Using Dynamic Invariant Detection to Support the Testing and Analysis of Database Applications

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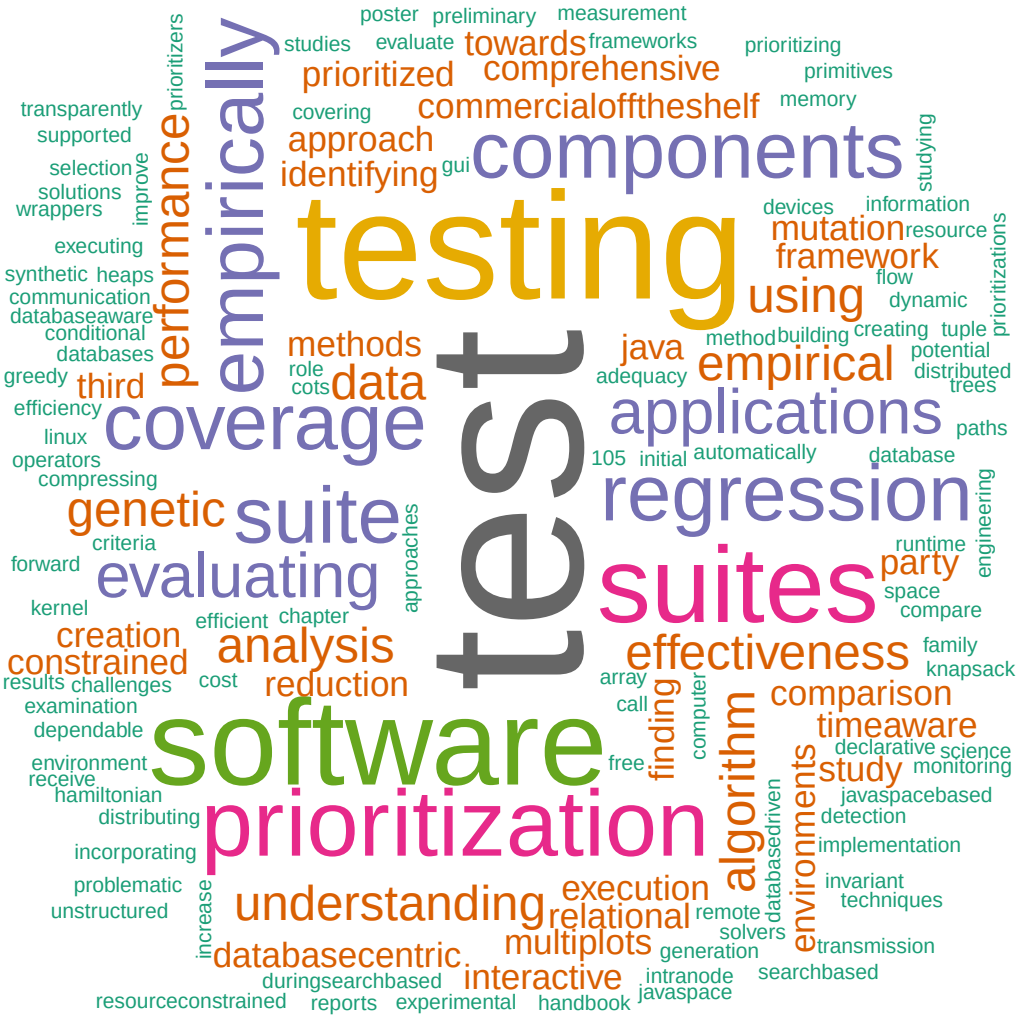
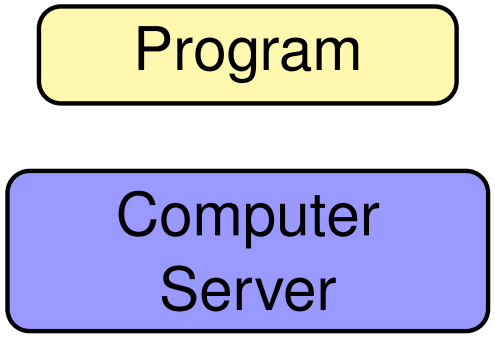
Presenter Introduction: Gregory M. Kapfhammer



Software and Data are Everywhere



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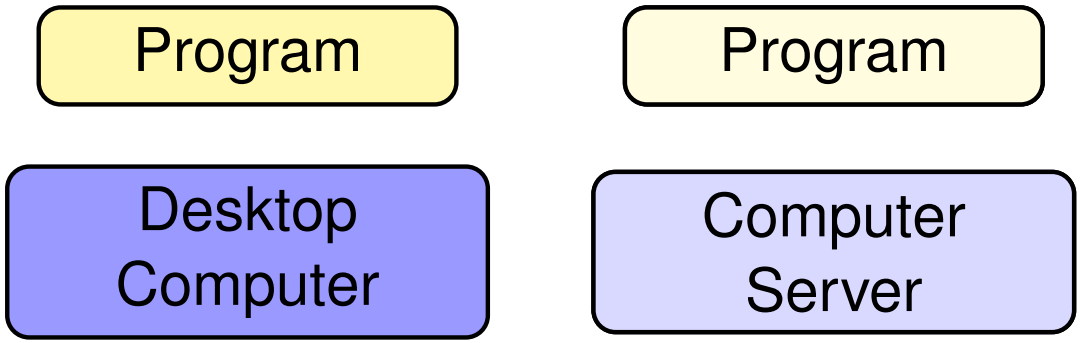

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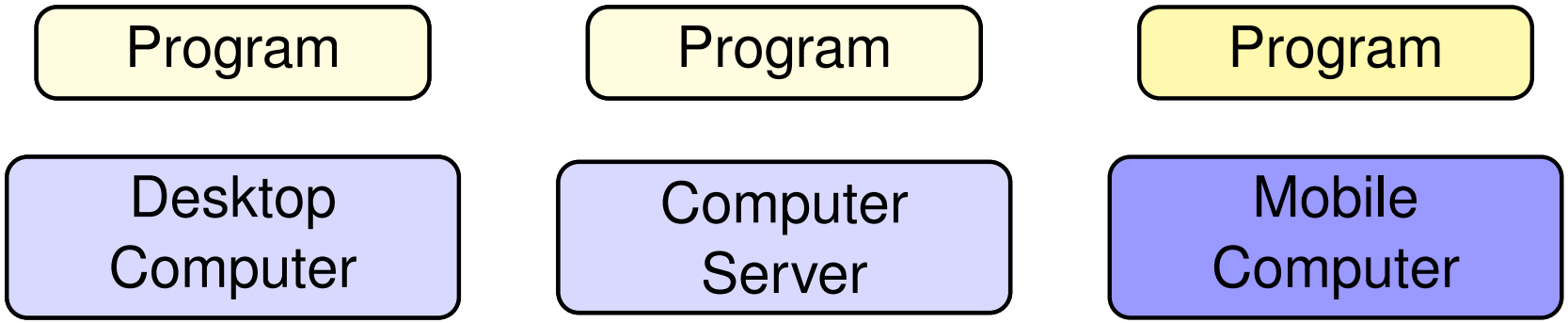

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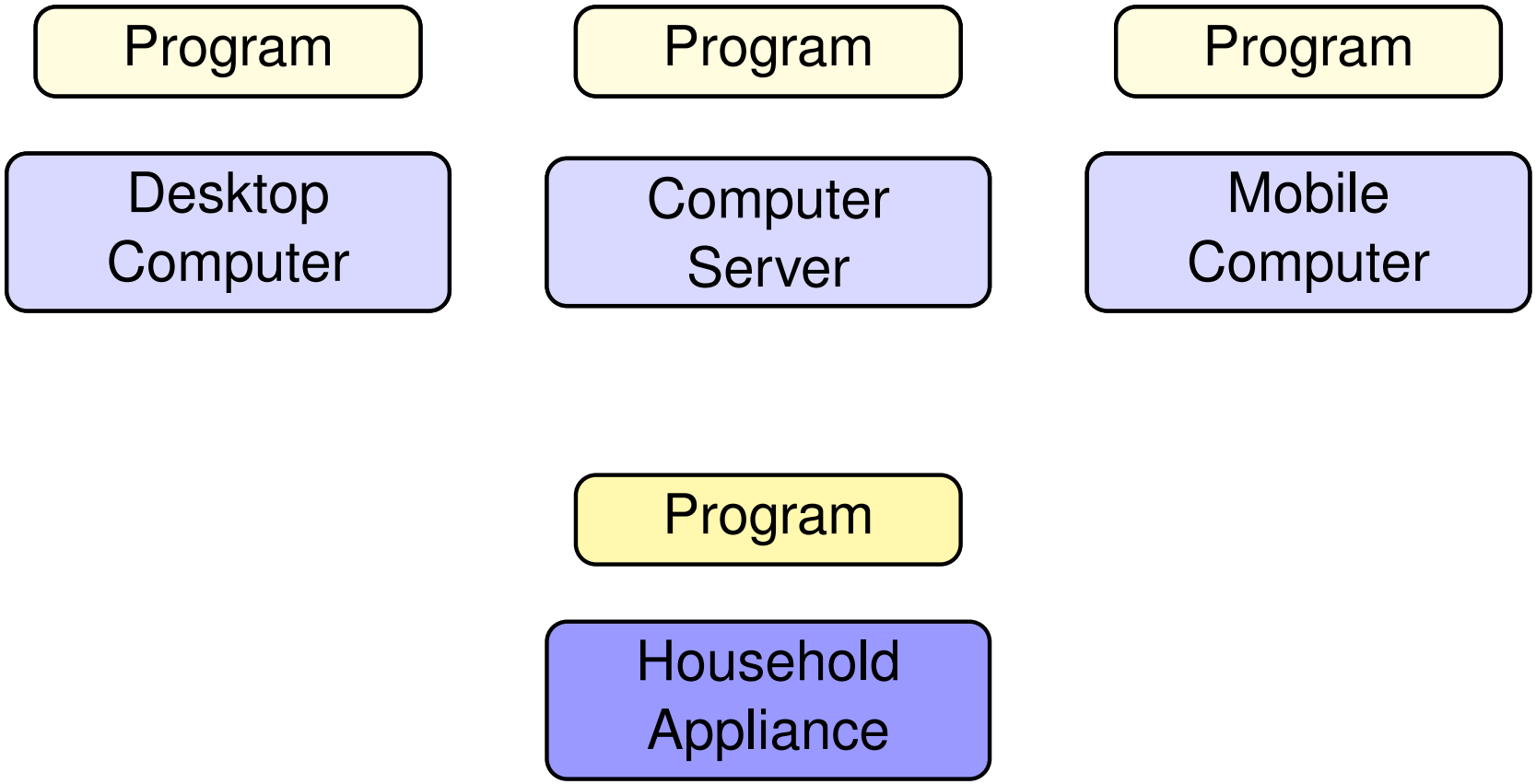

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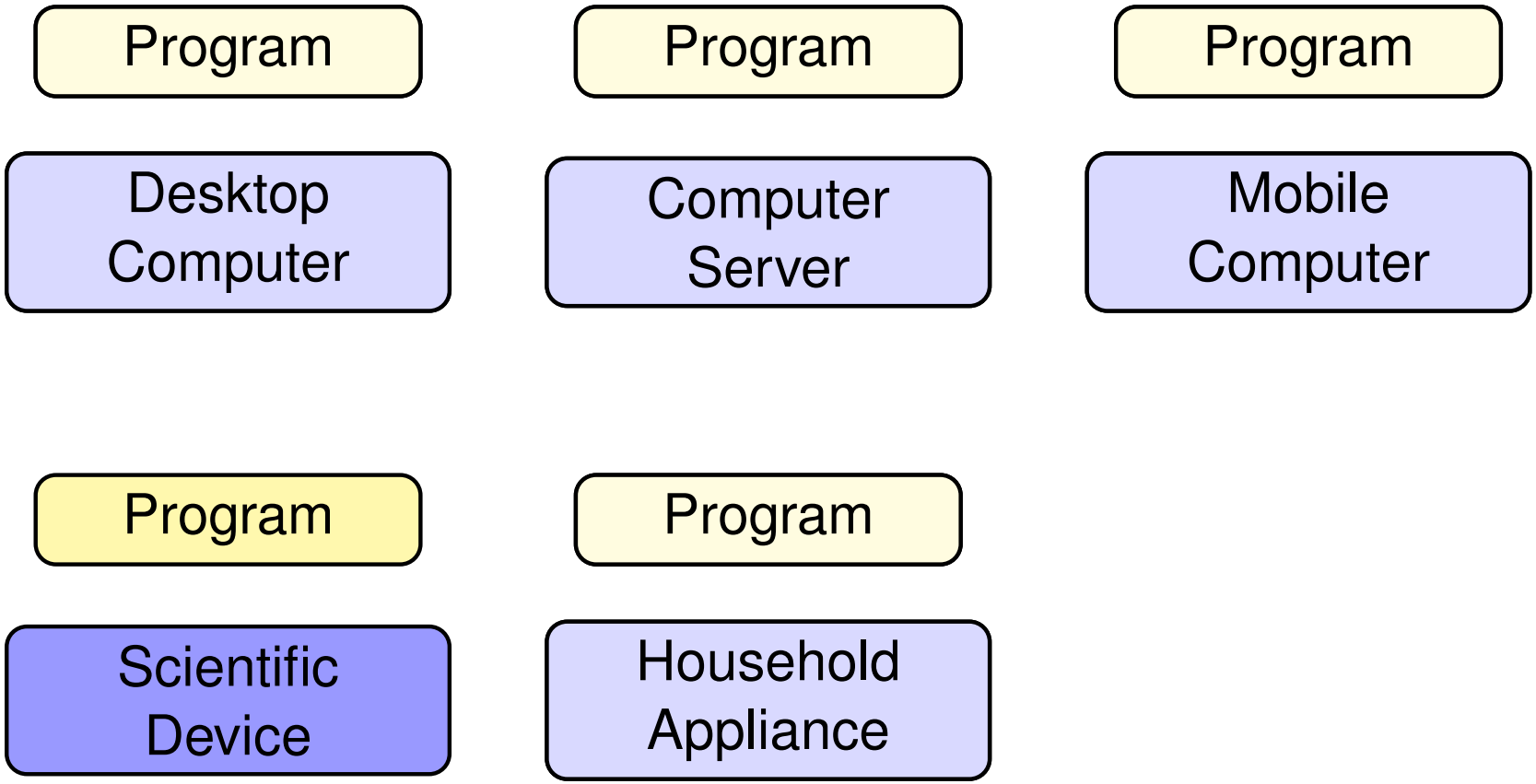

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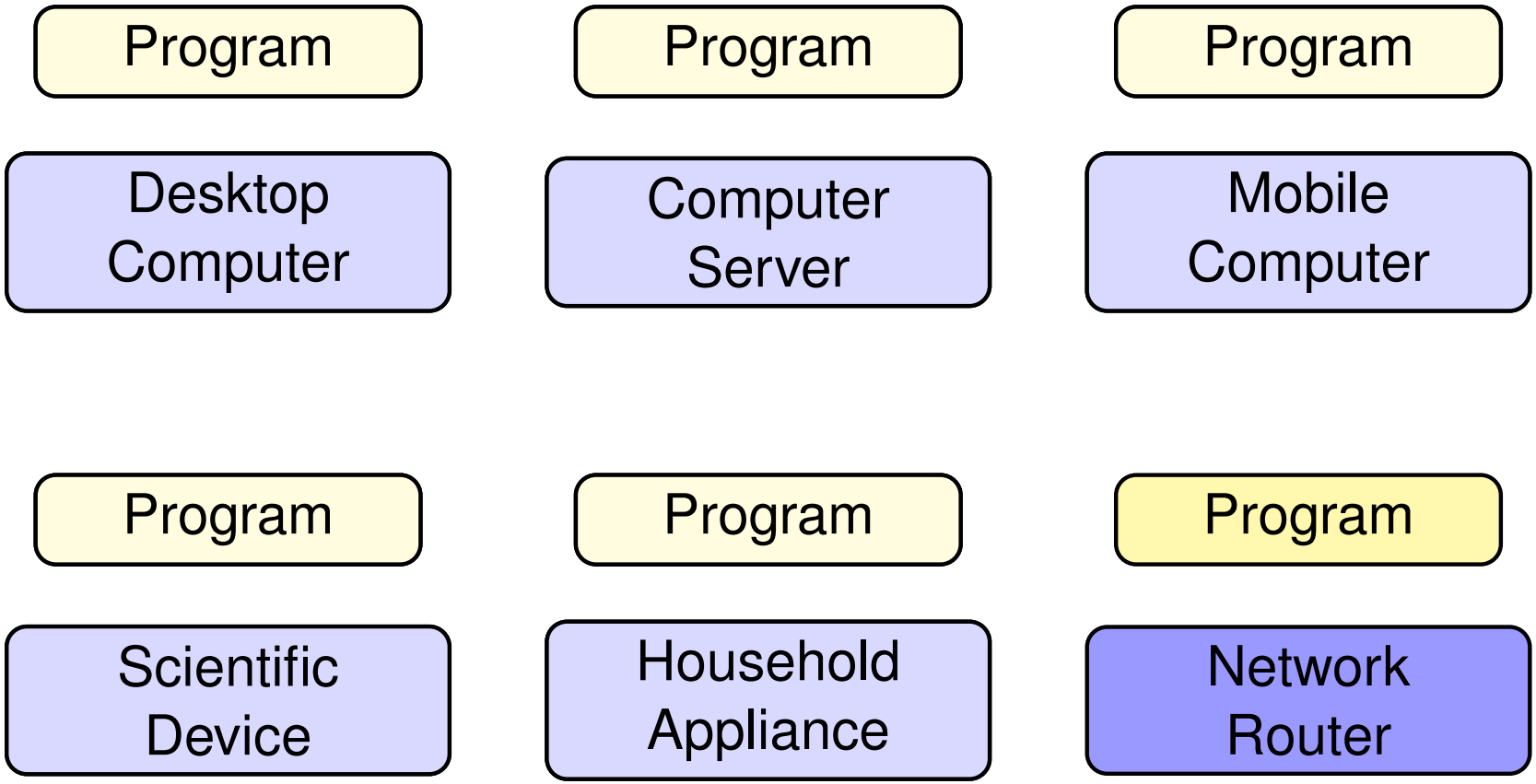

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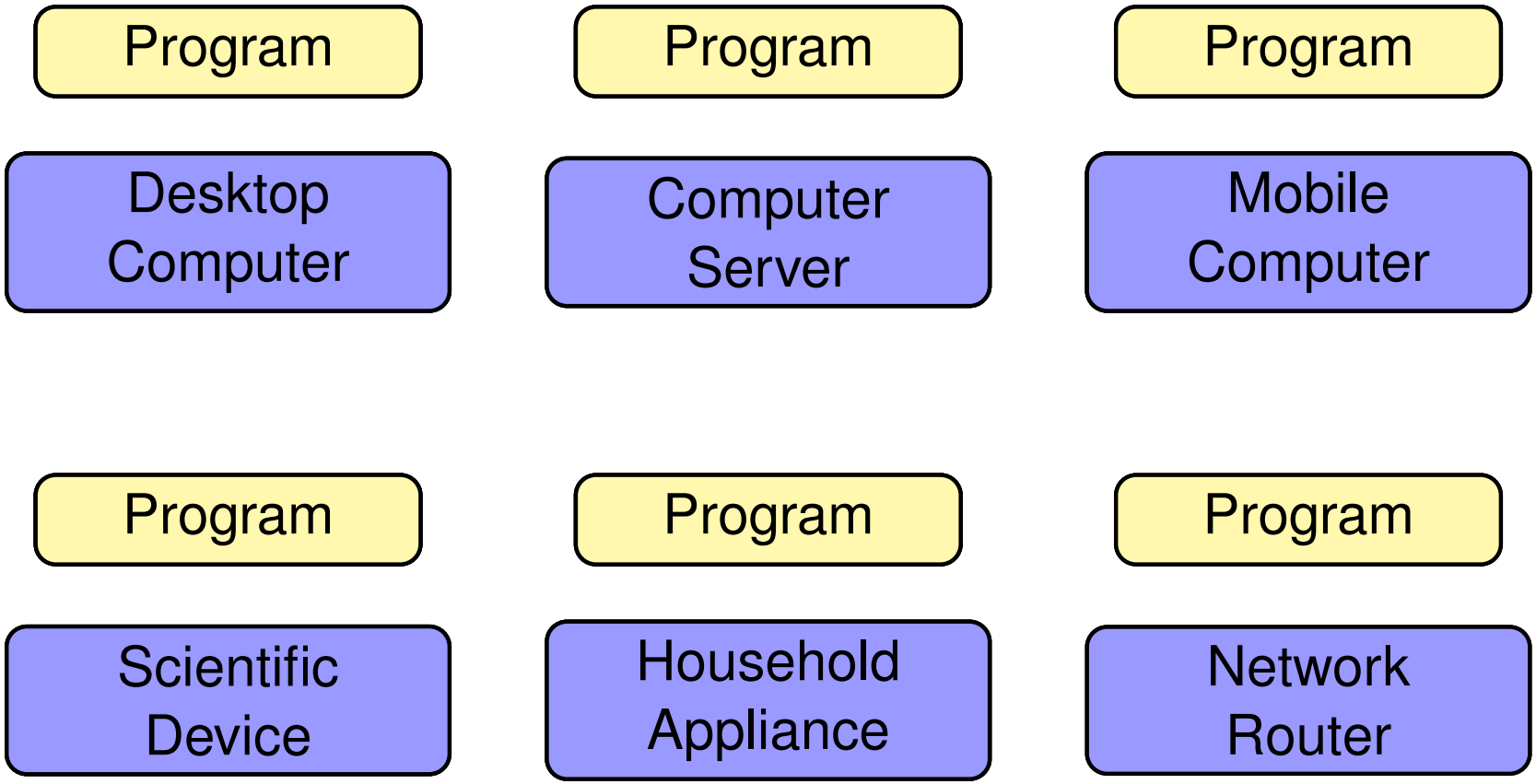

