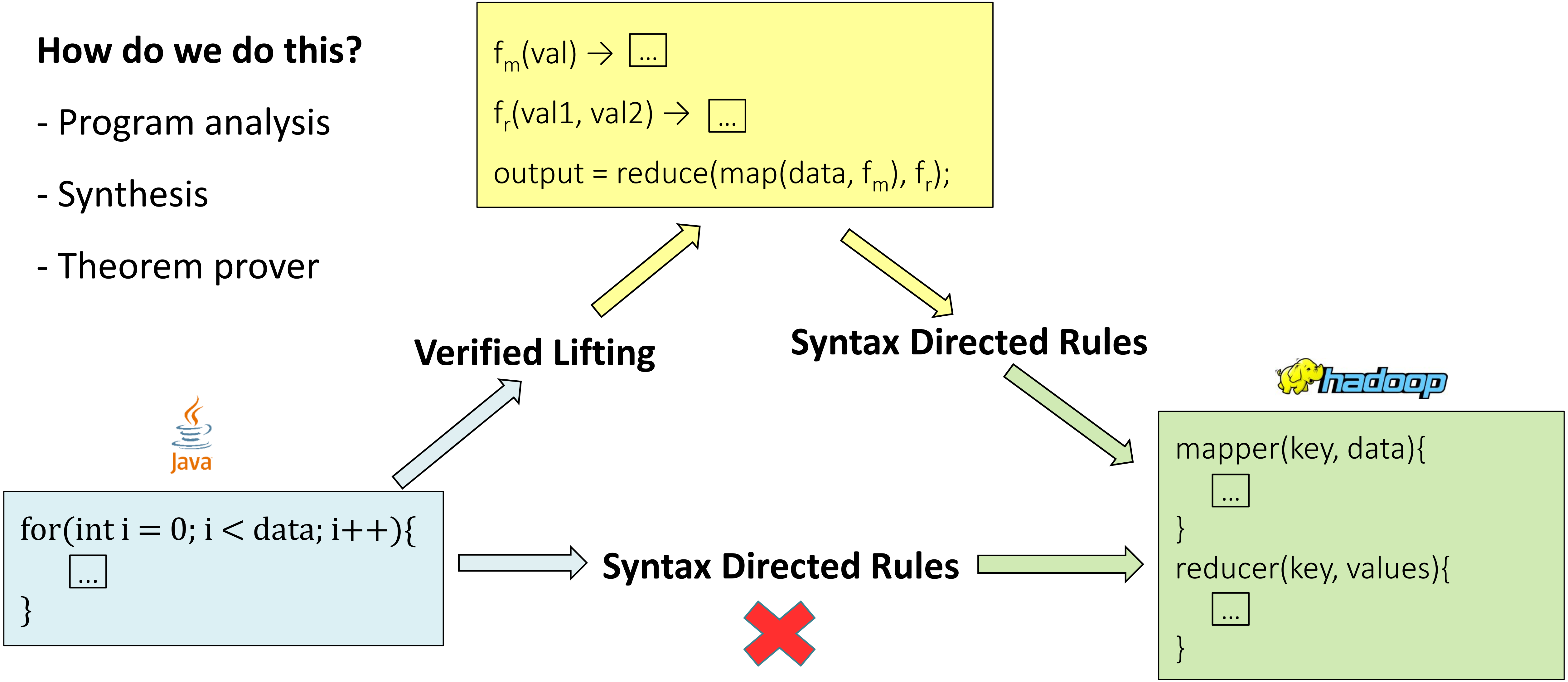
How do we do this?

- Program analysis
- Synthesis
- Theorem prover



Hard to come up with rules

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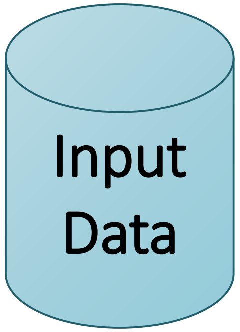
Introducing CASPER

- Re-targets sequential Java code fragments to Hadoop/Spark frameworks.
- **Input:** Unannotated sequential Java application source code.
- **Output:** Translated application source code that runs on top of Hadoop/Spark to leverage its parallel execution.