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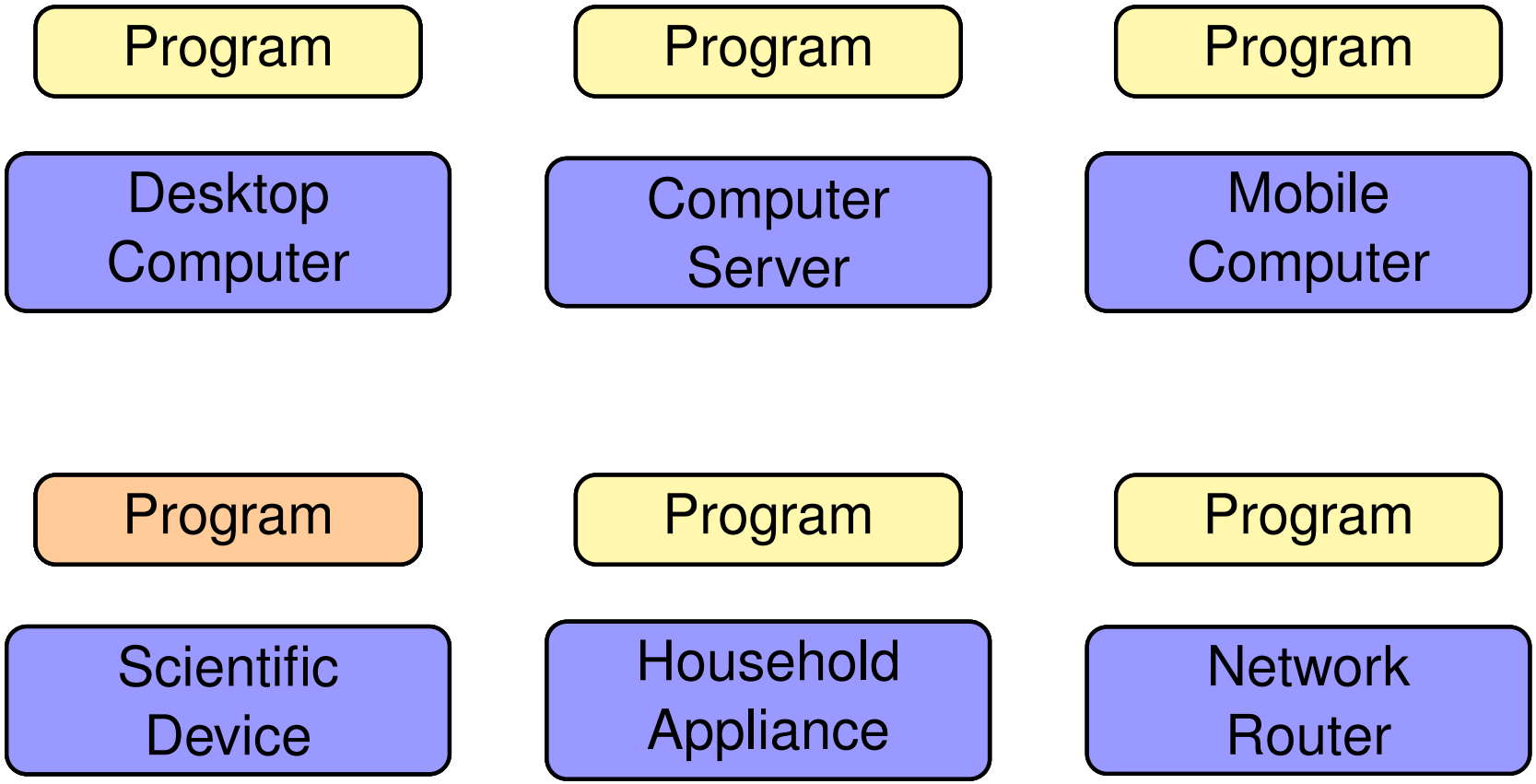

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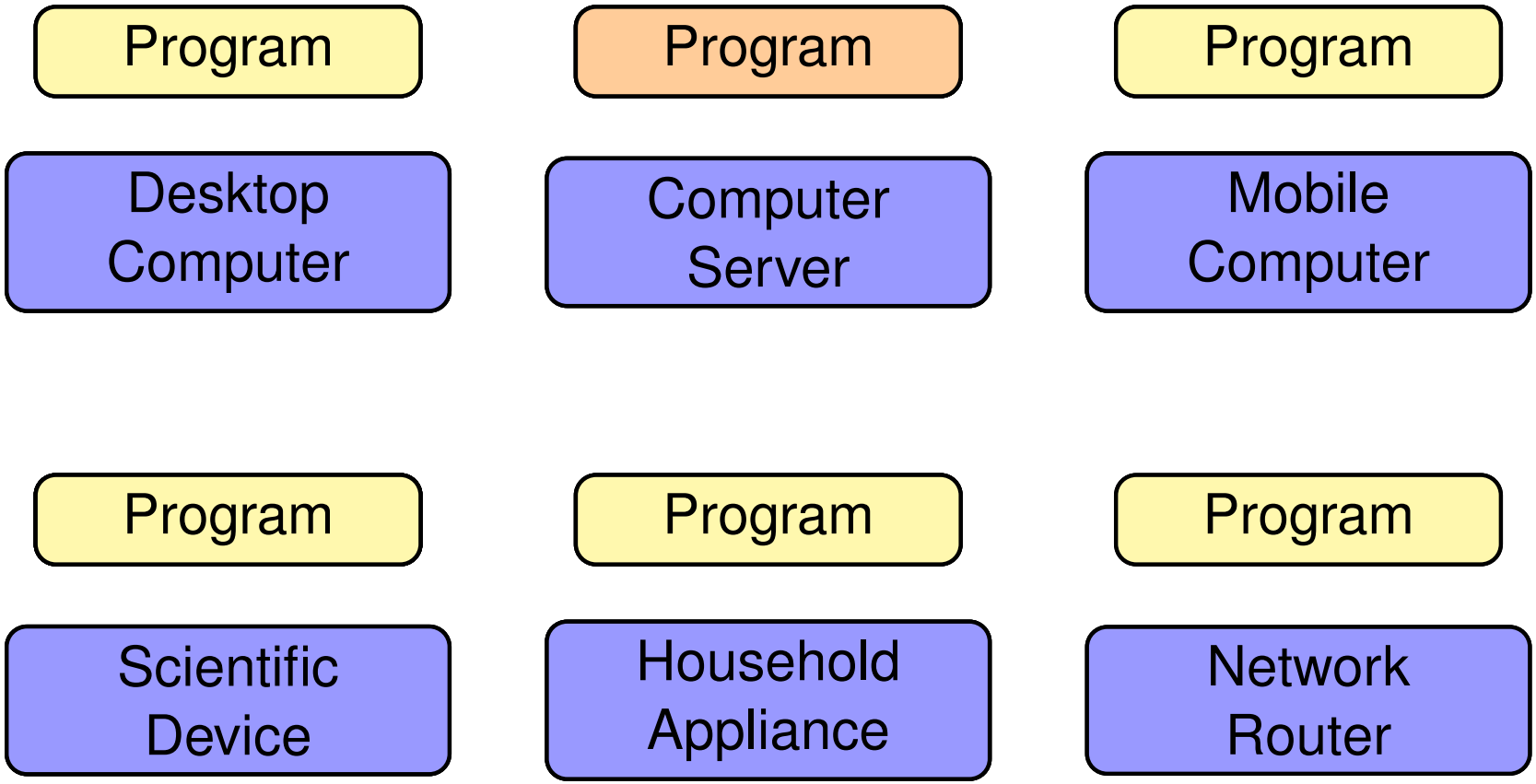

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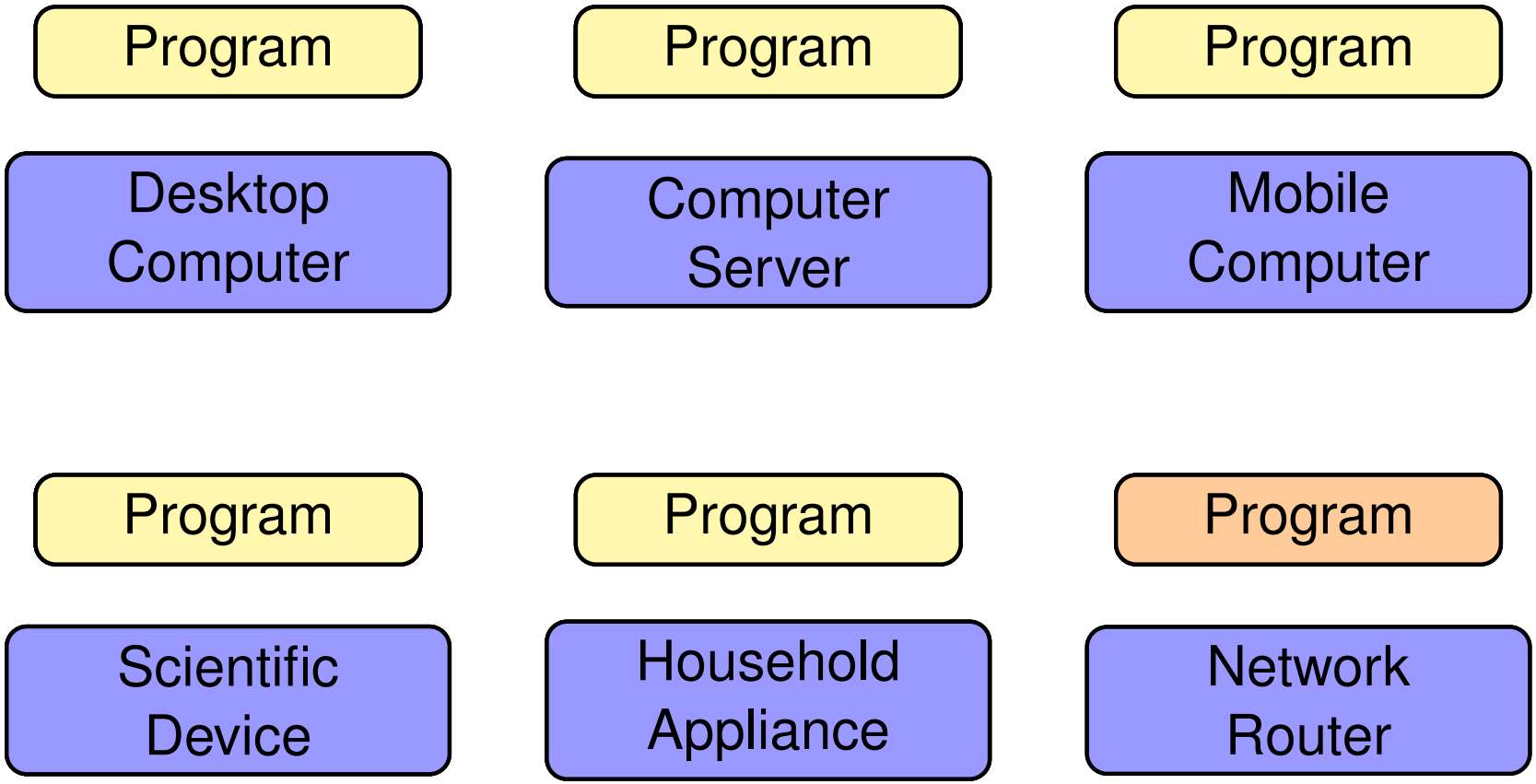

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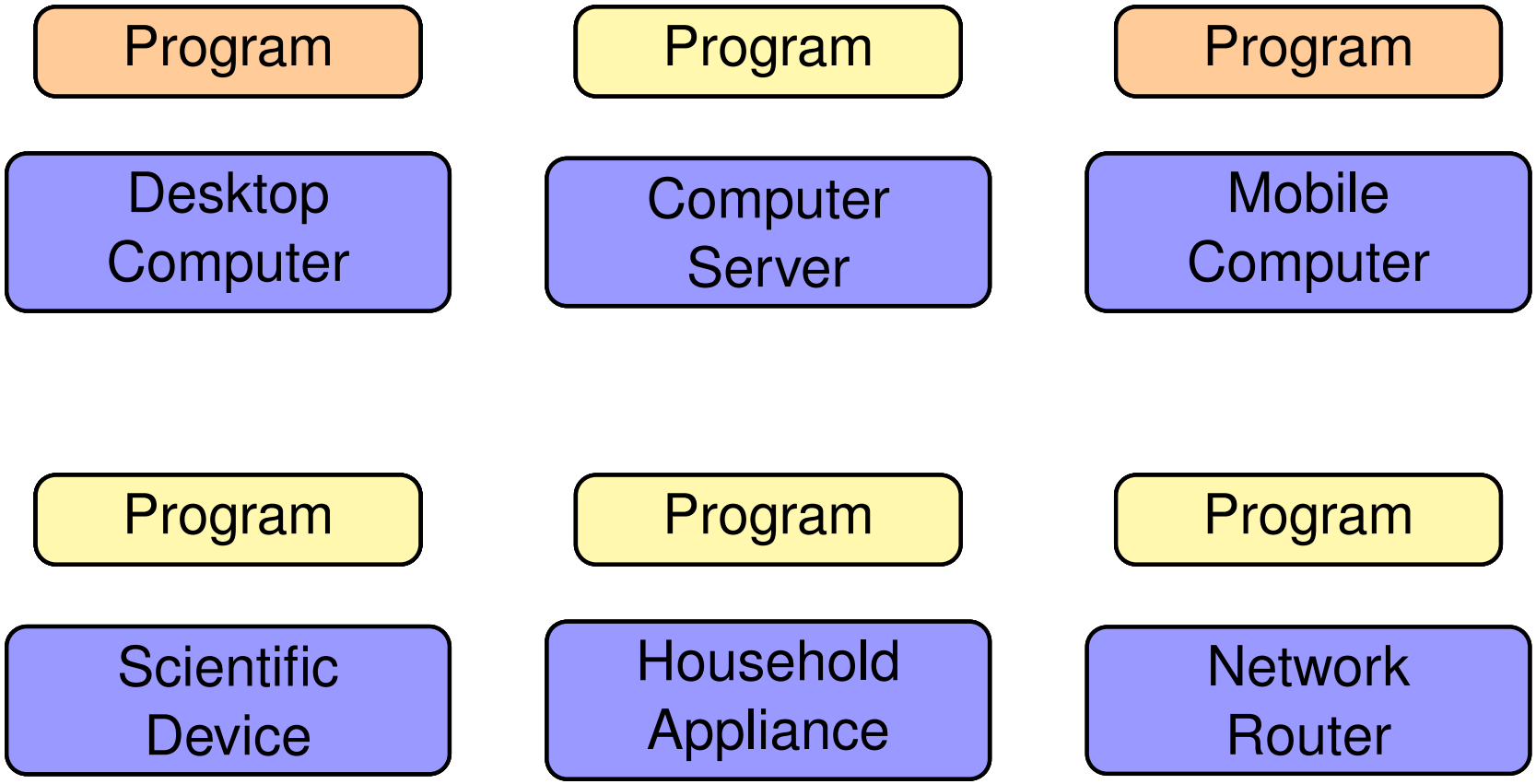

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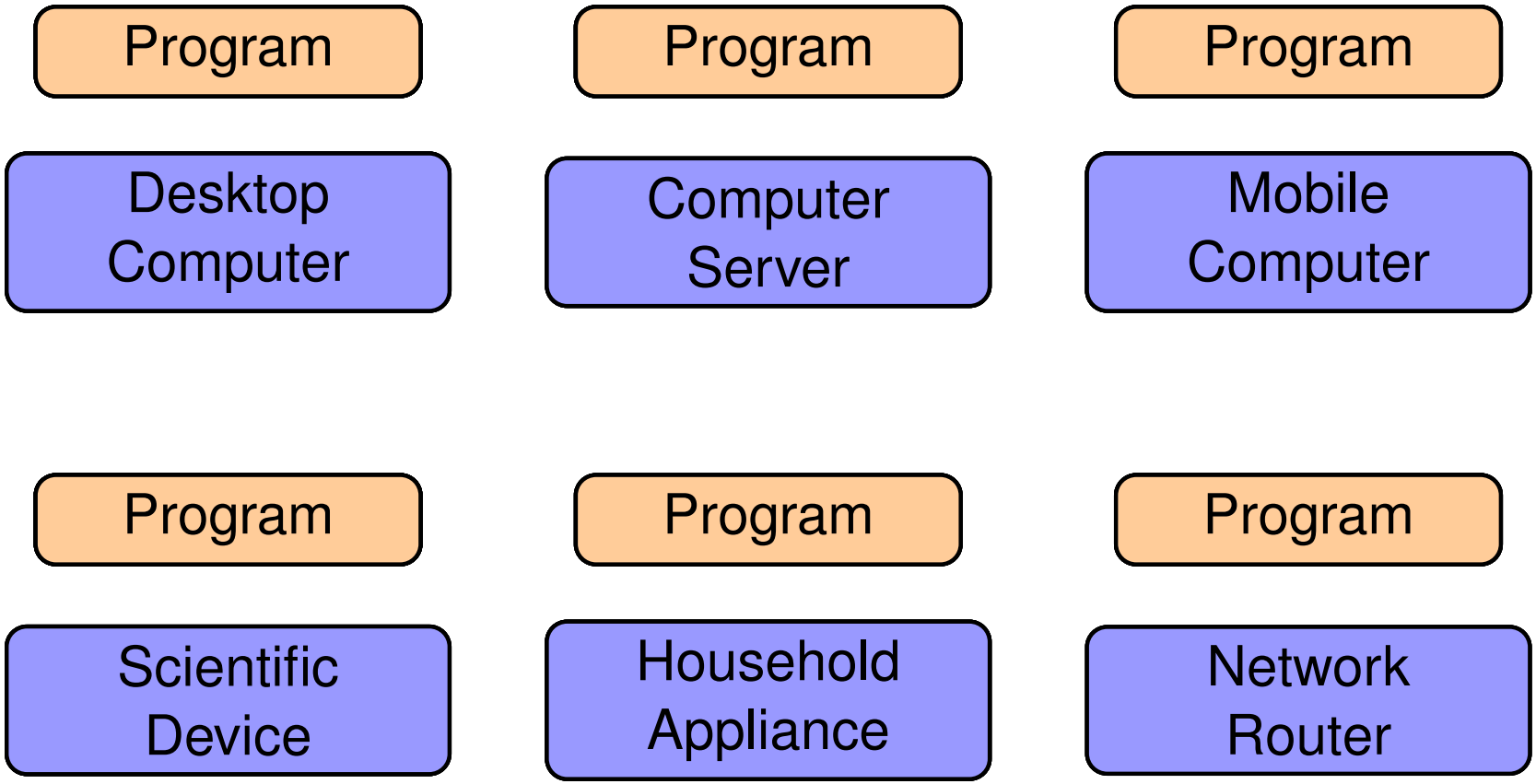
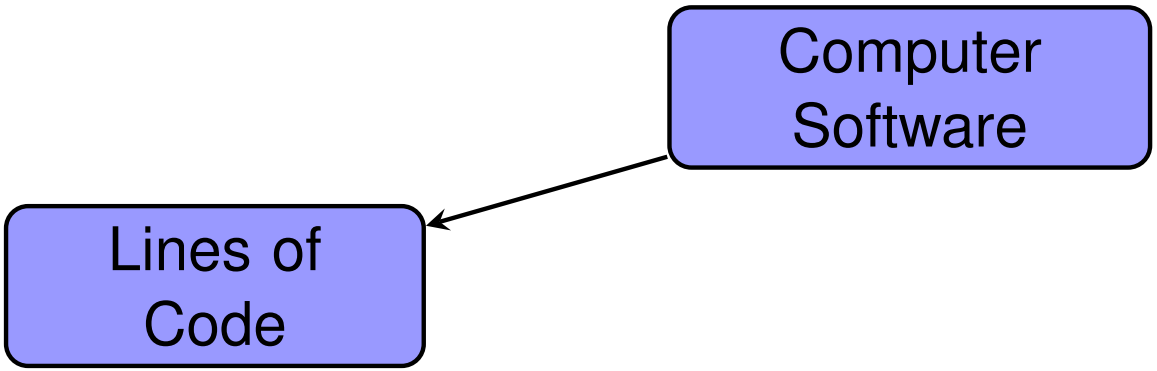


Software Complexity and Data Enormity

Computer Software

Software Complexity and Data Enormity



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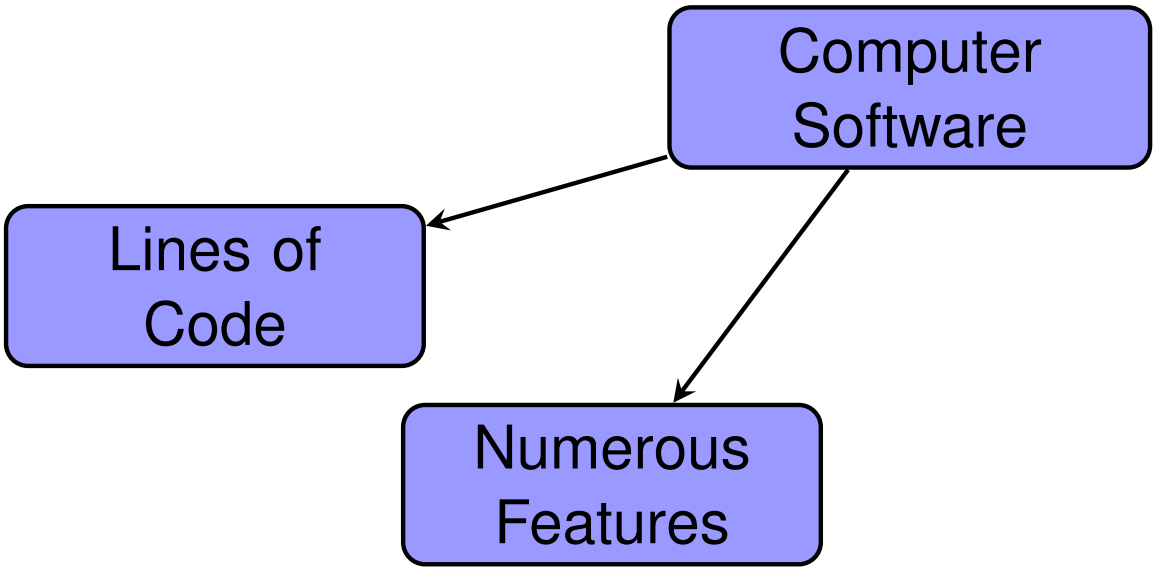