MapReduce Overview



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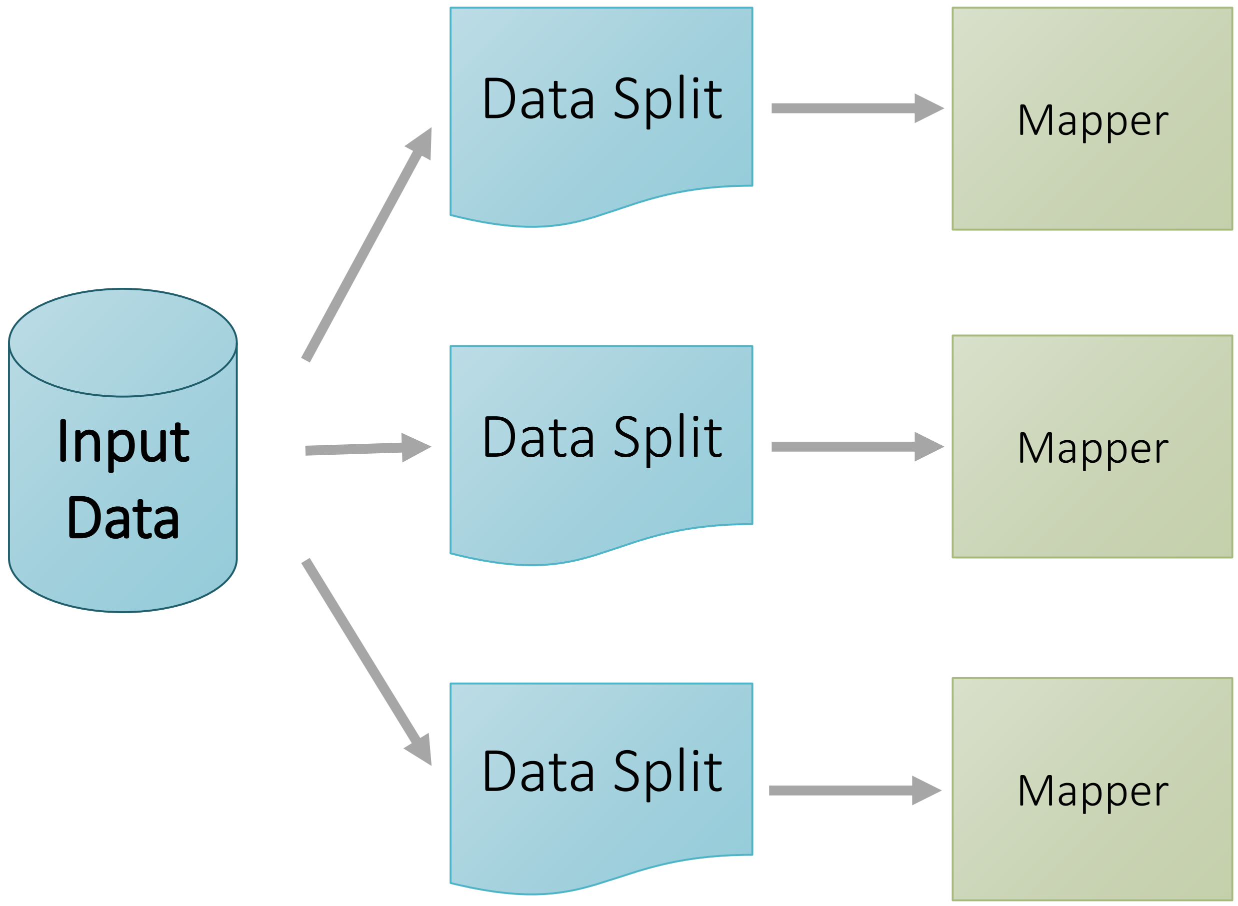

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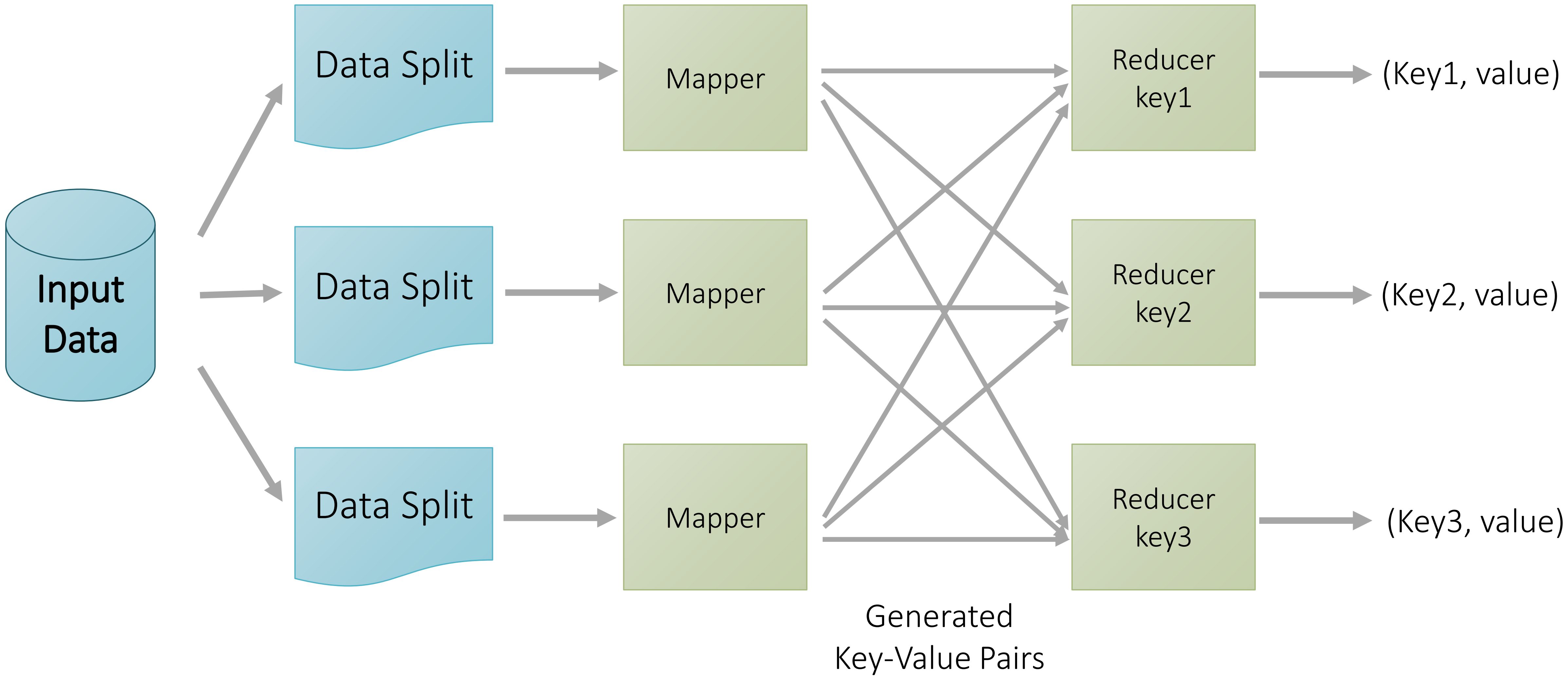

Verified Lifting

- Infer code semantics (summary) in a high level specification
- A summary describes the effect of code on the output variables

Java Code Fragment

```
data_sqr = 0;
for(int i = 0; i < data.size(); i++){
    data_sqr += data[i] * data[i];
}
```

Summary

$$data\_sqr \equiv \sum_{i=0}^{i=data.size()-1} data[i]^2$$

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Summary

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- Specifications must be trivial to translate.
- Program specification exhibits good parallelism.

Code Summaries in Casper

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$\forall v \in outputVariables.$

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Restricting Search Space

- Use Syntax-Guided Synthesis (SyGuS) to generate f_{map} and f_{reduce}.
- Use a grammar to specify a set of candidate summaries.
- Grammar is dynamically generated for each code fragment.

Grammar Generation: f_{map}

- The body of f_{map} is just a sequence of emits.
  - Begin with number of emits equal to number of output variables.
  - Incrementally add emits statements up to a user-defined bound.

$$Map \;\rightarrow Map\ Map \mid Emit$$

$$Emit \;\rightarrow\; emit(Key, Value);\ \mid\ if(Condition)\ emit(Key, Value);$$

$$Key \rightarrow IntExp \mid StringExp \mid BoolExp \mid\ \ldots$$

$$Value \rightarrow IntExp \mid StringExp \mid BoolExp \mid\ \ldots$$

Grammar Generation: f_{map}

- The key and value for each emit are generated using expression grammars.

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```

Integer Expression Grammar

$$IntExp \rightarrow IntExp + IntExp \mid IntExp * IntExp \mid data[IntExp] \mid IntVal$$

$$IntVal \rightarrow data\_sqr \mid i \mid literal$$

Grammar Generation: f_{reduce}

- The body of f_{reduce} implements a fold operation.

Java Code Fragment

```
data_sqr = 0;
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}
```

Fold Expression Grammar

$$Reduce \rightarrow int\ res = literal;\ for(value : values)\{ res = FoldExp; \}\ emit(key, res);$$

$$FoldExp \rightarrow FoldExp + FoldExp \mid FoldExp * FoldExp \mid IntVal$$

$$IntVal \rightarrow res \mid val \mid key \mid literal$$

Verifying Equivalence

- CASPER uses Hoare-style verification conditions.
- Verification conditions are the *weakest pre-conditions* for the post-condition (code summary) to hold.
- Proving post-conditions for code fragments containing loops requires loop-invariants.

Verifying Equivalence Pt. 2

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$$preCondition \equiv data\_sqr = 0$$

$$postCondition \equiv data\_sqr = reduce(map(data, f_{map}), f_{reduce})$$

$$loopInvariant \equiv data\_sqr = reduce(map(data[0..i], f_{map}), f_{reduce}) \wedge 0 \leq i \leq data.length$$

Formal Verification

- We have modelled the MapReduce library in Dafny.
- The generated summary is compiled down to Dafny code.
- Code annotations are automatically generated. These include:
  - Verification conditions
  - Proof lemmas

Lemma Example

lemma InductiveStep (data: seq<int>, i: int, data_sqr: int)

requires invariant(data, i, data_sqr) && i < |data|

ensures invariant(data, i + 1, data_sqr + (data[i] * data[i]));