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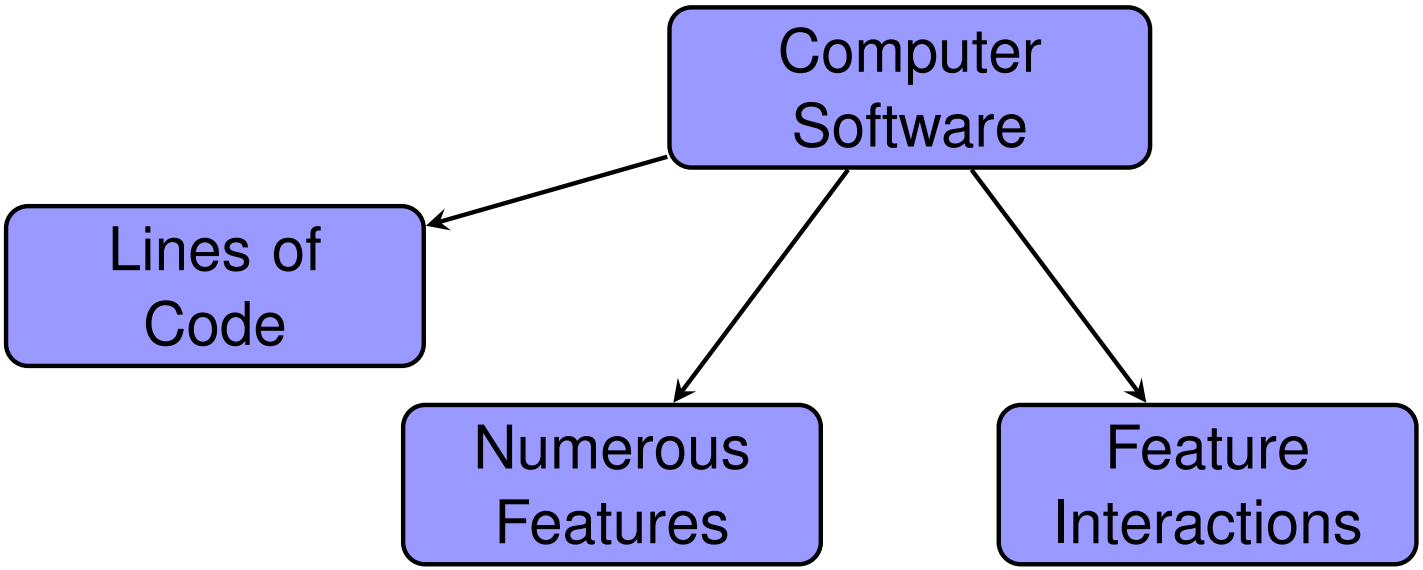

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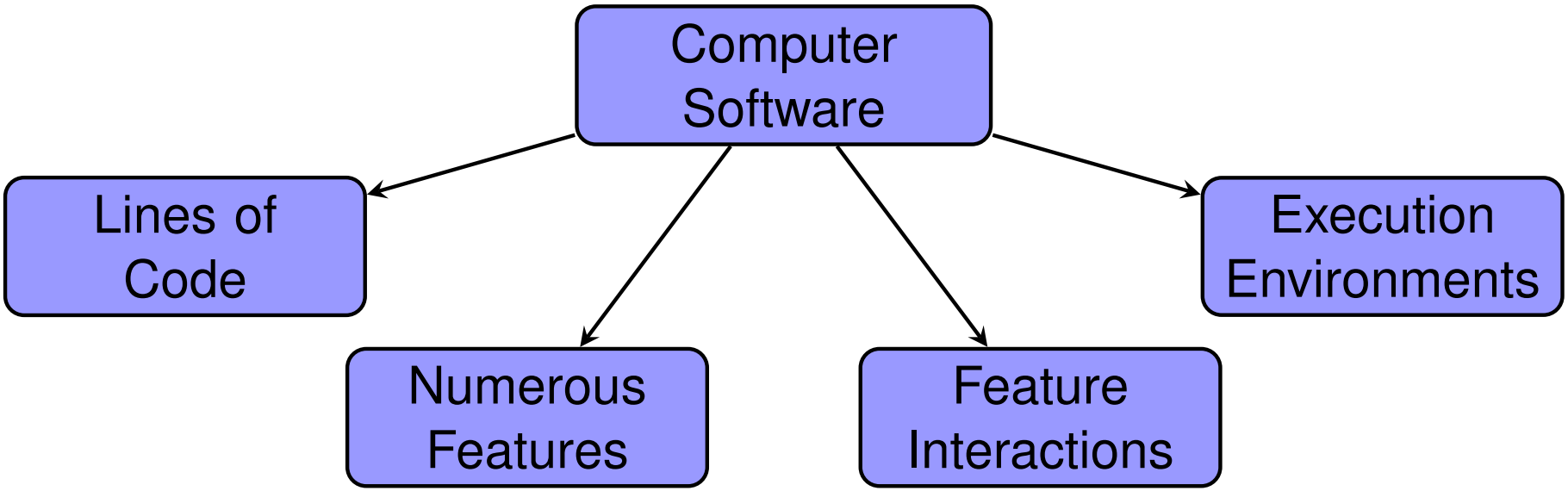
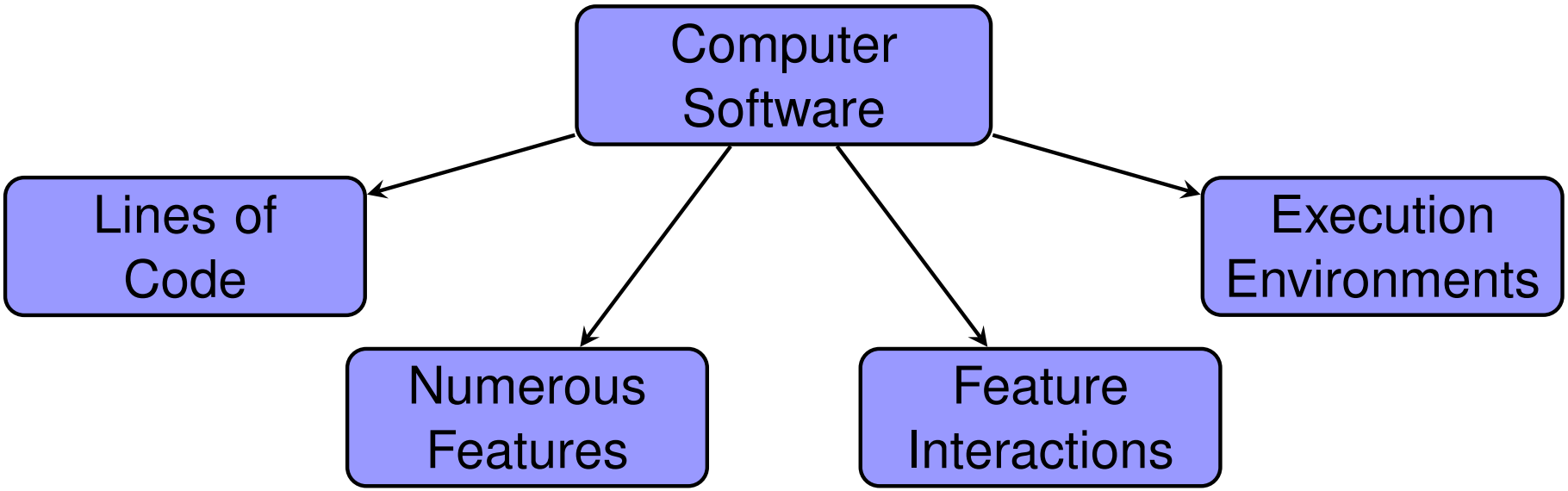


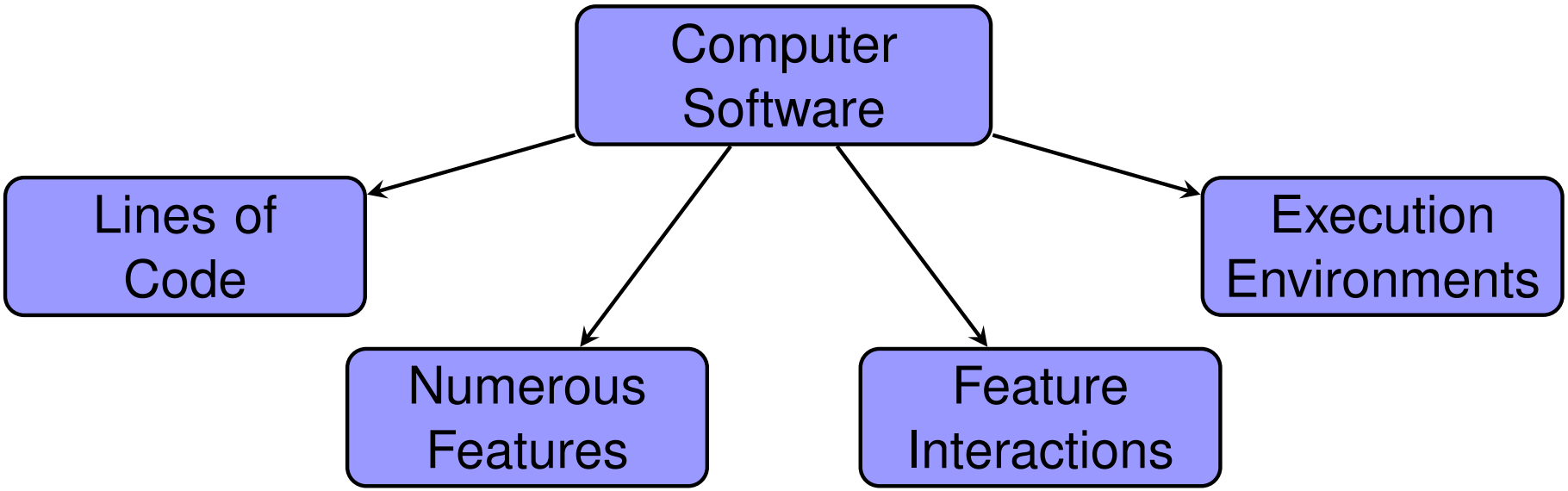
Software Complexity and Data Enormity

> Software entities are more complex for their size than perhaps any other human construct - Frederick P. Brooks, Jr.

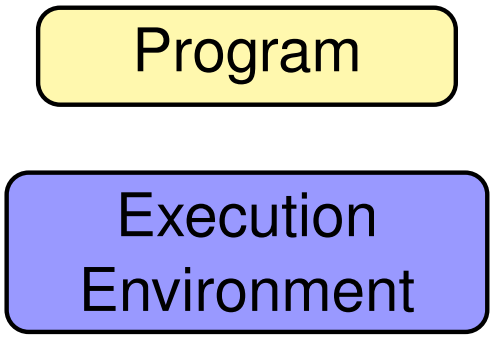


Software Complexity and Data Enormity

Prediction: in 2011, 1.8 zettabytes (i.e., 1.8 trillion gigabytes) of data will be created - IDC Digital Universe Study



Software and Data are Evolving



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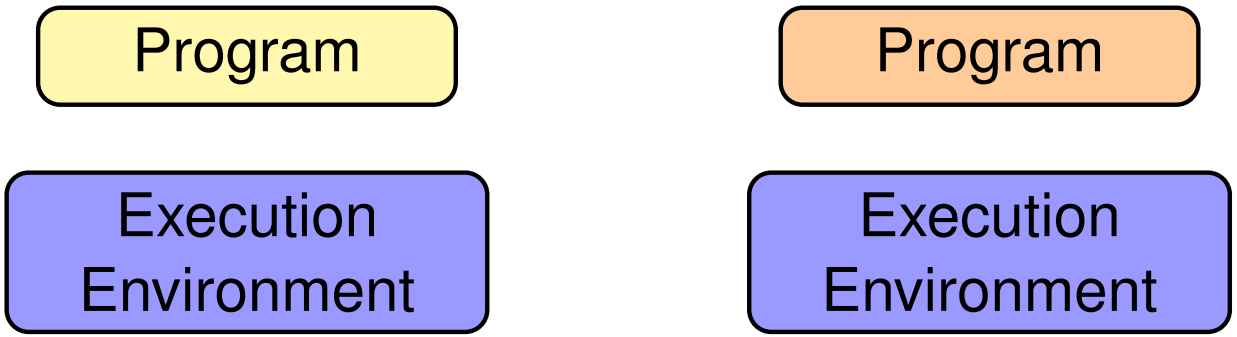

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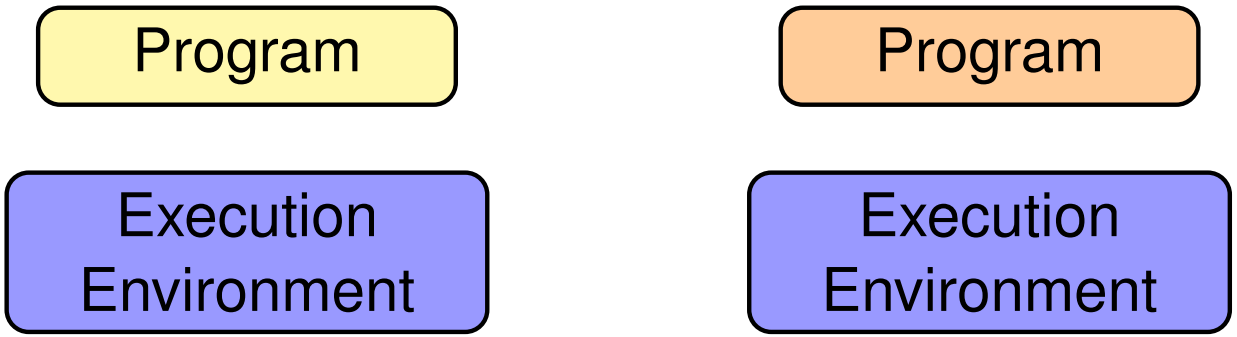
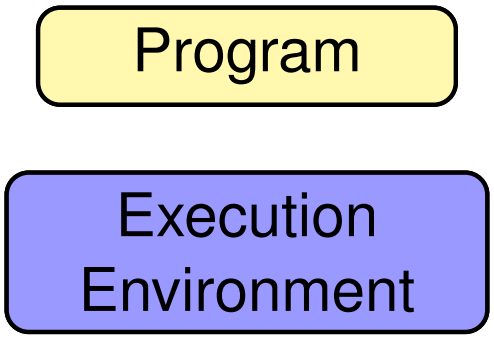


Program Changed because of the addition of a new feature or the correction of a defect

Software and Data are Evolving



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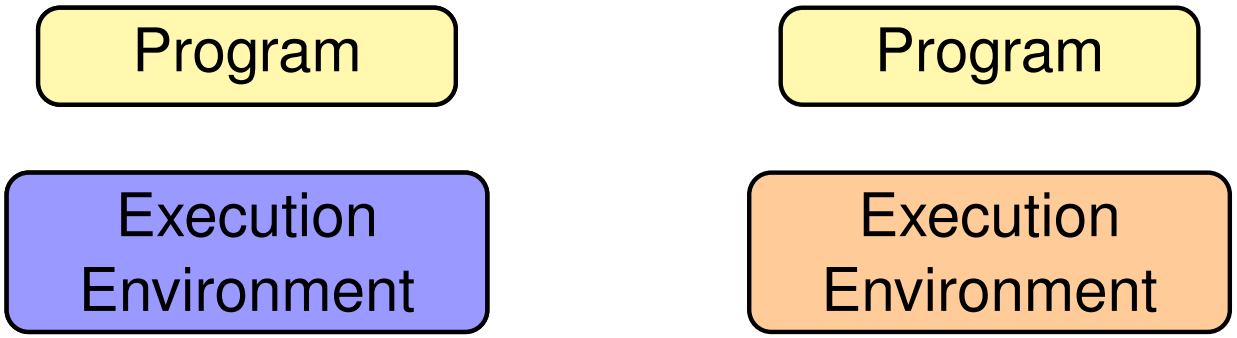

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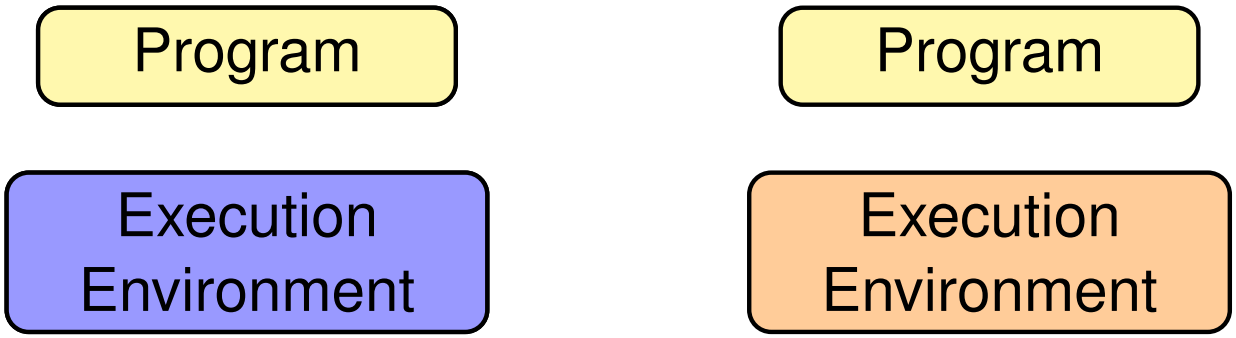

Execution Environment Changed due to modification of a kernel, device driver, or relational database

An Interesting Defect Report

Database
Server Crashes

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Server Crashes

When you run a complex query against Microsoft SQL Server 2000, the SQL Server scheduler may stop responding. Additionally, you receive an error message that resembles the following: **Date Time server Error: 17883 Severity: 1, State: 0 Date Time server Process 52:0 (94c) ...**

An Interesting Defect Report

Input-Dependent Defect

An Interesting Defect Report

Input-Dependent Defect

This problem occurs when one or more of the following conditions are true: The query contains a `UNION` clause or a `UNIONALL` clause that affects many columns. The query contains several `JOIN` statements. The query has a large estimated cost. **BUG 473858 (SQL Server 8.0)**

Real-World Defective Database Application

The Risks Digest, Volume 22, Issue 64, 2003

Jeppesen reports airspace boundary problems

About 350 airspace boundaries contained in Jeppesen NavData are incorrect, the FAA has warned. The error occurred at Jeppesen after a software upgrade when information was pulled from a database containing 20,000 airspace boundaries worldwide for the March NavData update, which takes effect March 20.

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Practically all use of databases occurs from within application programs [Silberschatz et al., 2006, pg. 311]

Structured Query Language

The *structured query language* (SQL) is an established standard and a query and manipulation language for *relational database management systems* (RDBMS)

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A *schema* is a collection of table definitions:

```
CREATE TABLE person (
id INT,
name VARCHAR(100) NOT NULL,
age INT(3),
PRIMARY KEY (id)
)
```

Structured Query Language

The *structured query language* (SQL) is an established standard and a query and manipulation language for *relational database management systems* (RDBMS)

The *data manipulation language* supports several operations:

```
SELECT name FROM person WHERE age >= 30 AND age <= 40
```

Structured Query Language

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The *data manipulation language* supports several operations:

```
UPDATE person SET name = Jan WHERE id = 2
```

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The *data manipulation language* supports several operations:

```
INSERT INTO person (id, name, age) VALUES
                   (1, John, 38)
```

Structured Query Language

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The *data manipulation language* supports several operations:

```
DELETE FROM person WHERE id = 2
```

Relational Database Tables

id	name	age
1	Chalker Conrad	12
2	Abby Clulow	14
3	David Rogan	18
4	Stacie Reckling	32
5	Megan Hartnup	29

Relational Database Tables

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Database Applications

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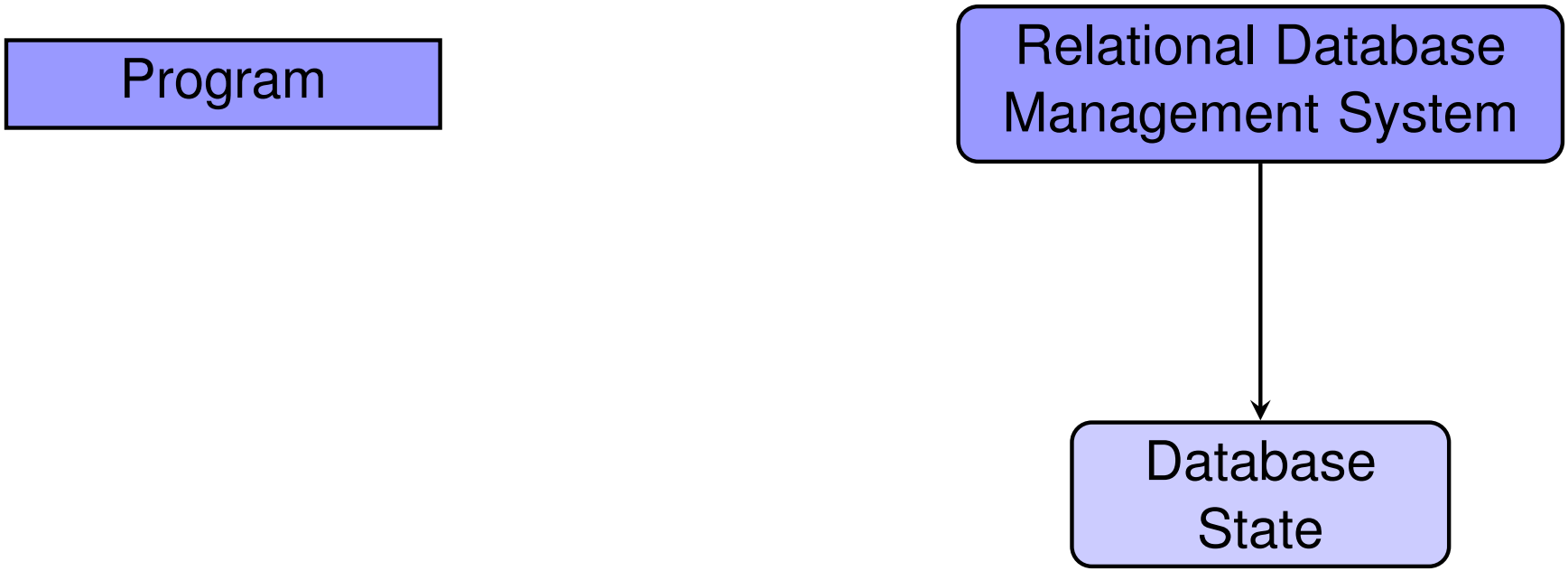