{

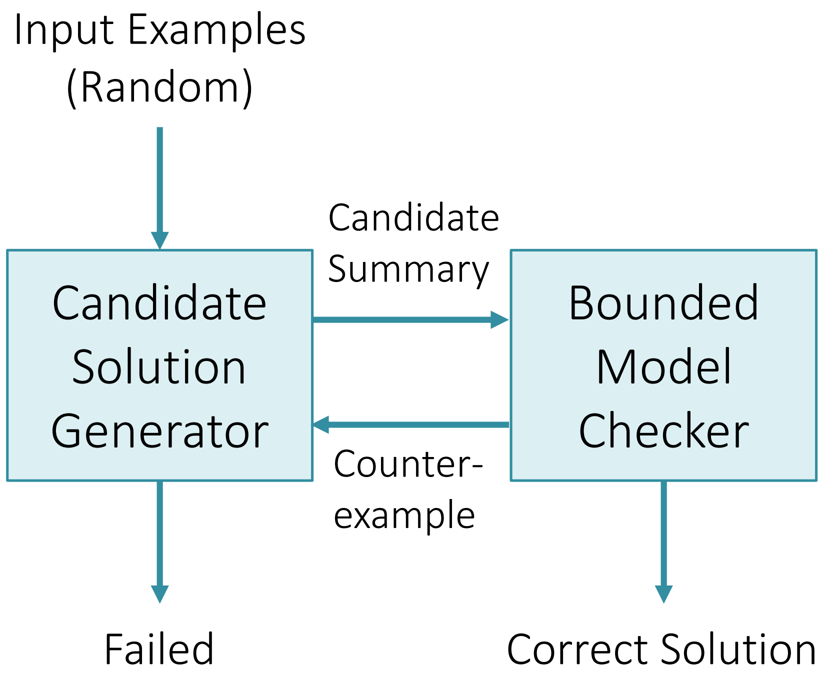
assert map (data, i+1) == f_{map}(data, i) + map(data, i);

assert f_{reduce}(f_{map}(data, i), 0) == data[i] * data[i];

...

}

CASPER Architecture Diagram



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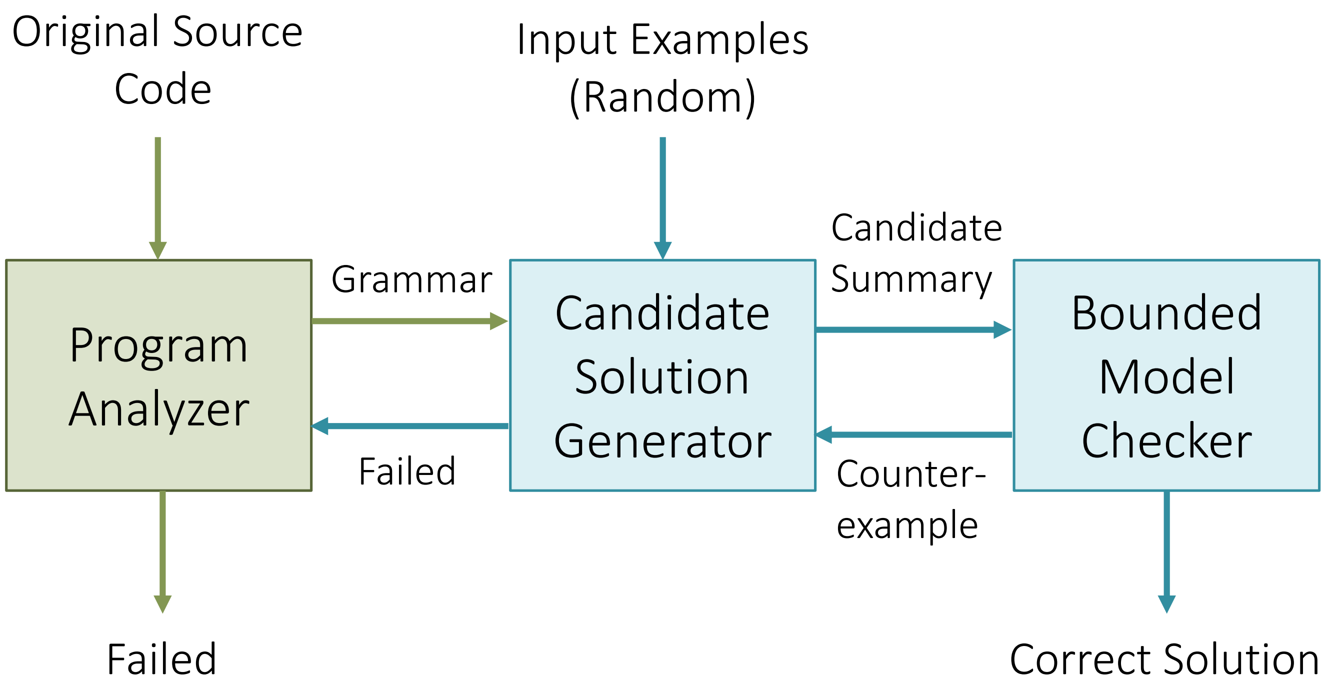

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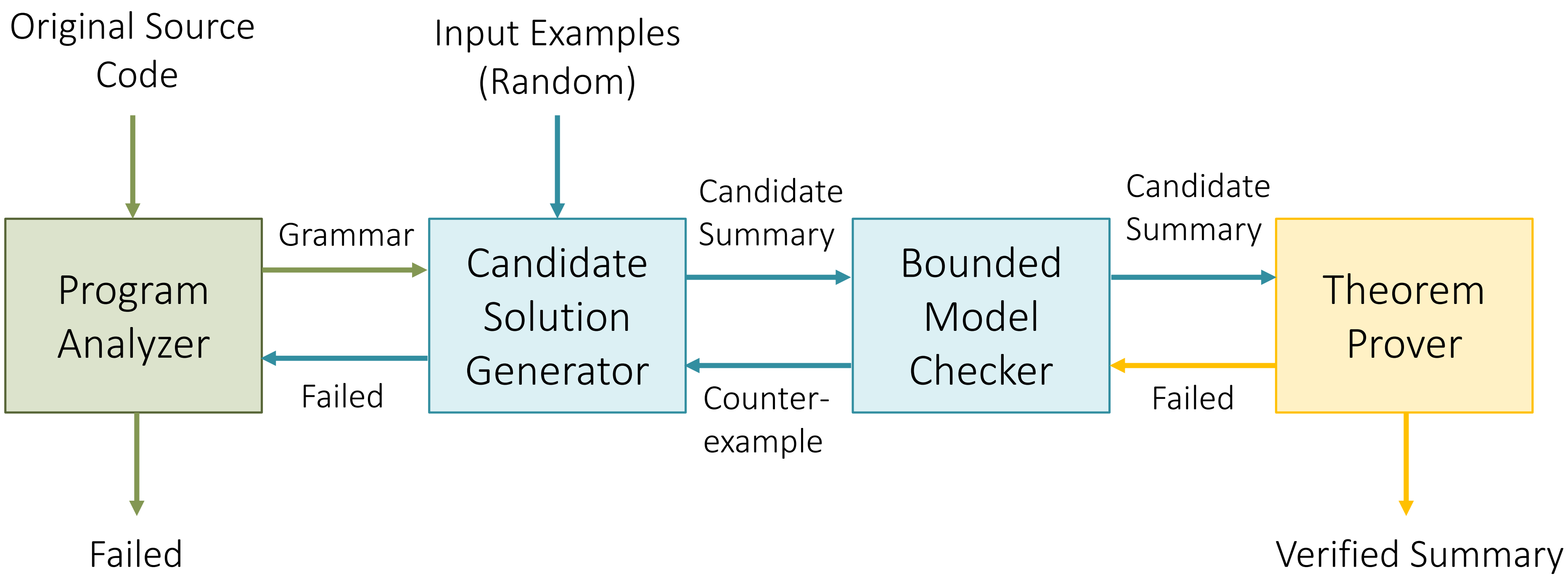

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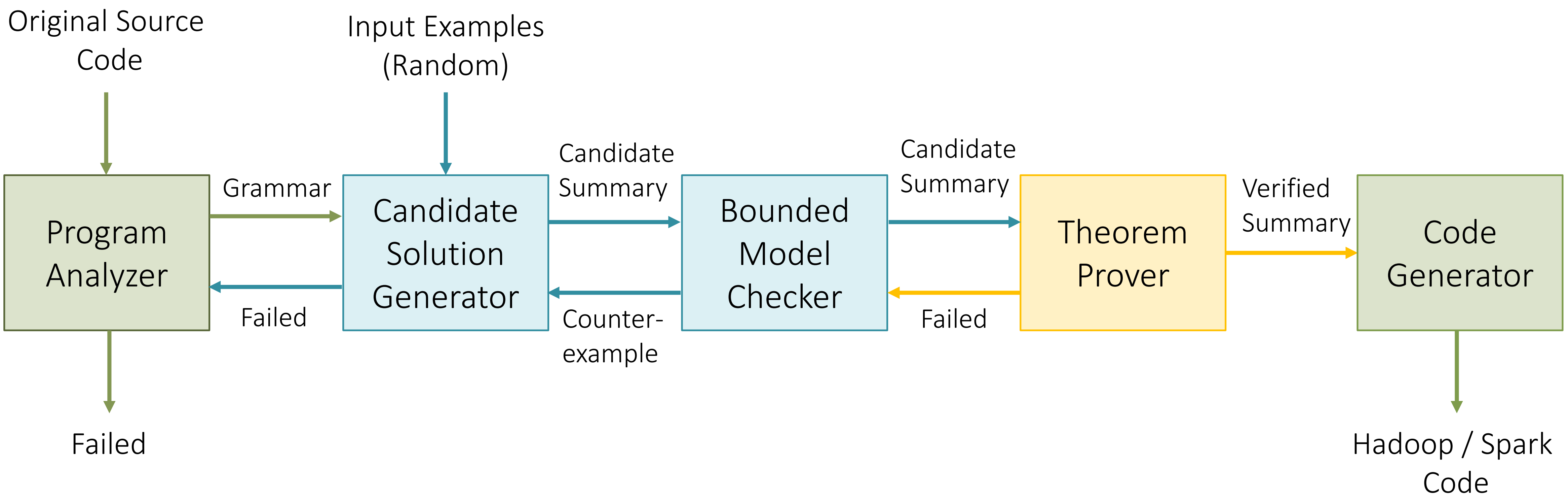