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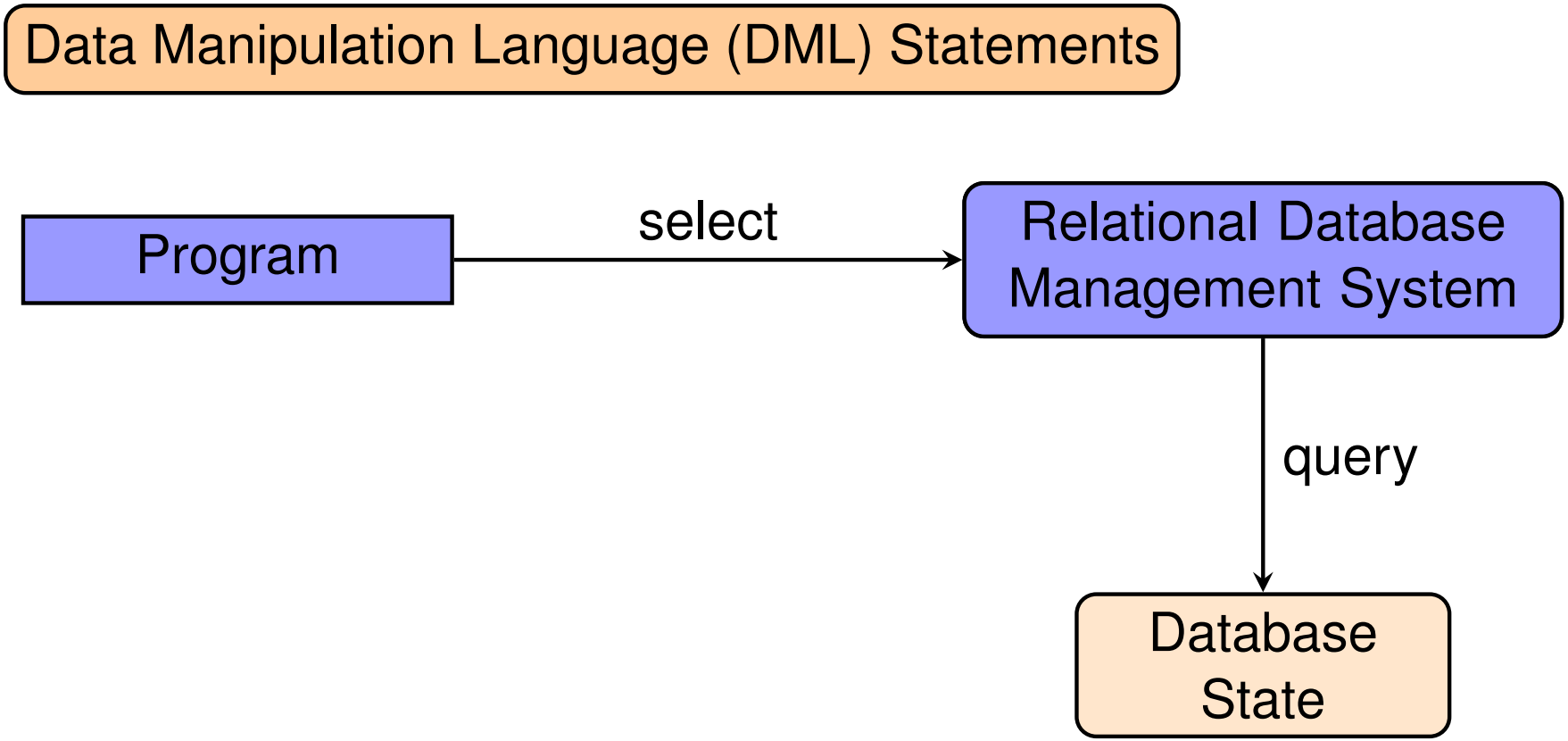

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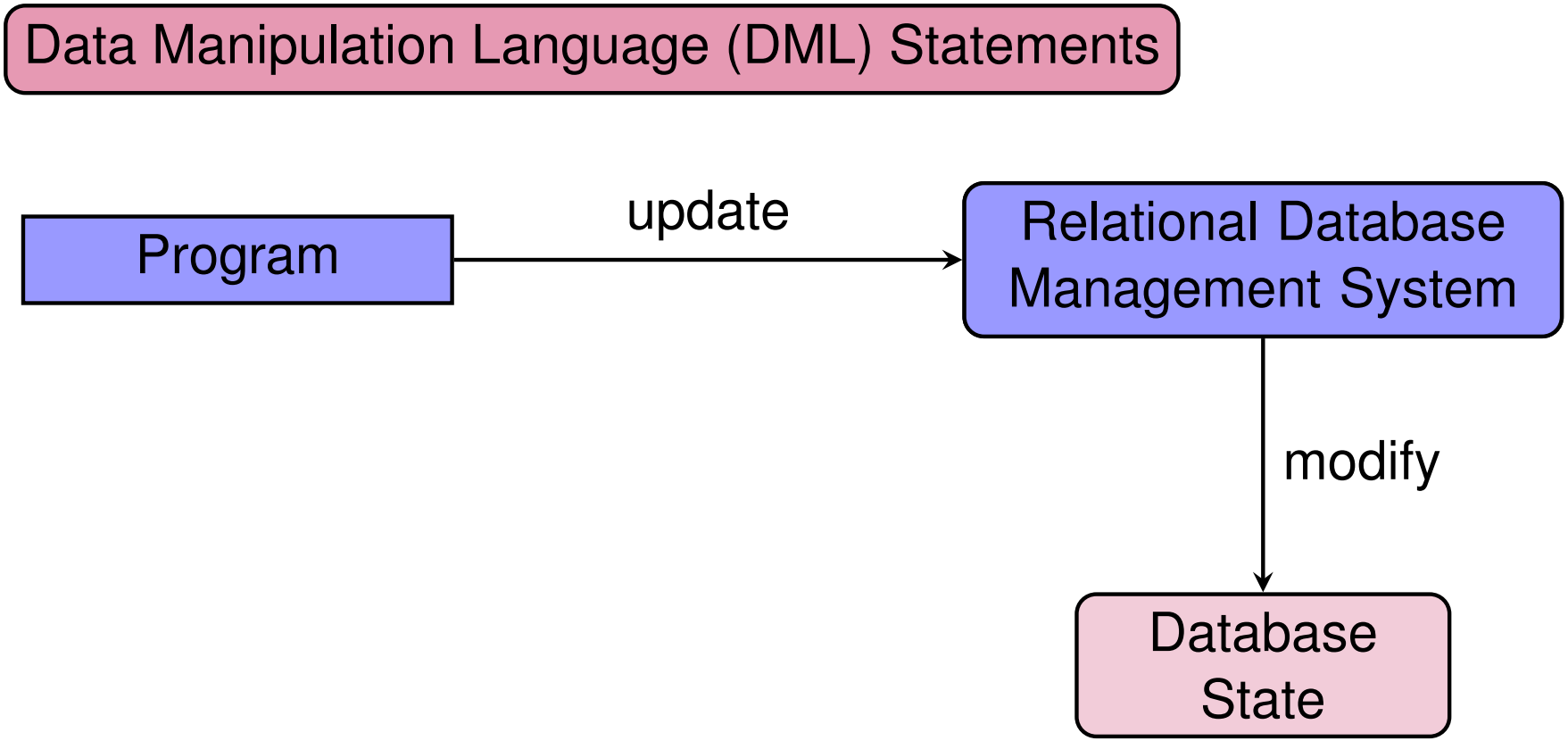

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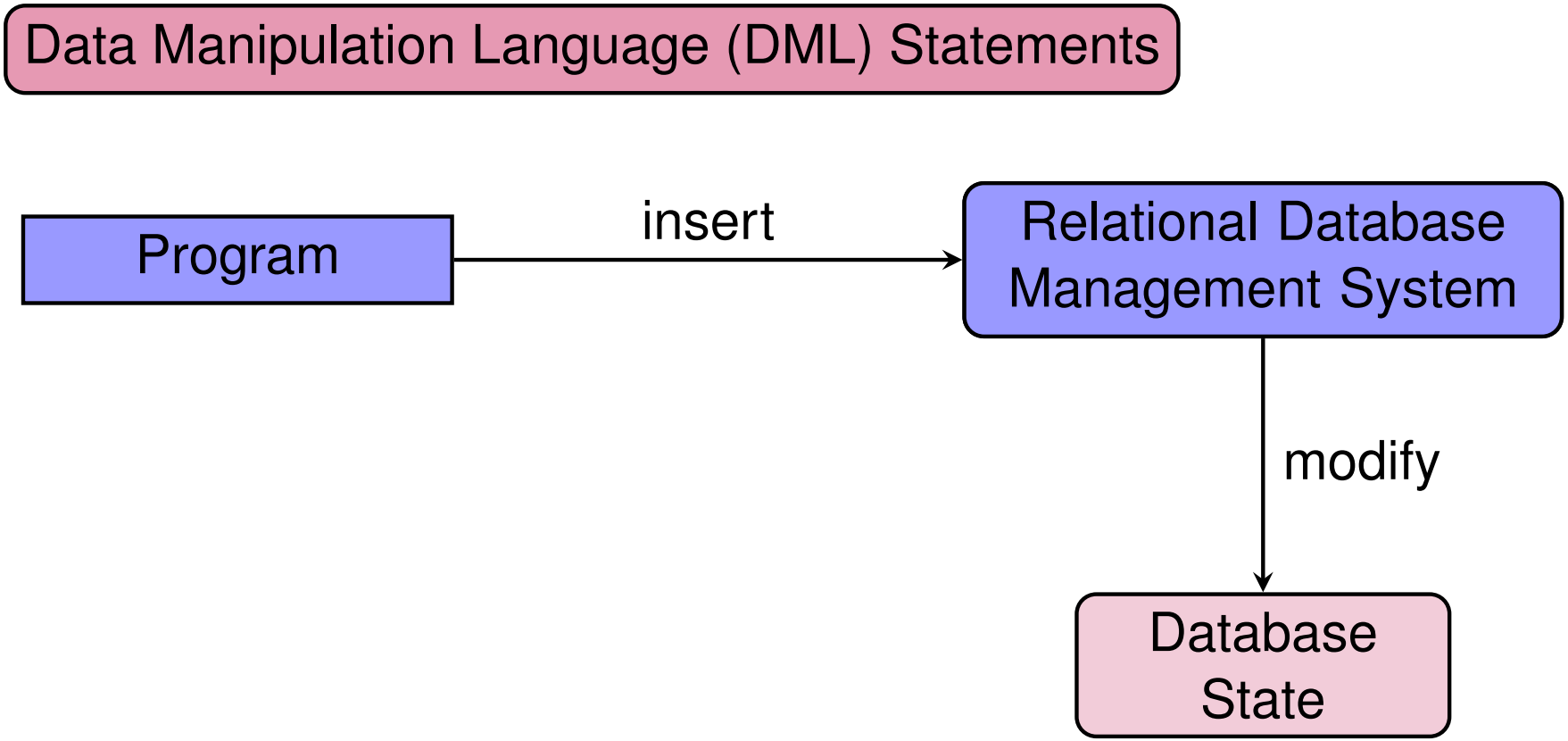

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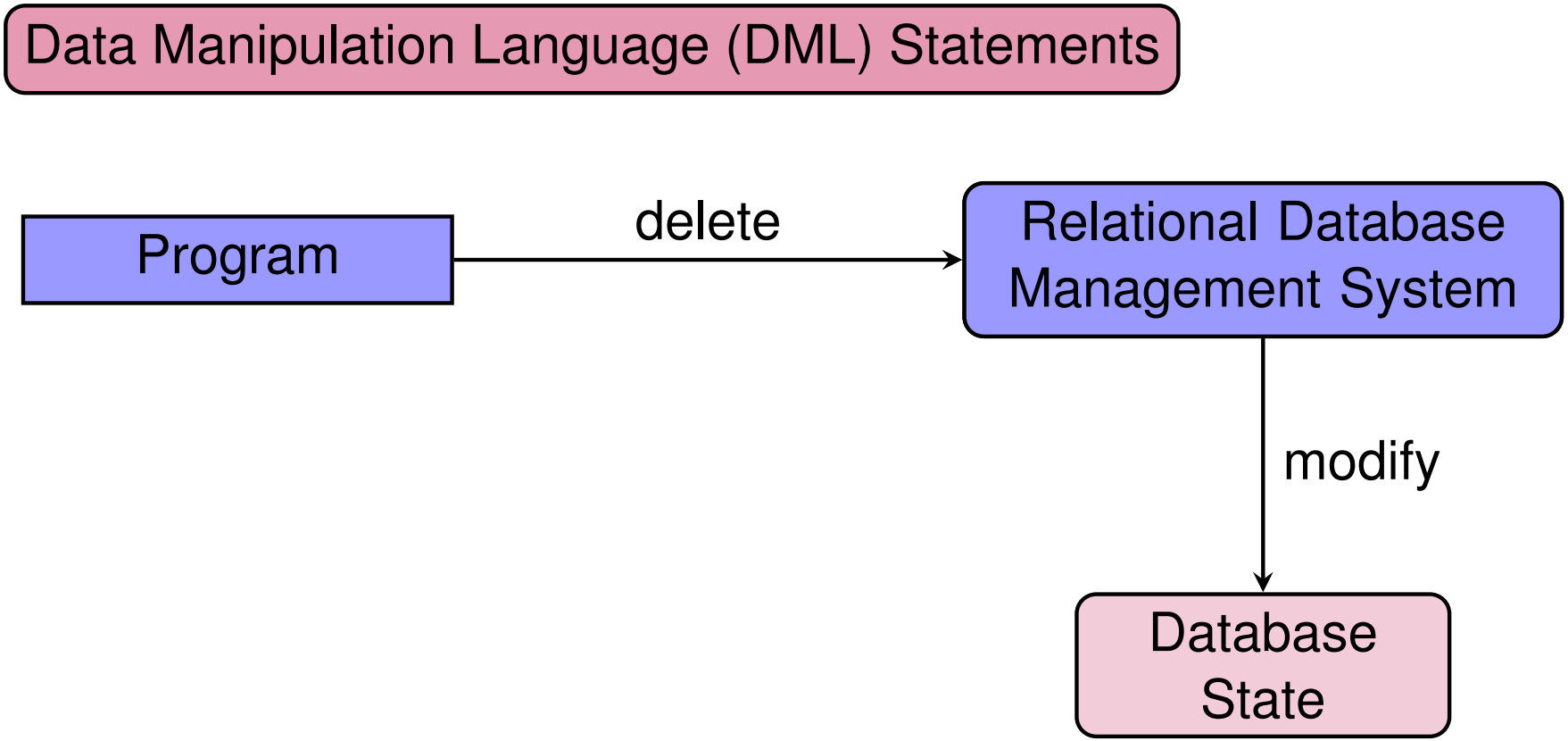

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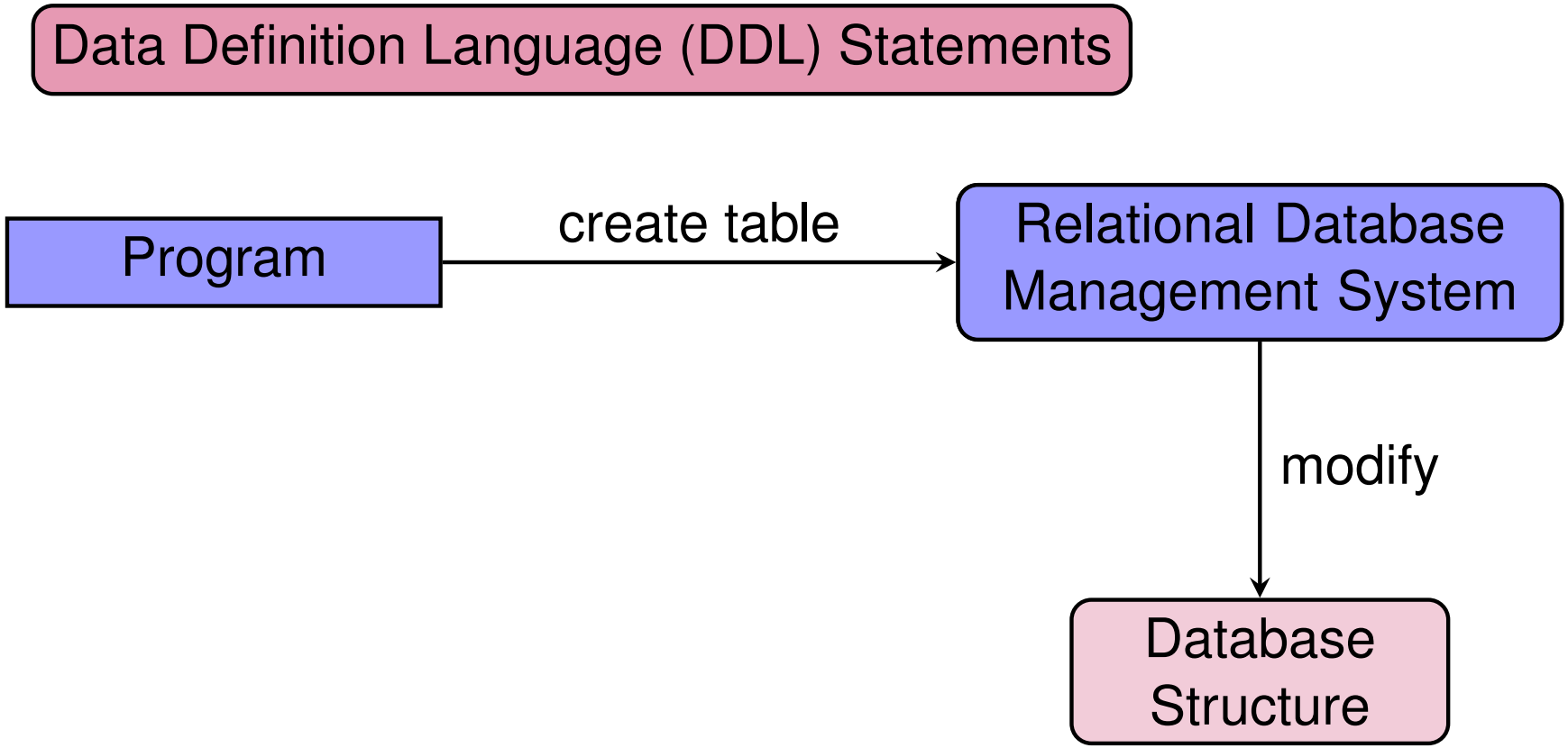

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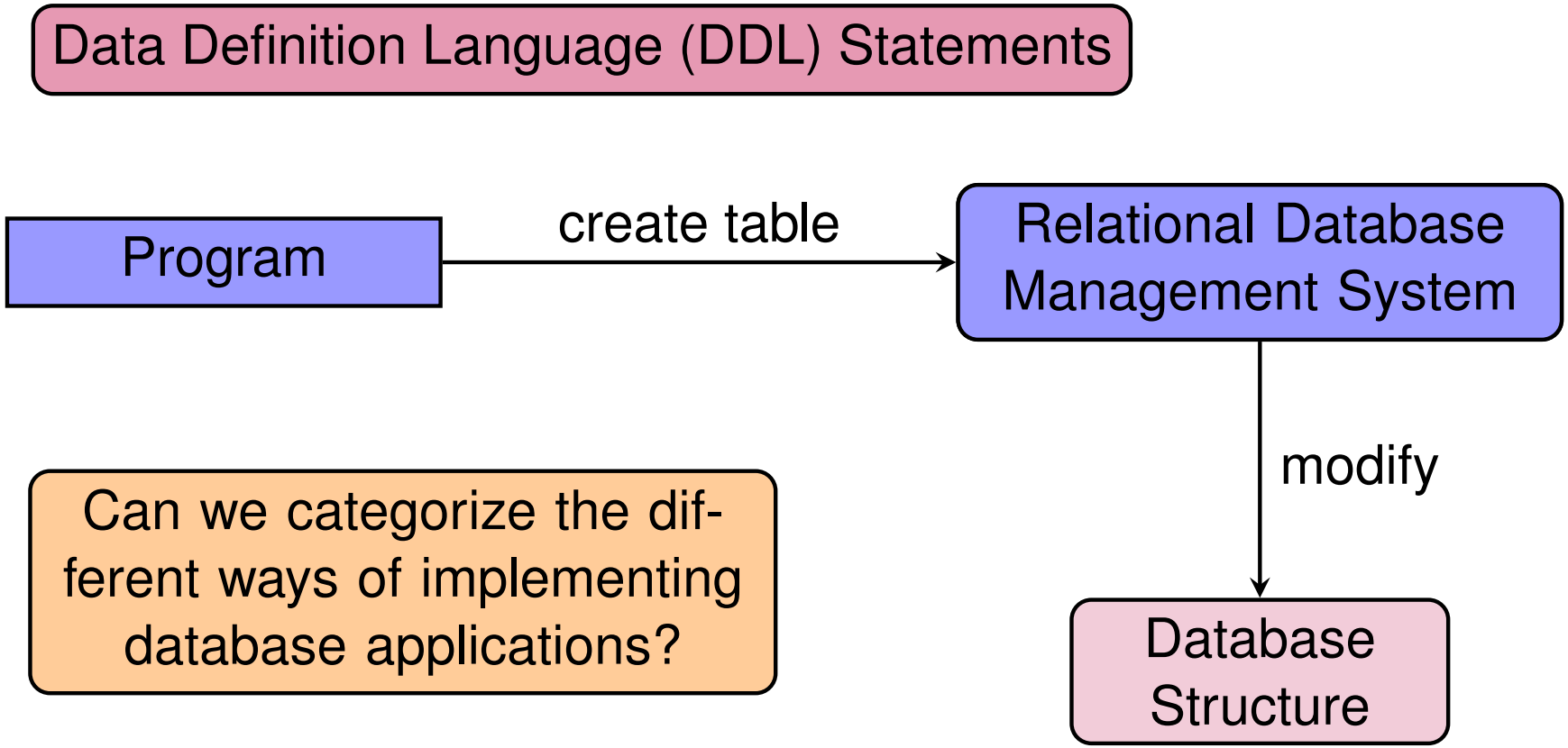

Categorizing Database Applications

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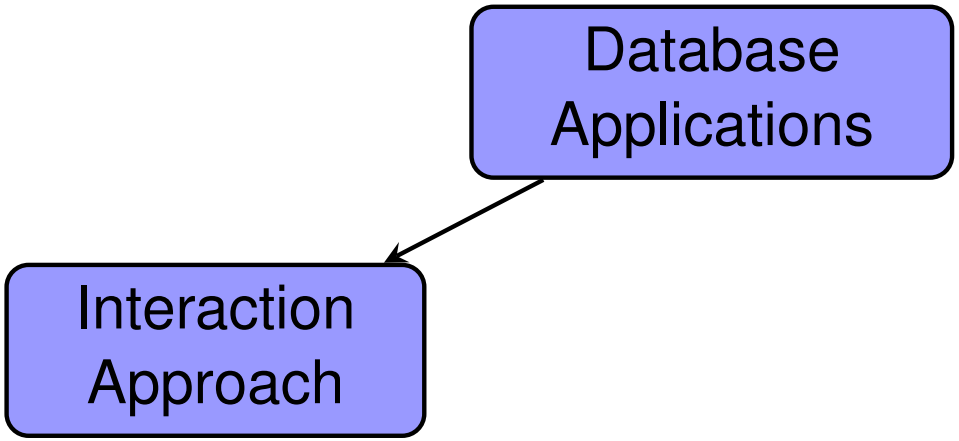