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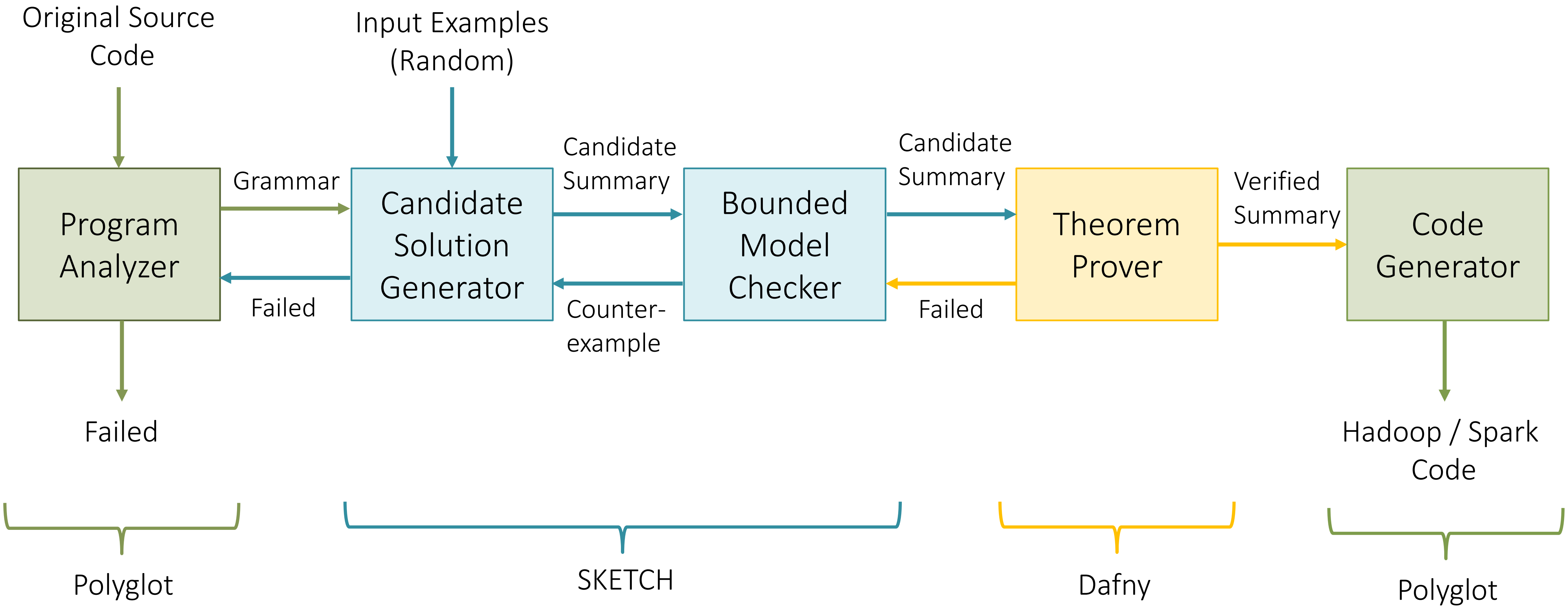