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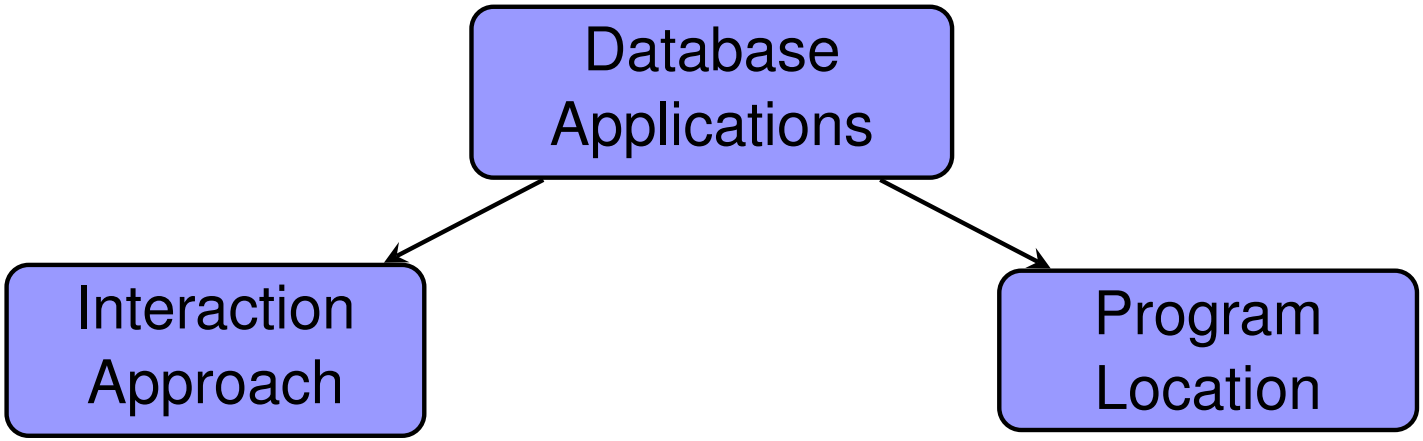

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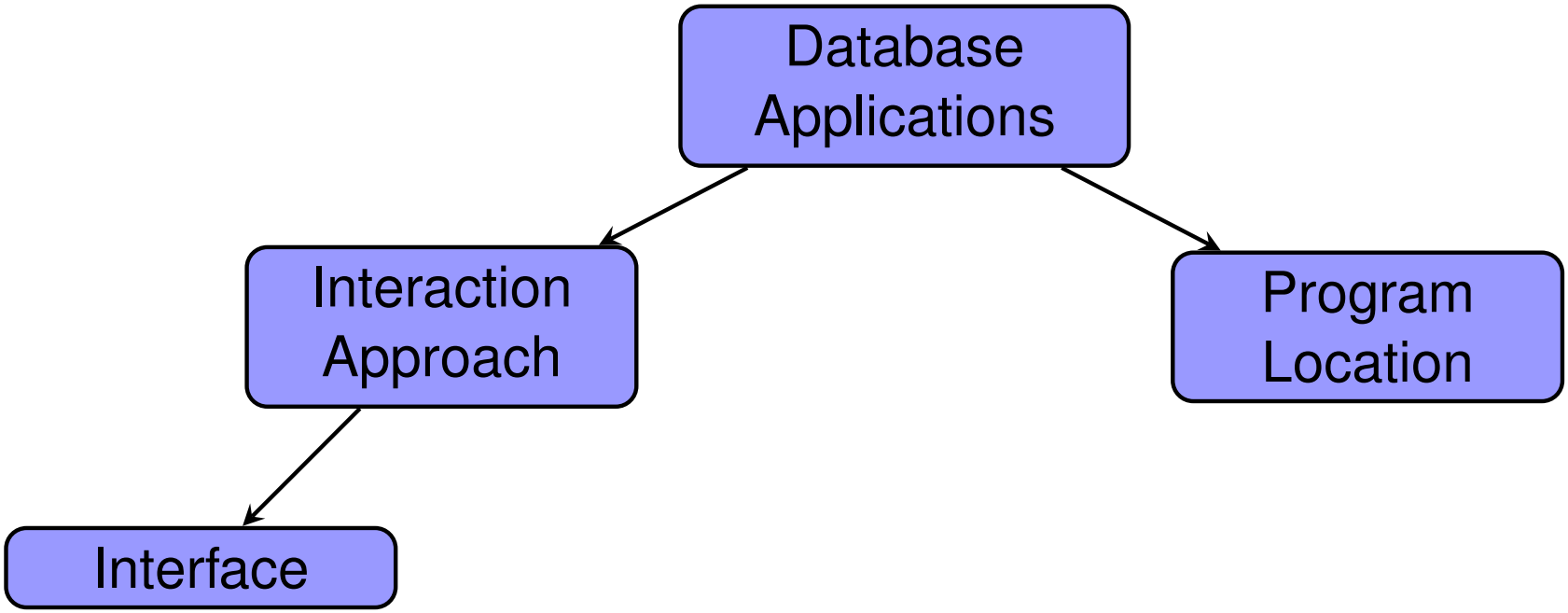

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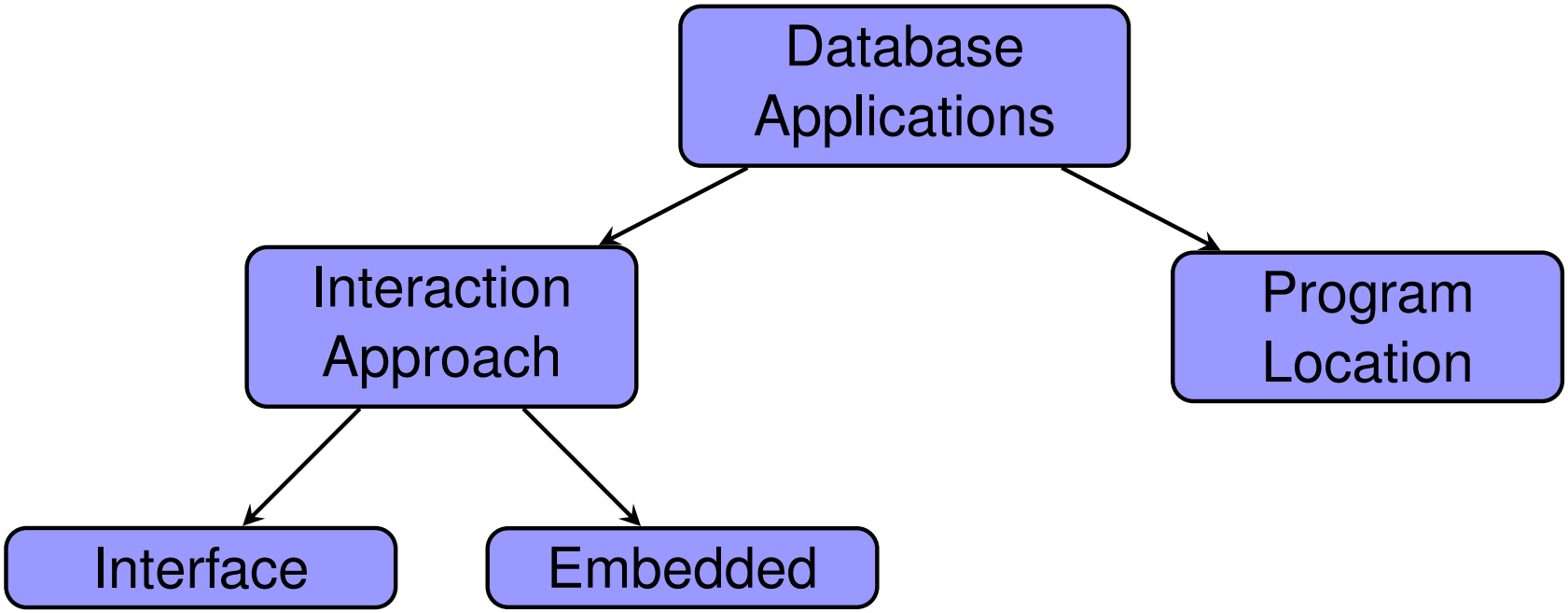

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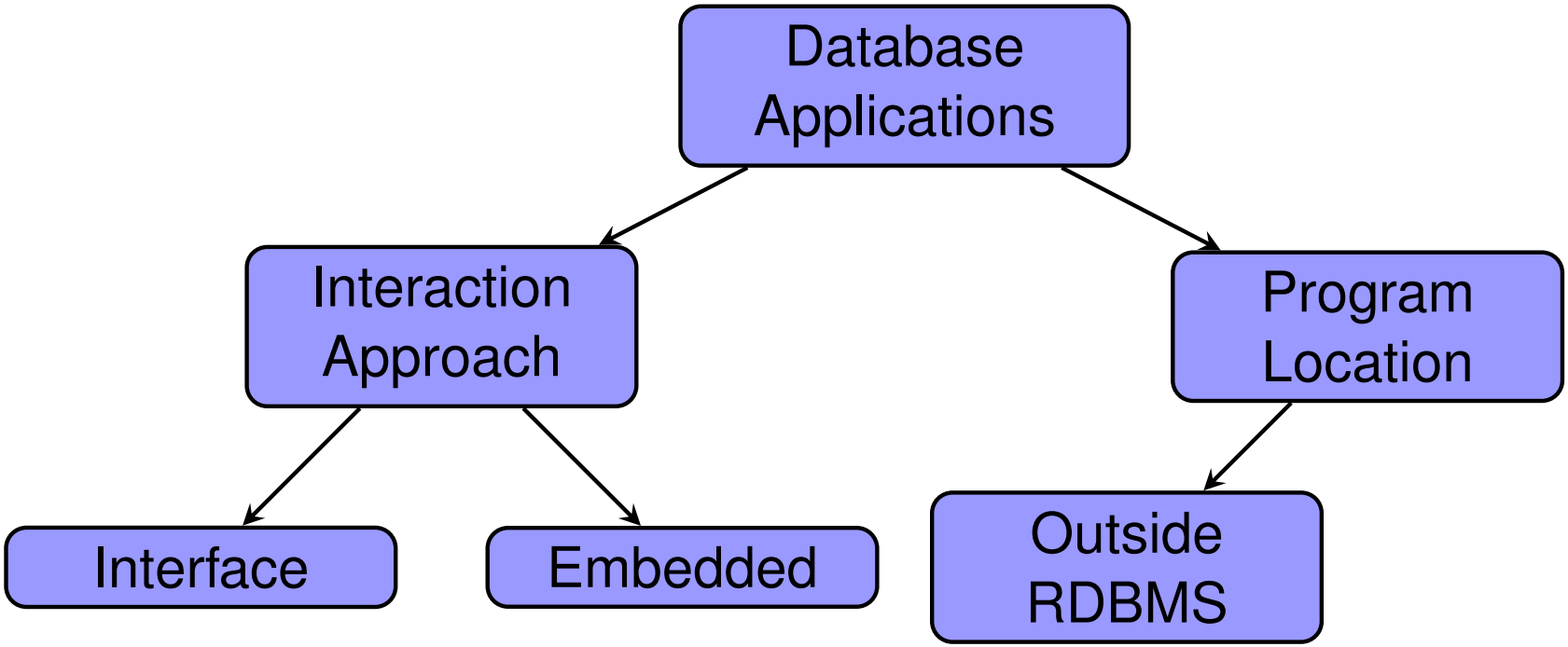

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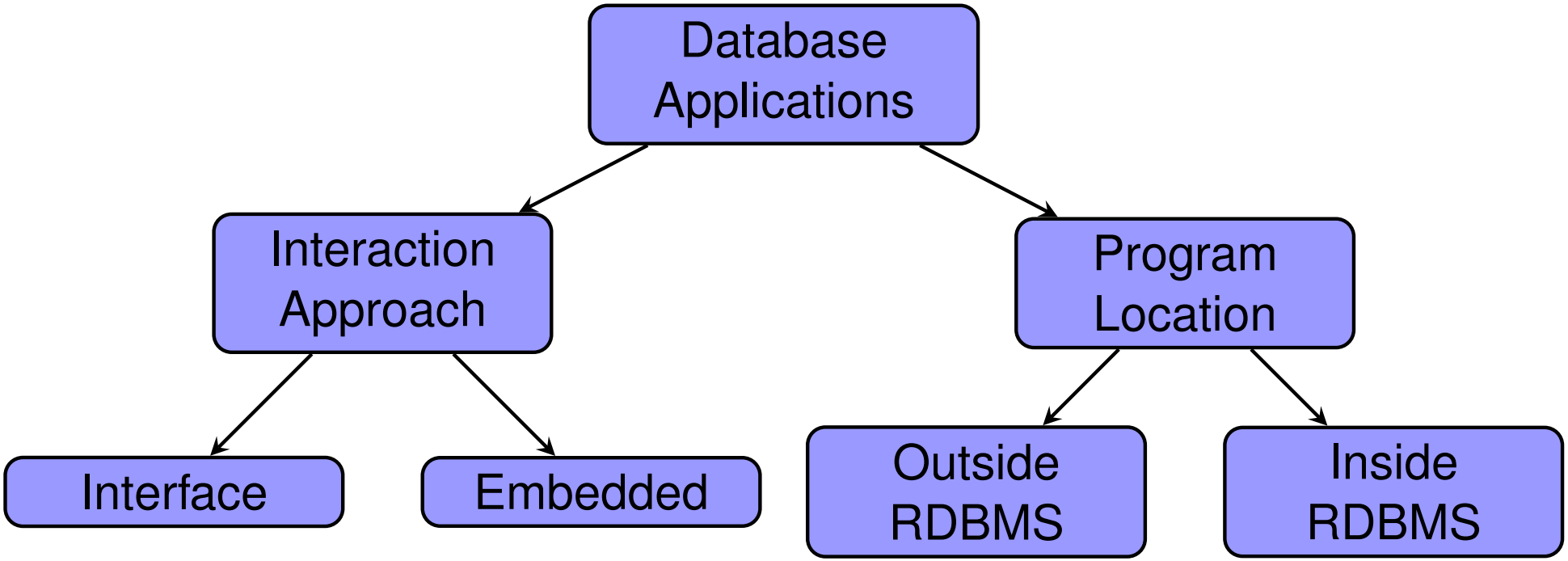

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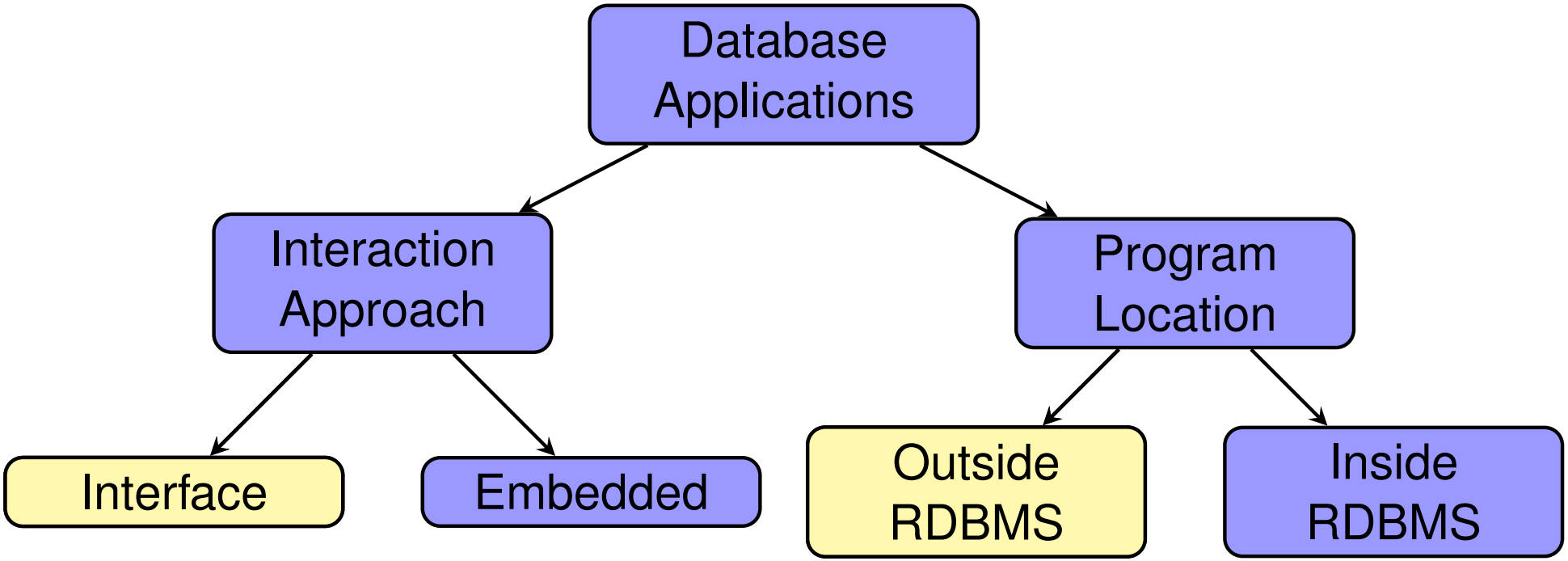

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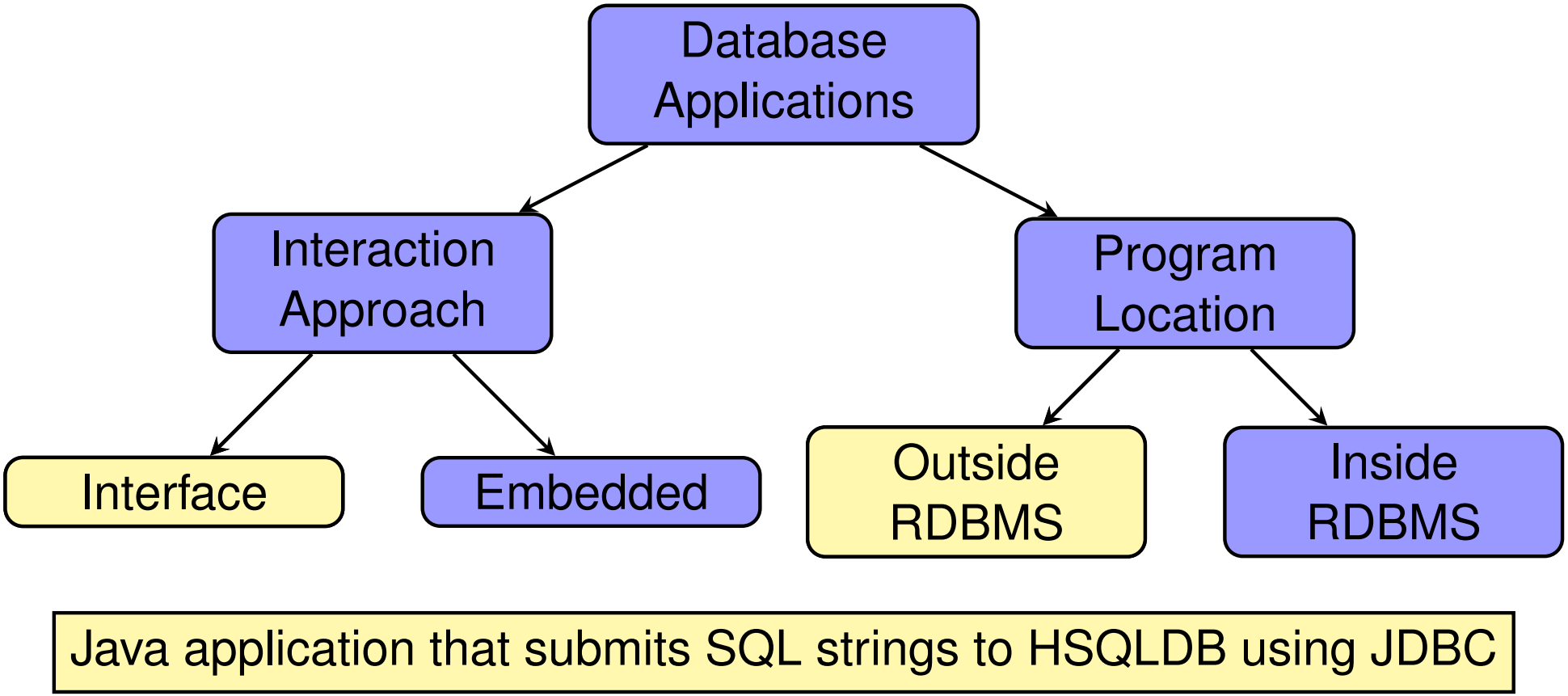
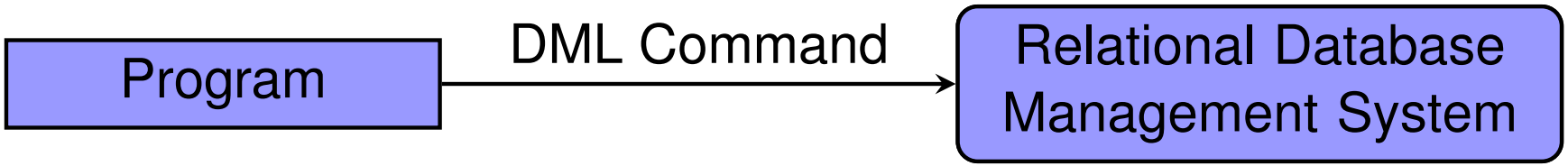