Evaluation

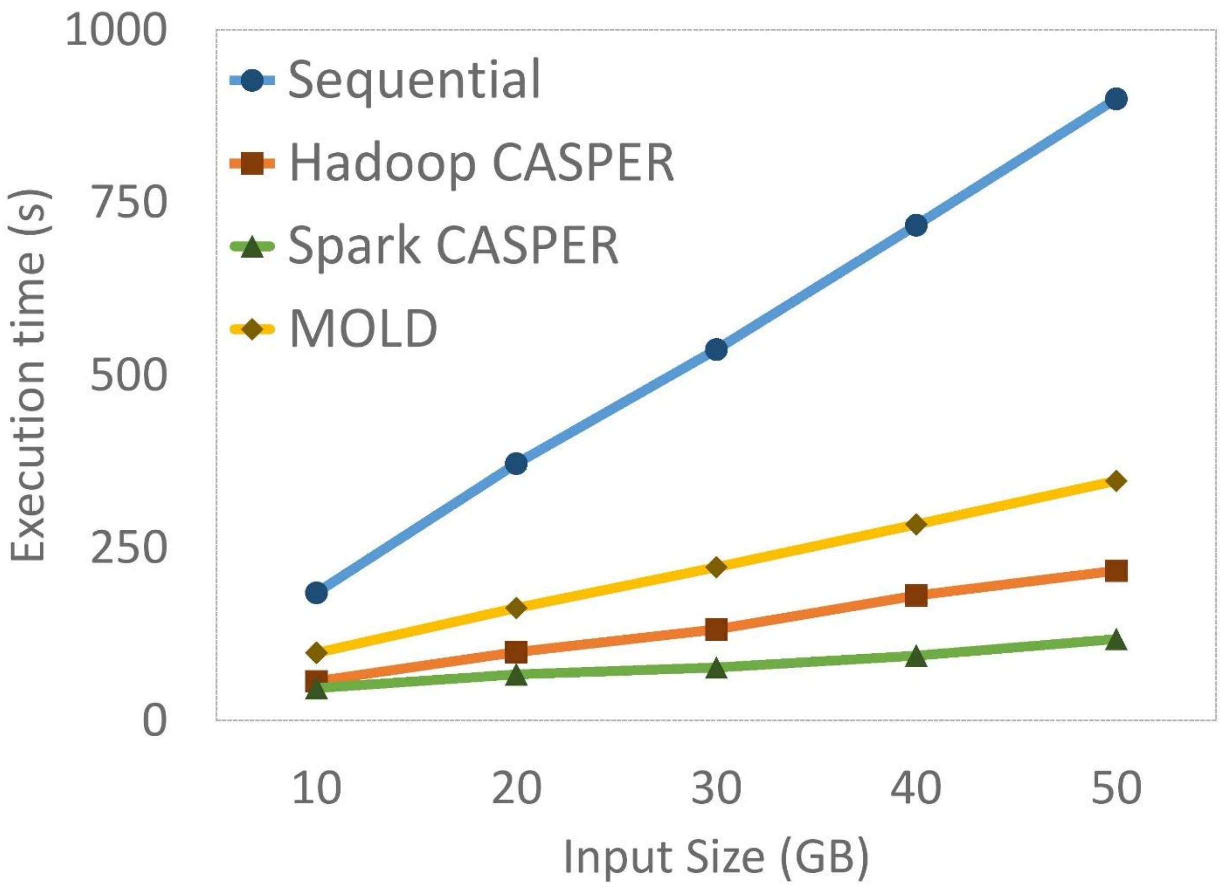
- Compilation performance
- Run-time performance
- Five benchmarks:
  - Summation
  - Word Count
  - String Search (Grep)
  - Linear Regression
  - 3D Histogram

Compilation Performance

Benchmark	Program Analysis	Synthesis and BMC	# of grammar Iterations	Formal Verification
Summation	< 1s	13s	1	2.8s
Word Count	< 1s	44s	1	3.4s
String Match	< 1s	1406s	2	3.3s
3D Histogram	< 1s	2355s	2	4.2s
Linear Regression	< 1s	1801s	2	4.8s

Runtime Performance

- Configuration:-
  - 10 node cluster
  - 8 vCPU, 15GB Memory
  - HDFS for data storage
  - Hadoop 2.7.2 and Spark 1.6.1
- Average Speedup:
  - **6.1x** on Spark
  - **3.3x** on Hadoop