Java application that submits SQL strings to HSQLDB using JDBC

Evolution of Database Applications



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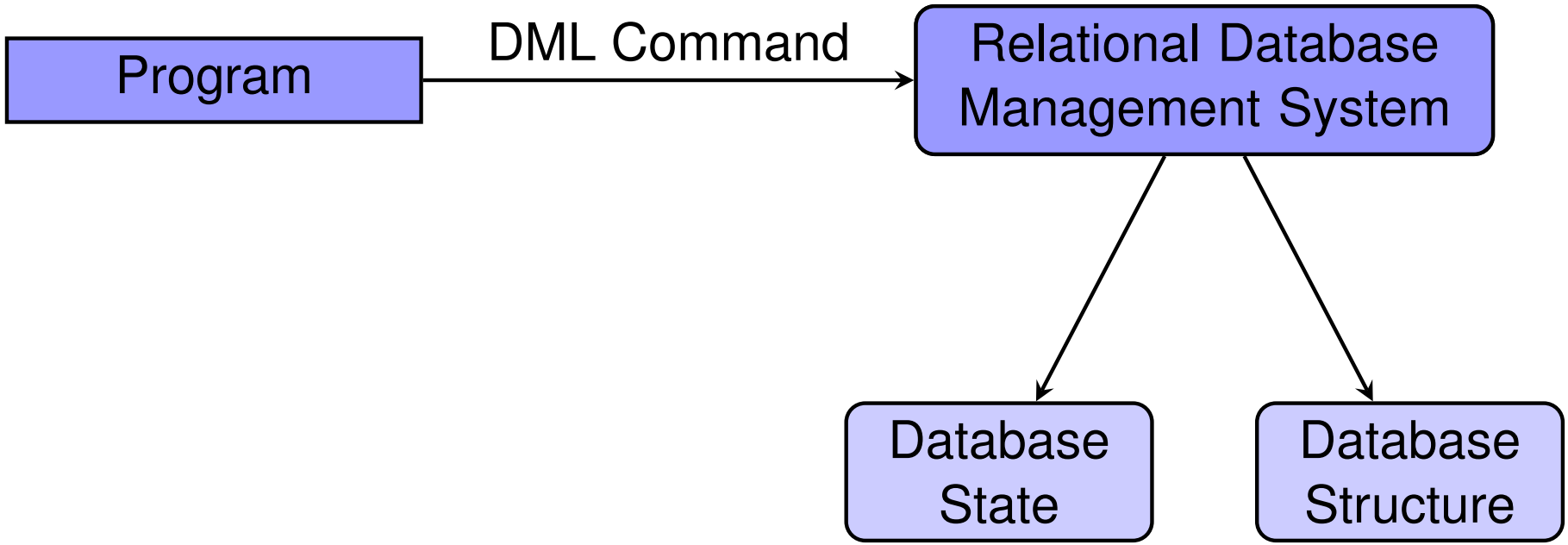
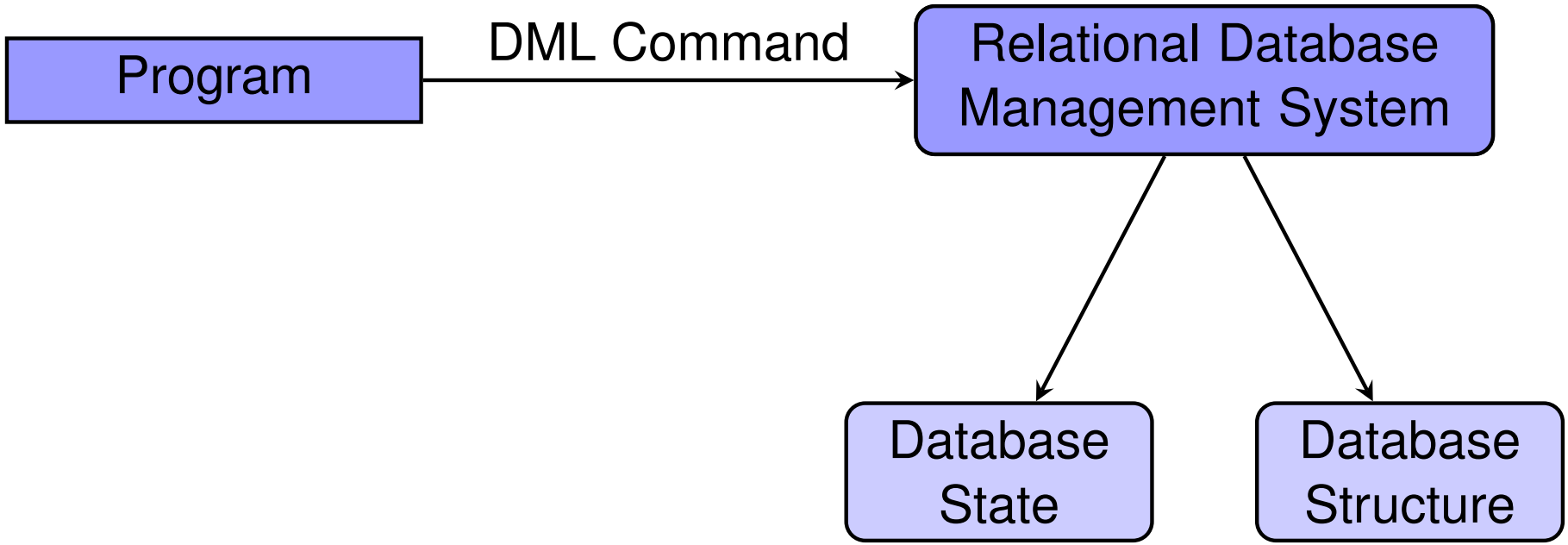


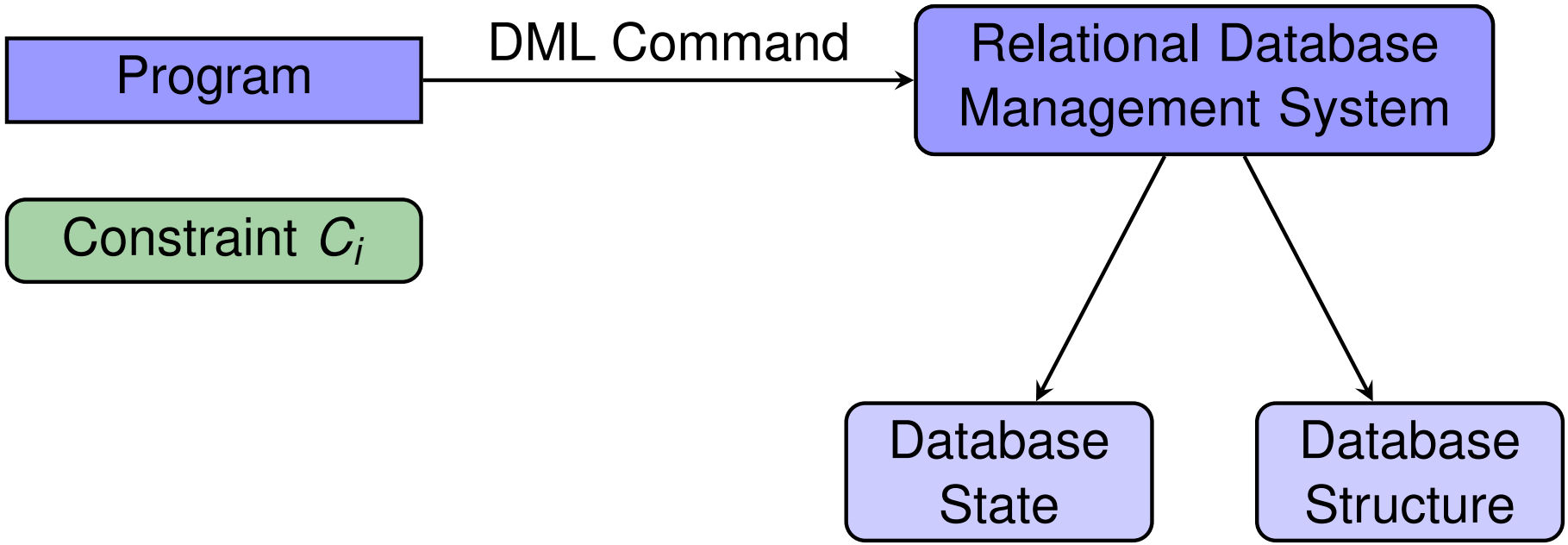
Evolution of Database Applications

Only the database administrator can add new constraints to the schema!



Evolution of Database Applications

The programmers encode the constraints in the program's source code!



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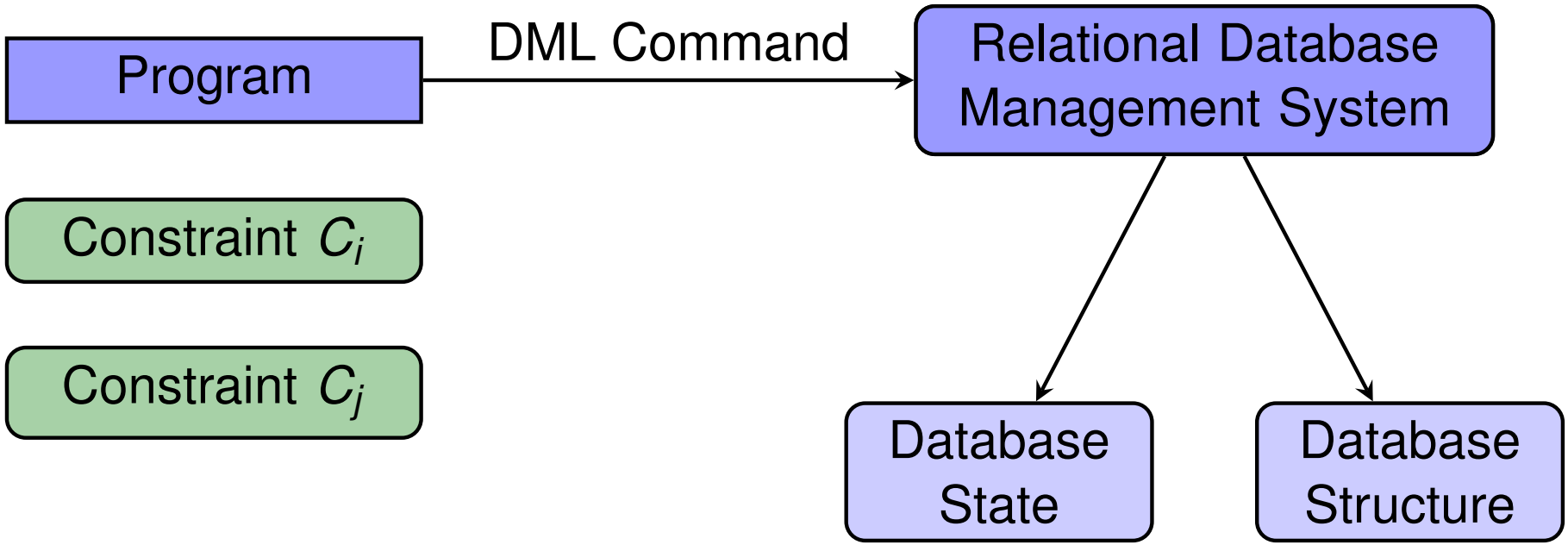

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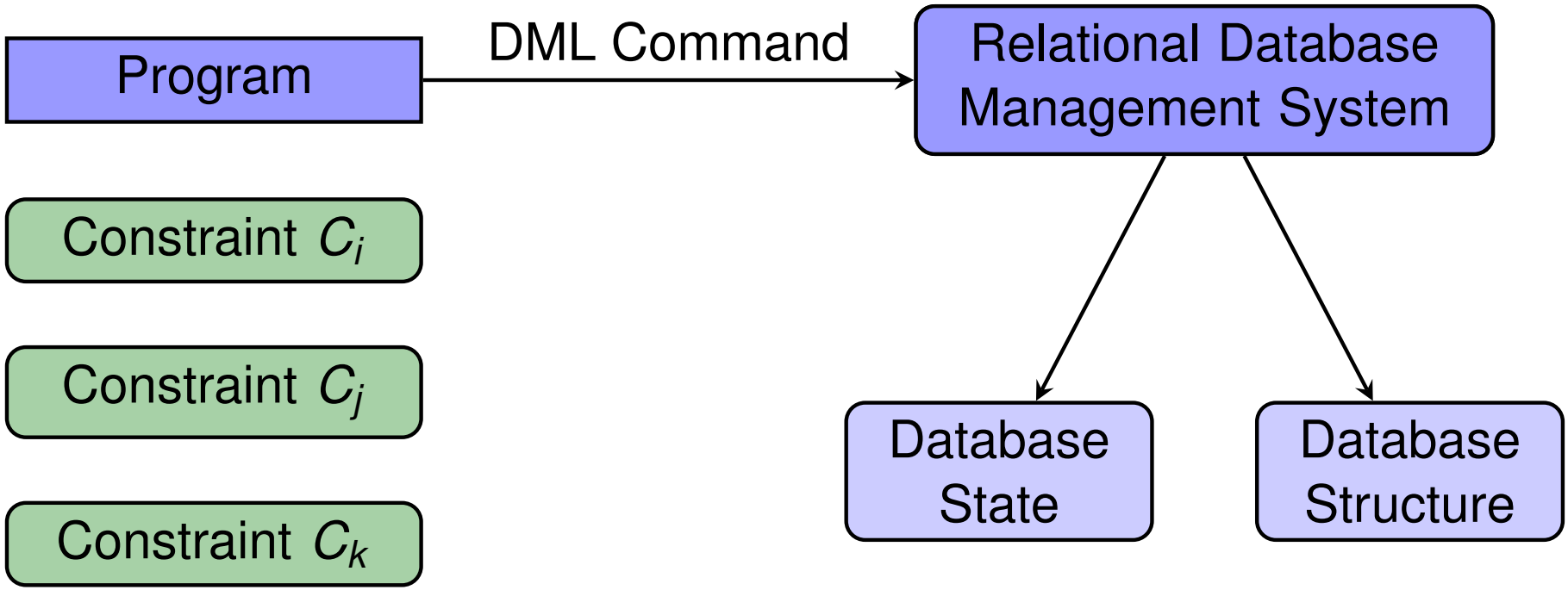

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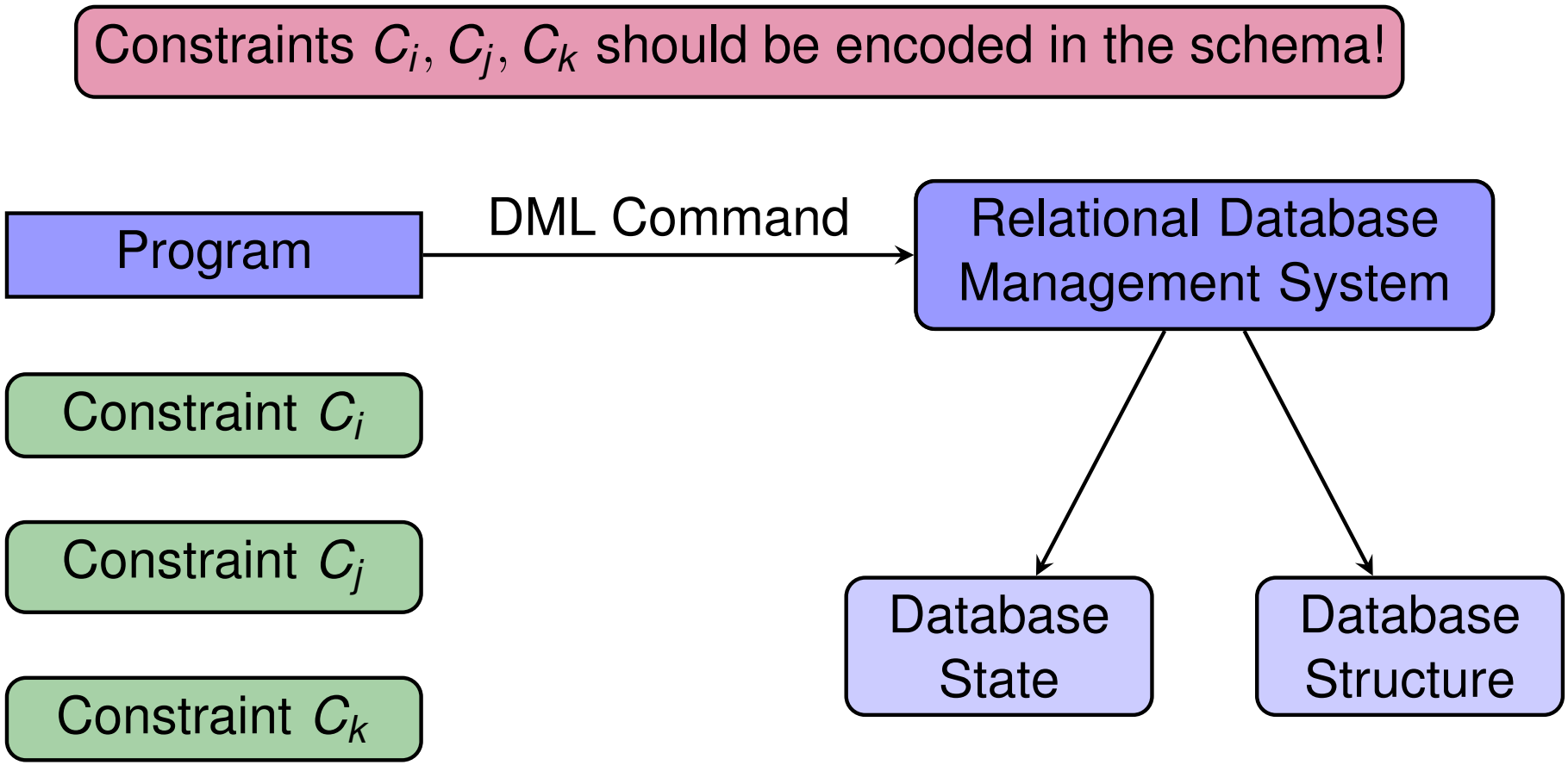
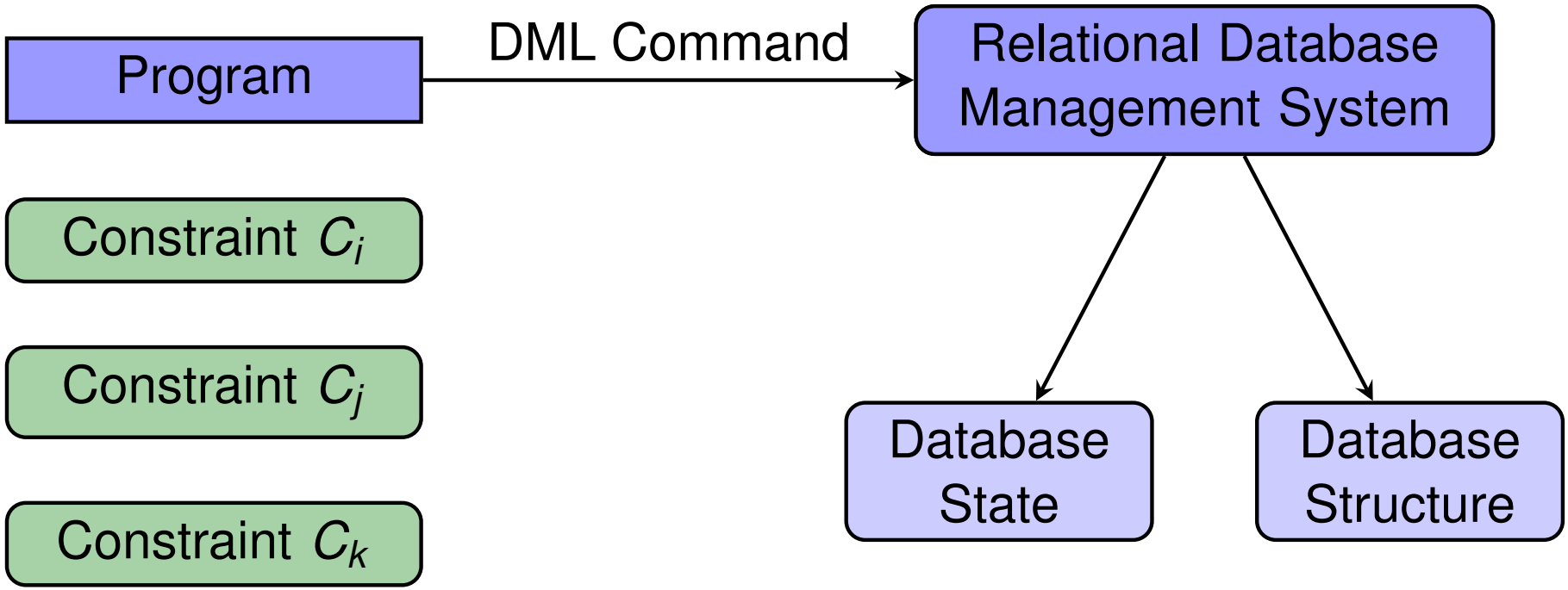


Evolution of Database Applications

Goal: extract C_i, C_j, C_k from the source code of the program



Evolution of Database Applications

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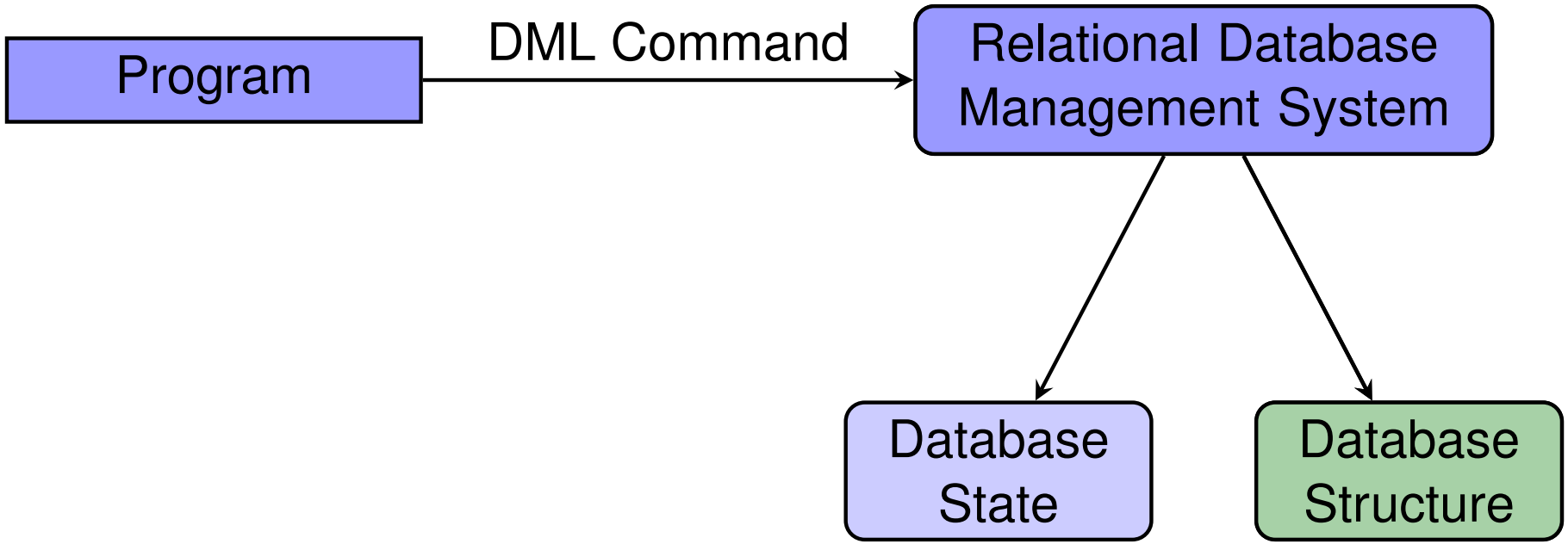

Invariants

Definition

An *invariant* is a mathematical property that holds through some set of transformations

Motivating Examples

- $0 \times y = 0$
- $|x| \geq 0$
- $\frac{c}{d} = \pi$

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Program Invariants

Invariant with respect to:

- State
- Input/Output

Simple Examples

- $0 \leq x \leq 10$
- $1 \leq nextX() \leq 11$
- $nextX() = (x+1) \mod 11$

```
1  class Invariant {
2    static int x = 0;
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4      if( ++x > 10 )
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- Not guaranteed for all possible executions
- May reflect property of:
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Daikon Invariant Detector

Daikon [Ernst et al. 2001] is a dynamic invariant detection engine originally designed for traditional C and Java programs

Detection Process

- Collect data traces for variables at *program points*
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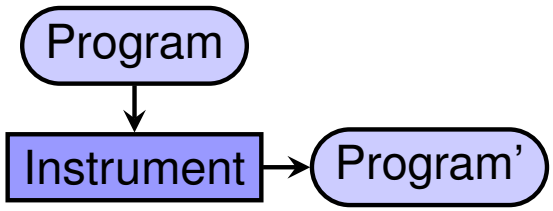

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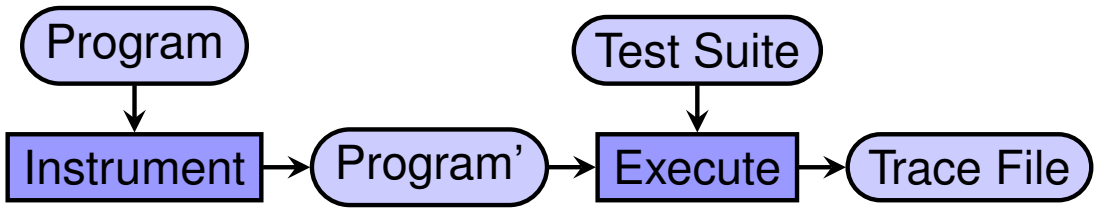

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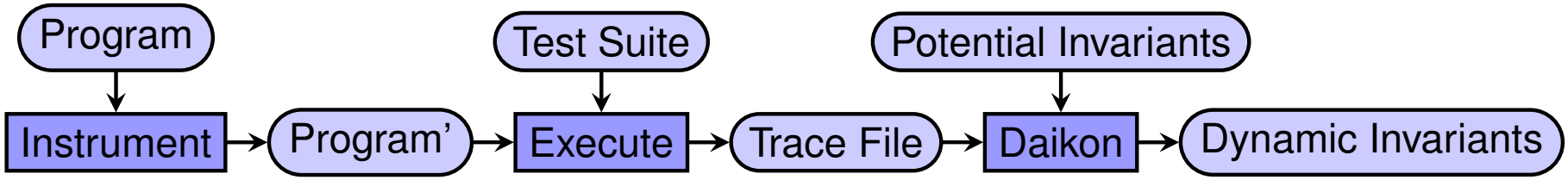

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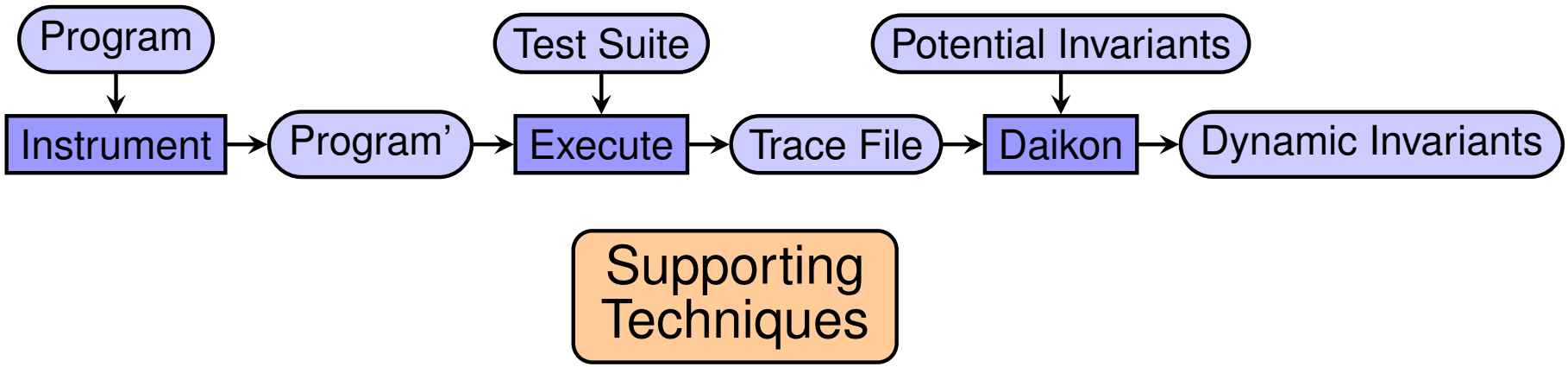

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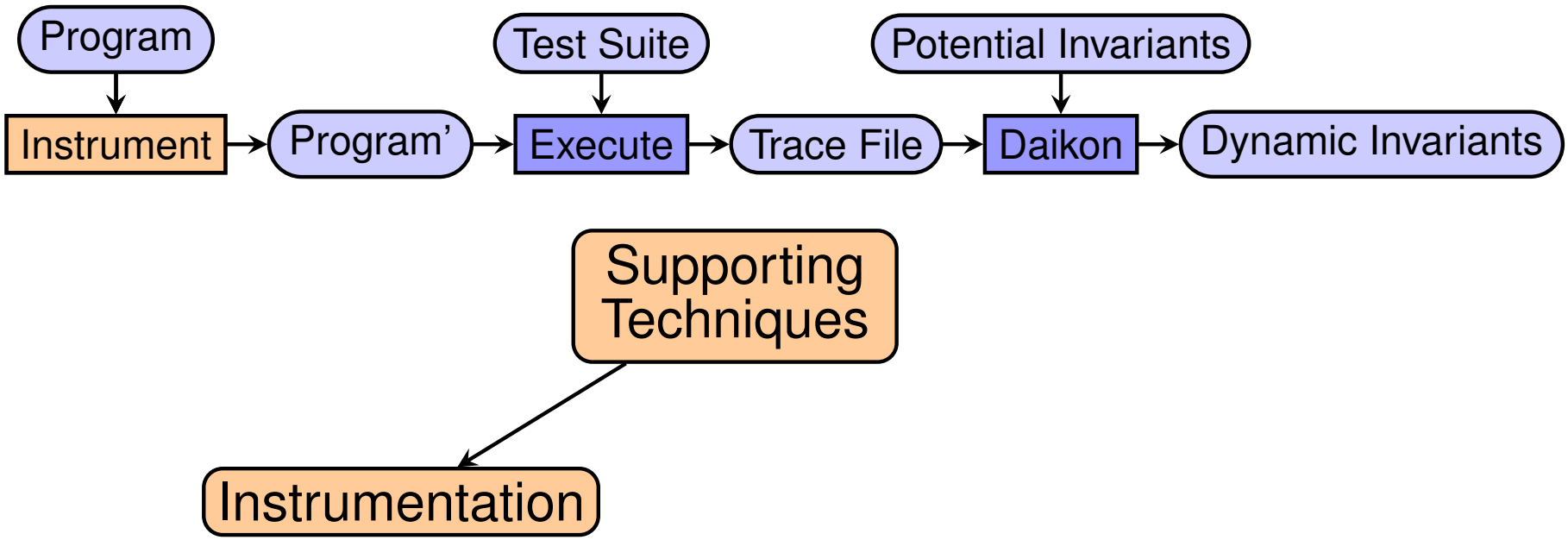

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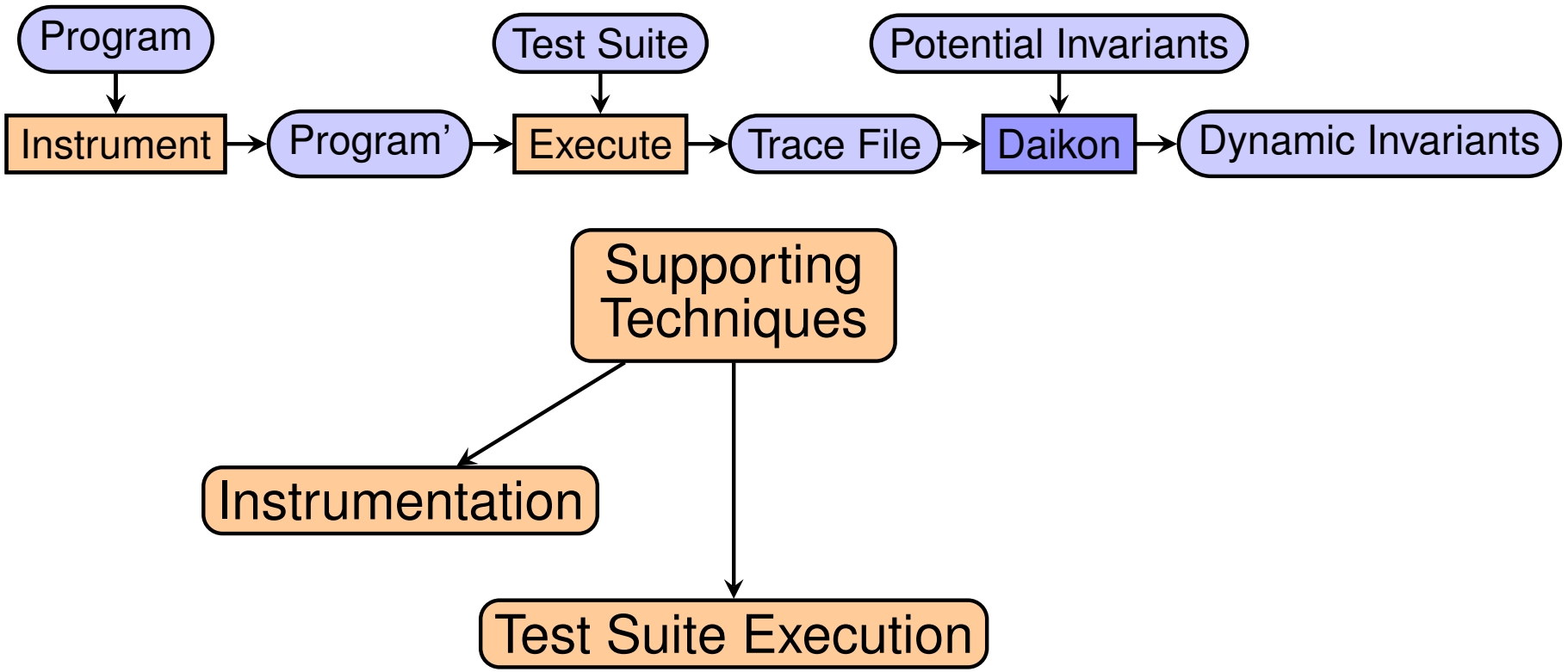

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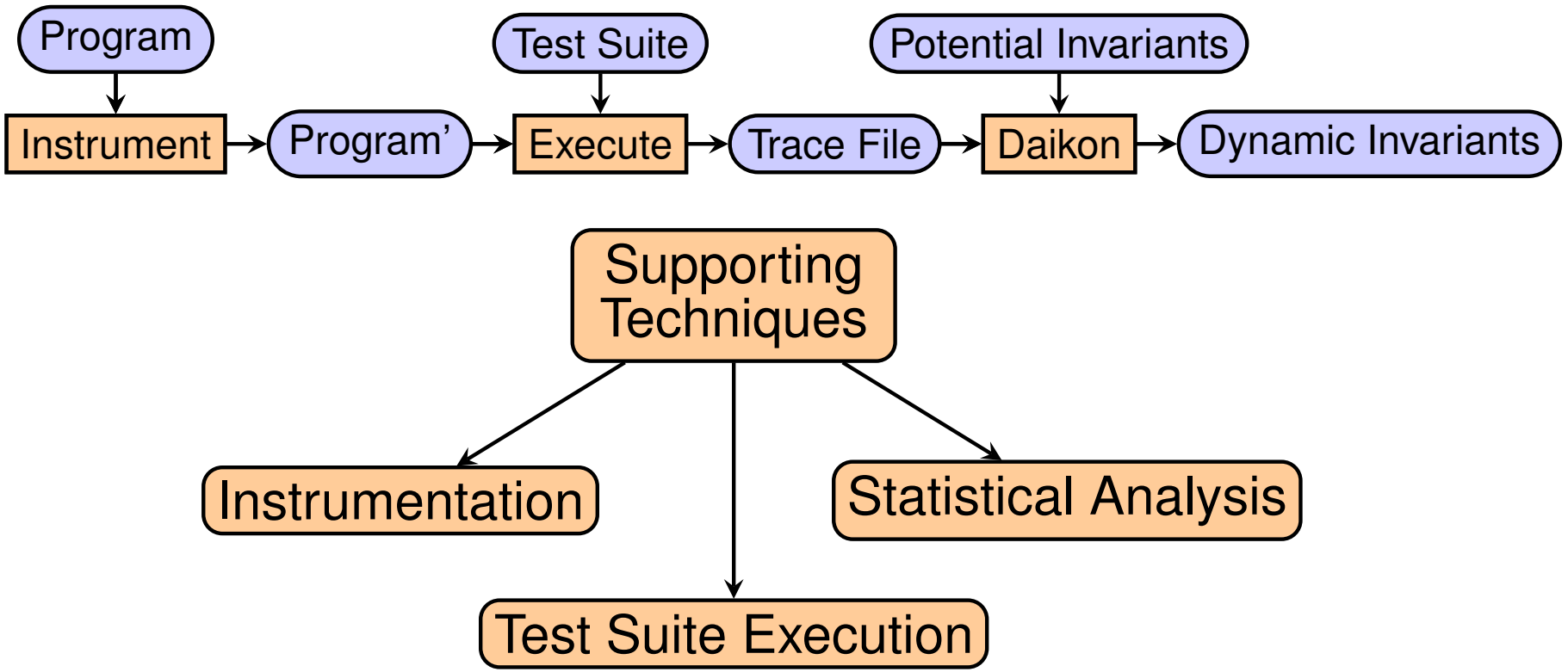
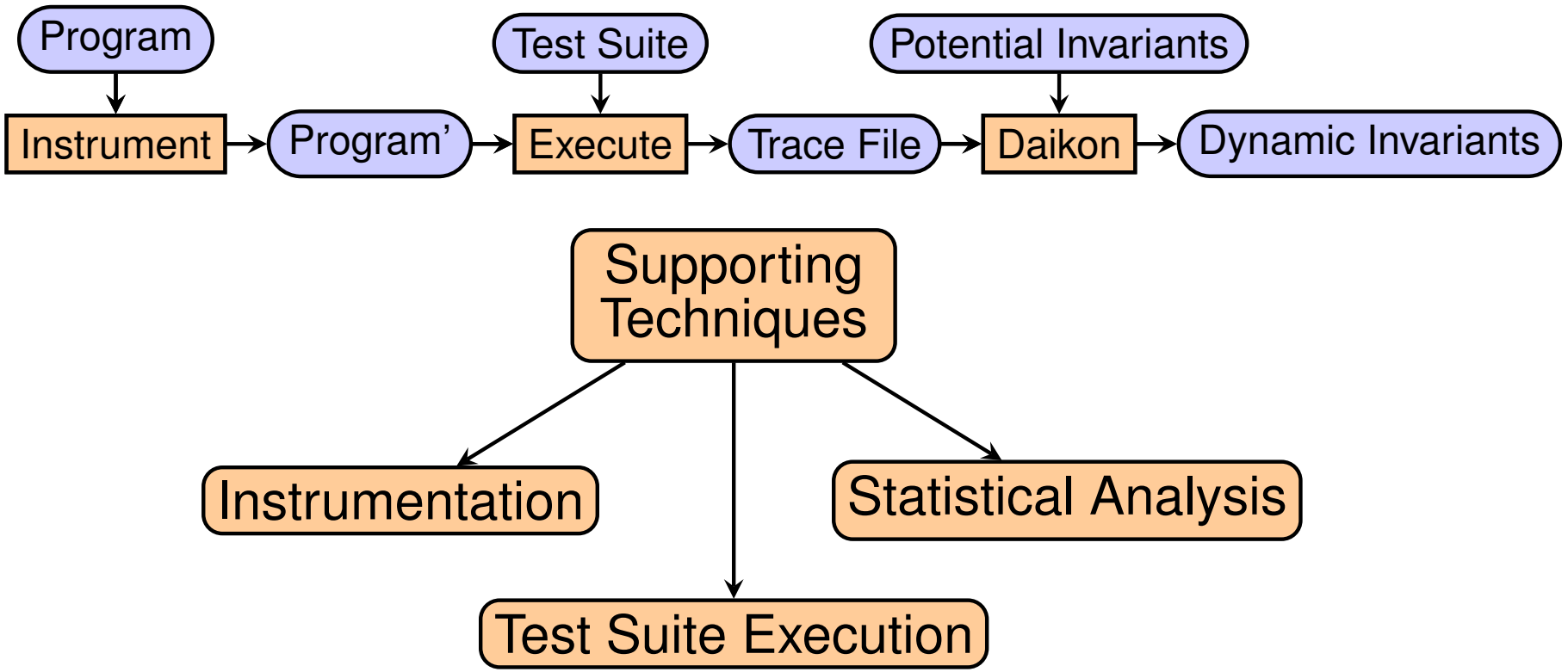


Invariant Detection Process

Refer to [Ernst et al. 2001] for additional details about these techniques



Applications of Daikon

Applications of dynamic invariants in software engineering:

- Programmer understanding
- Run-time checking
- Integration testing
- Interface discovery
- Test-input generation
- Test-suite reduction
- Many additional techniques

Structural Mapping

Program Element	Database Element
Program Point	Table
Variable	Column
Occurence	Row

Detect invariants for:

- Individual columns
- Between columns in a given row

id	name	age	employed	...
1	'John Smith'	38	5	...
2	'Jan Downing'	22	2	...

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Data Mapping

Daikon Concepts

- Representation type
  - `int`
  - `double`
  - `String`
  - `int[]`
- Comparability

Data Mapping

Group	Name	SQL Types	Java Type
1	Text	CHAR VARCHAR TEXT	String
2	Integer	INTEGER NUMERIC BIT	int
3	Decimal	FLOAT DOUBLE REAL DECIMAL	double
4	Binary	BLOB BIT	byte[]
5	Text Set	SET	String[]
6	Datetime	DATETIME TIMESTAMP	String
7	Date	DATE	String
8	Time	TIME	String
9	Interval	INTERVAL	int
10	Primary Key	INTEGER	*reference*

Data Mapping

Handling `NULL` Values

- `NULL` is a possible value for any SQL type
- Daikon does not accept `null` for primitive representation types such as `int`
- Introduce synthetic variable for each `NULL`-able column
  - Representation type is `hashcode` (*reference*)
  - Value is either `null` or a constant

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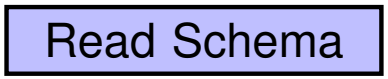