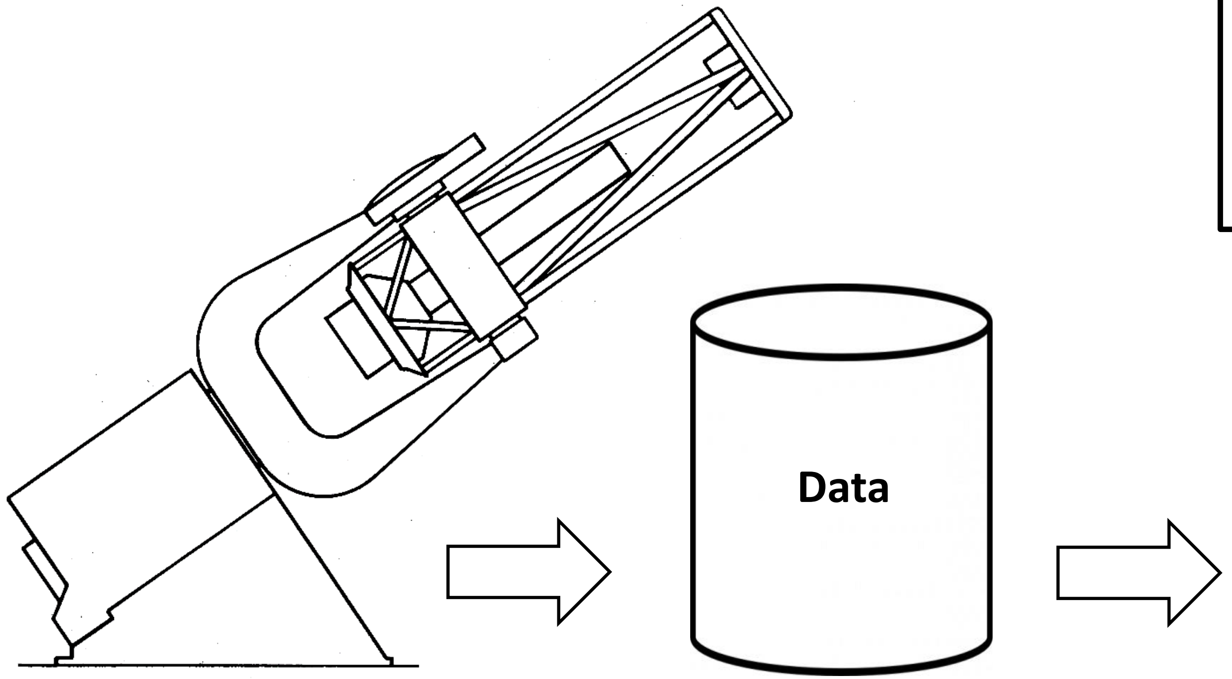


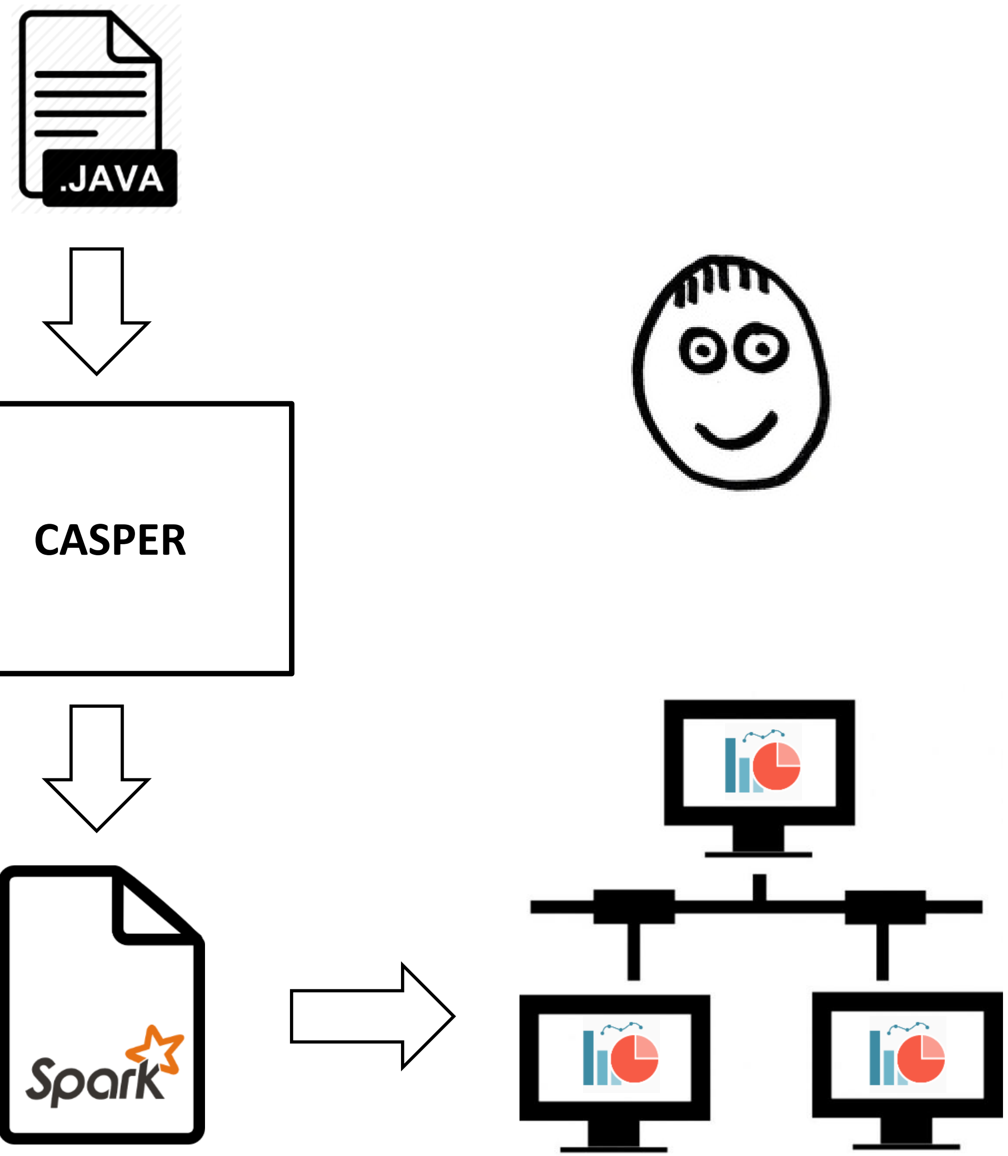
Benchmark: String Matching (Grep)

Demo!

Summary

Web-page: http://tinyurl.com/casper-homepage
Mailing-list: http://tinyurl.com/casper-subscribe





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