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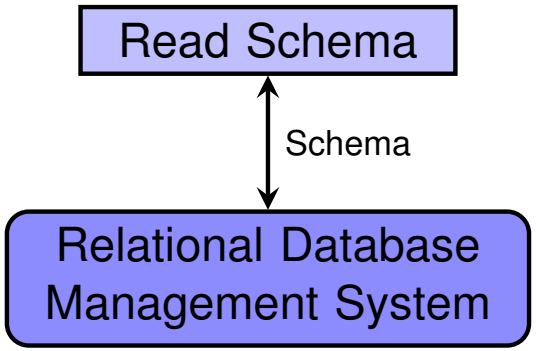

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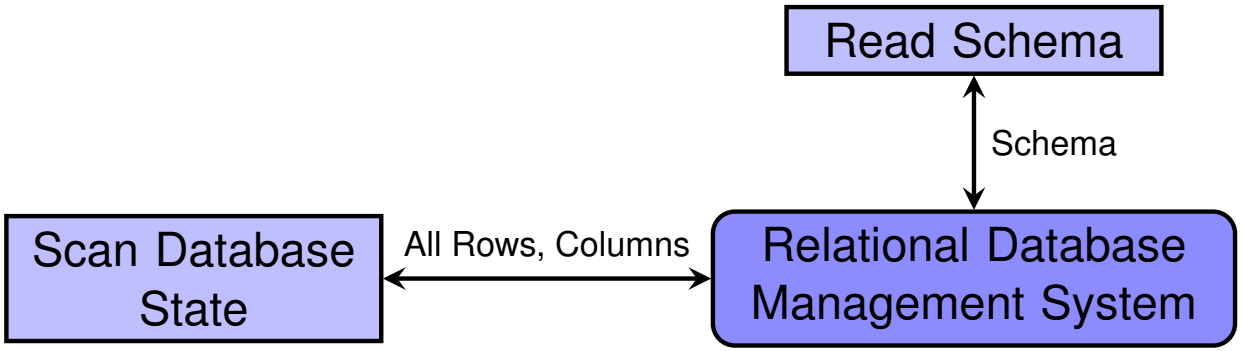

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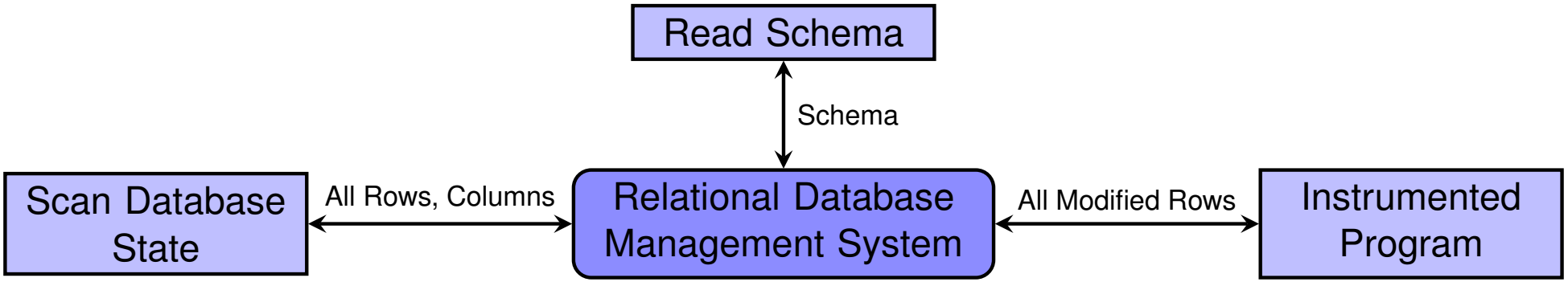

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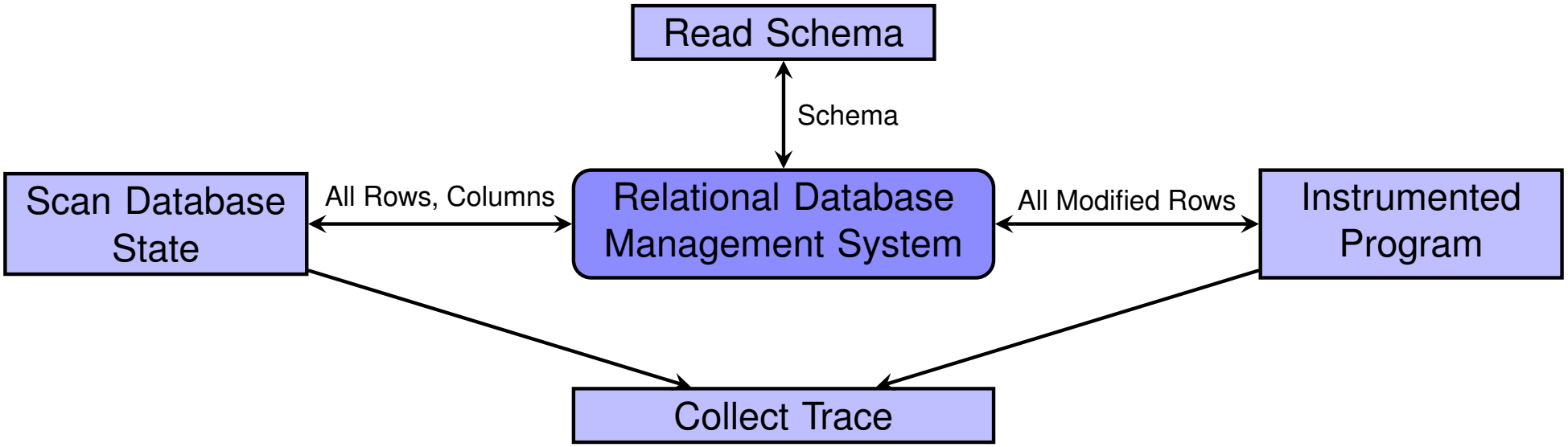

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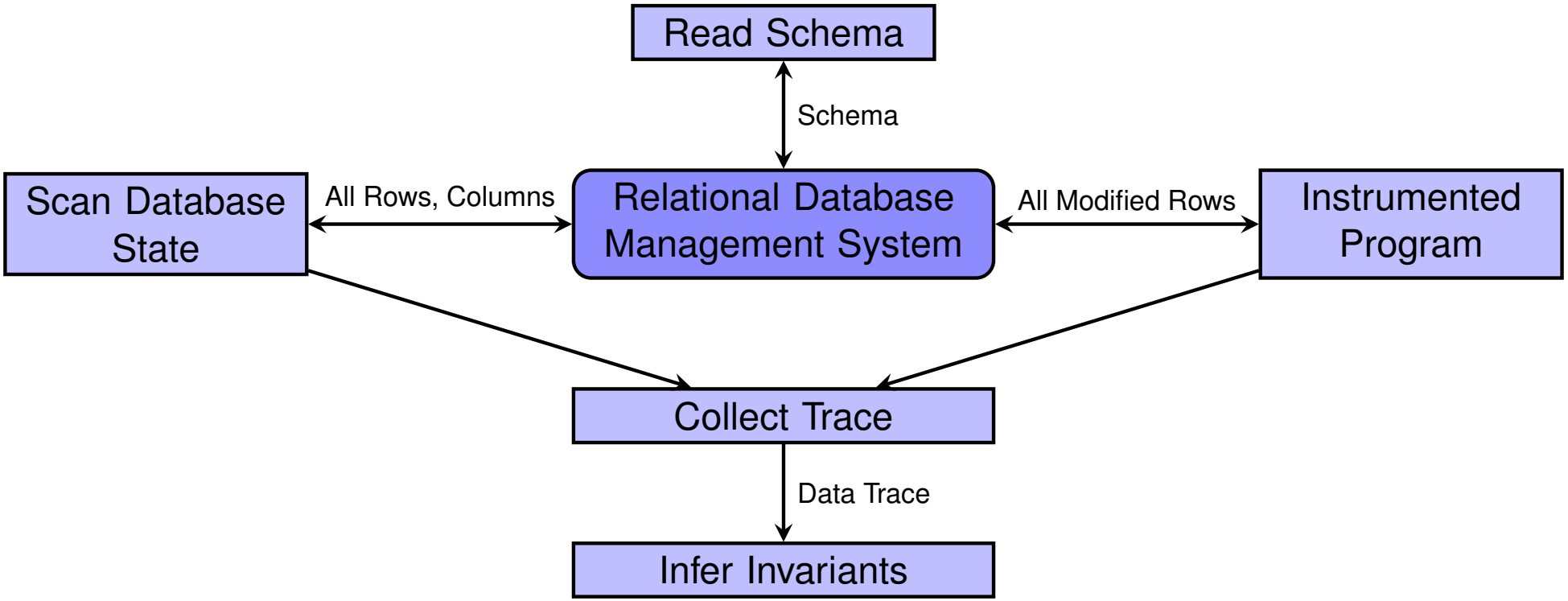

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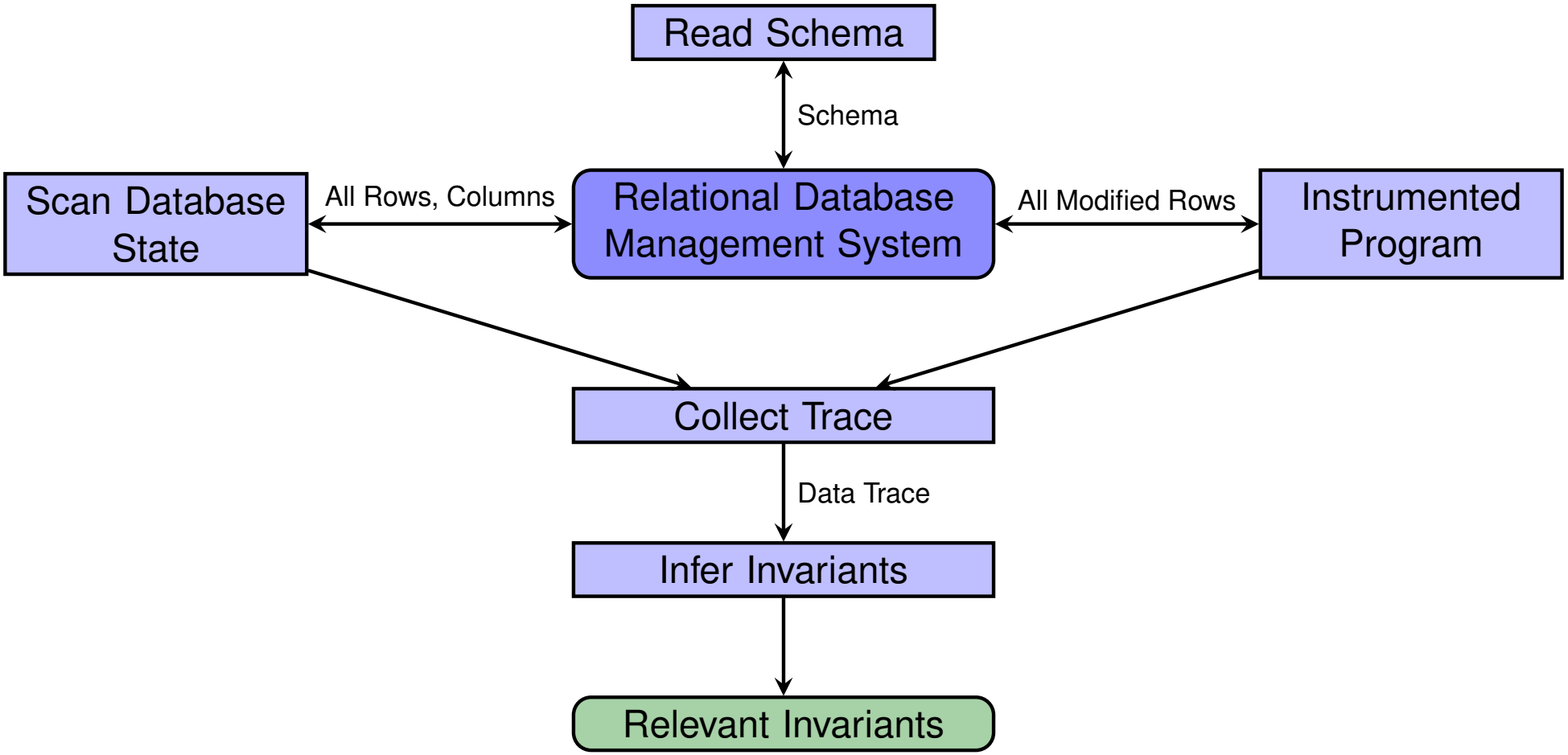

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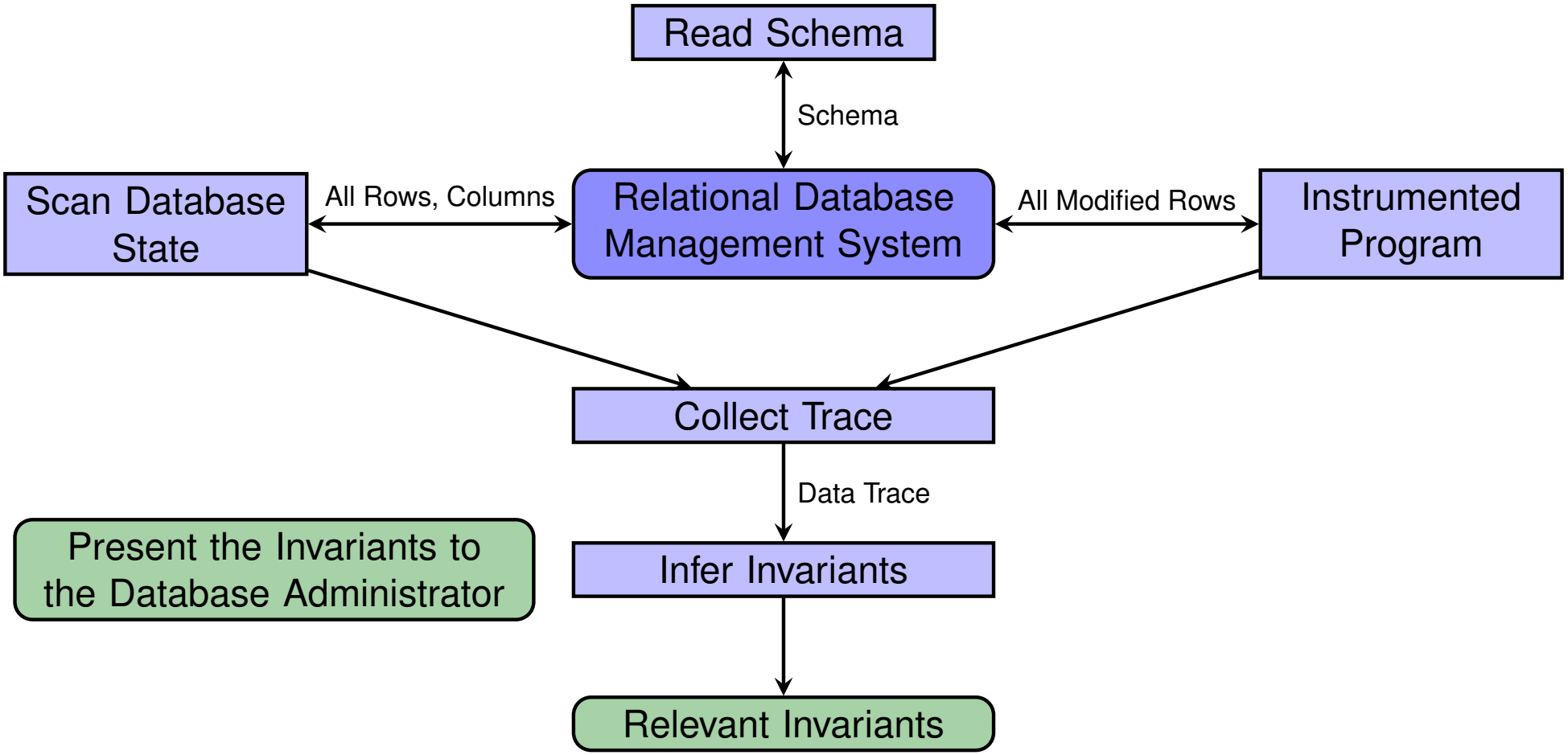

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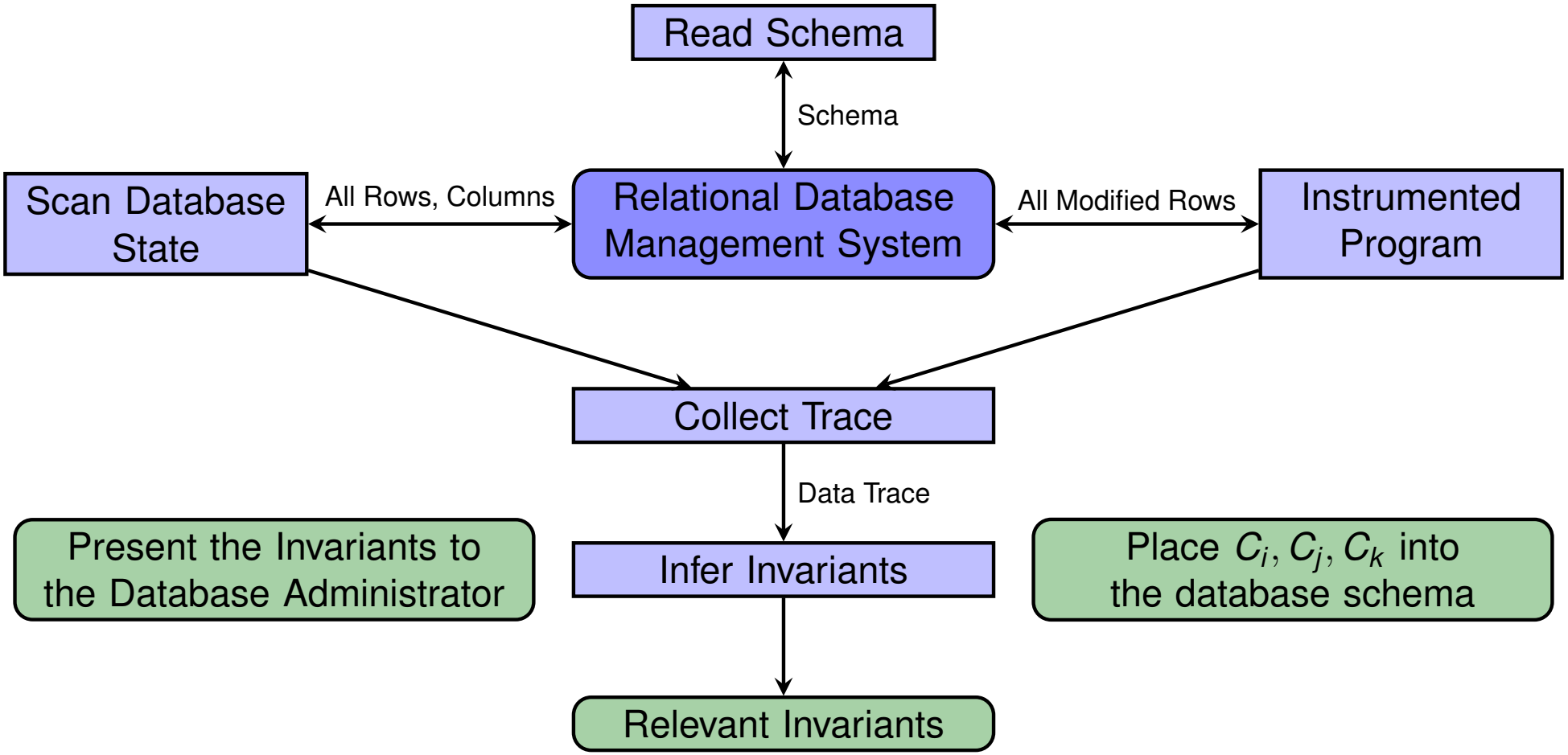

Implementation

Trace Collector

- Python[a] program:
  - Input: Database connection information
  - Output: Daikon declarations and data trace files
- Process:
  1. Read schema metadata to determine tables, columns, and data mapping
  2. Write declarations file and serialize mapping info for reuse
  3. `SELECT` table contents, transform data by mapping, write to GZip'd trace file
- Supports various RDBMS with the SQLAlchemy toolkit

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Instrumentation Wrapper

- Modified P6Spy JDBC driver wrapper
- On connection, capture information and initiate initial metadata read and trace
- On statement execution, append the trace file if the database could be modified
  - `INSERT` statement
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Objects of Analysis

Fixed Data Sets

Database	Tables	Columns	Rows
world	3	24	5302
sakila	23	131	50,086
menagerie	2	10	19
employees	6	24	3,919,015

- MySQL sample databases commonly used for training, certification, and testing
- Trace the entire dataset during invariant detection

Objects of Analysis

Database Applications

Program	iTrust	JWhoisServer	JTrac
Tables	30	7	13
Columns	177	57	126
KLOC	25.5 (Java), 8.6 (JSP)	6.7	12
Test Cases	787	67	41

- Java applications that interact with a relational database
- Wrap real database driver in a modified P6Spy driver
- Execute the entire test suite during invariant detection

Invariant Quality

Meaningful Invariants

Invariants that capture a semantic relationship

- `dept_emp.from_date <= dept_emp.to_date`
- `employees.gender one of { "F", "M" }`
- `employees.birth_date < employees.hire_date`
- `country.Population >= 0`
- `icdcodes.Chronic one of { "no", "yes" }`

All of these invariants were automatically generated!

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Spurious Invariants

Spurious Invariants

- Vacuous invariants reflect a meaningless relationship.
  - `patients.phone1 <= patients.BloodType`
  - `patients.lastName >= patients.address1`
  - `cptcodes.Description != cptcodes.Attribute`
- Lack-of-data invariants result from limited data samples.
  - `mntnr.login == "mntnt"`
  - `inetnum.changed == "2006-10-14 16:21:09"`
  - `person.name one of { "no name company", "persona non grata"}`

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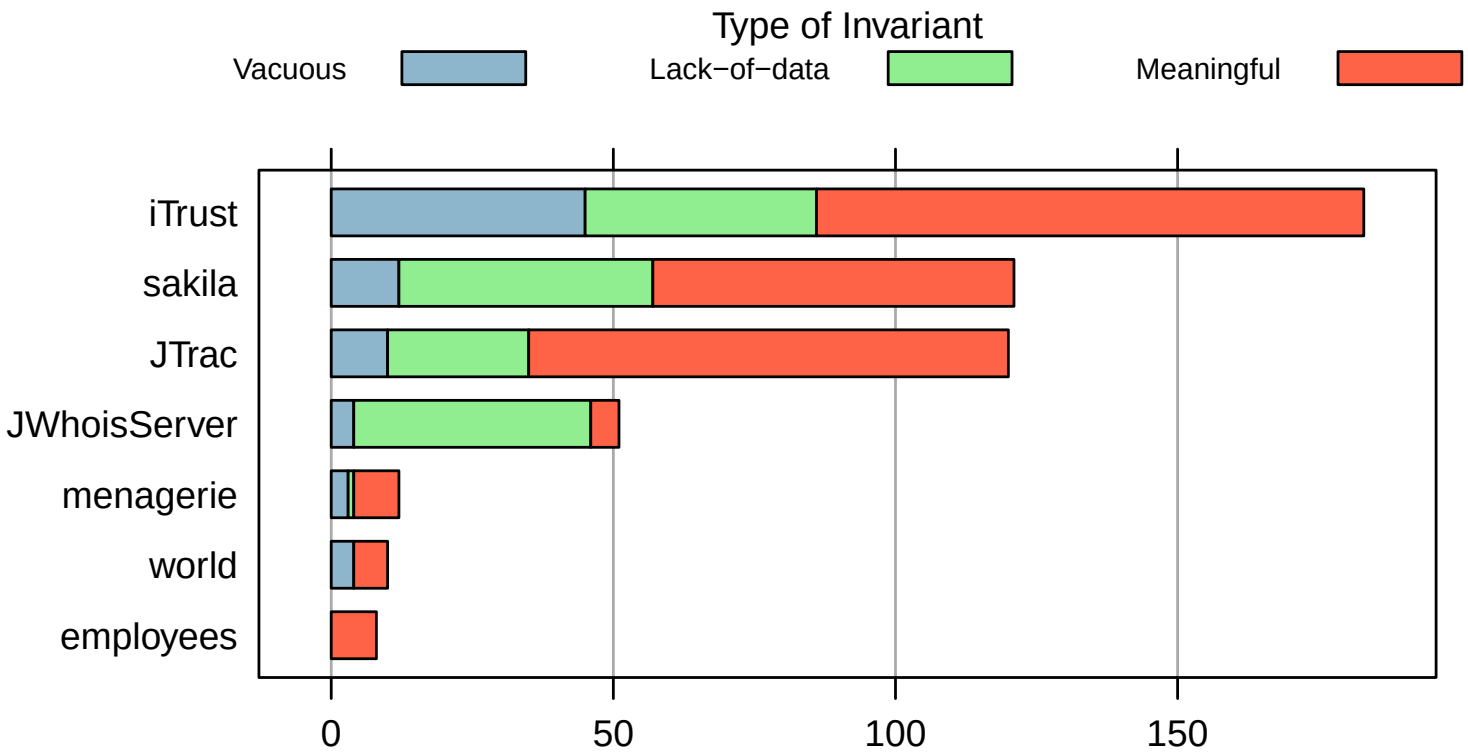
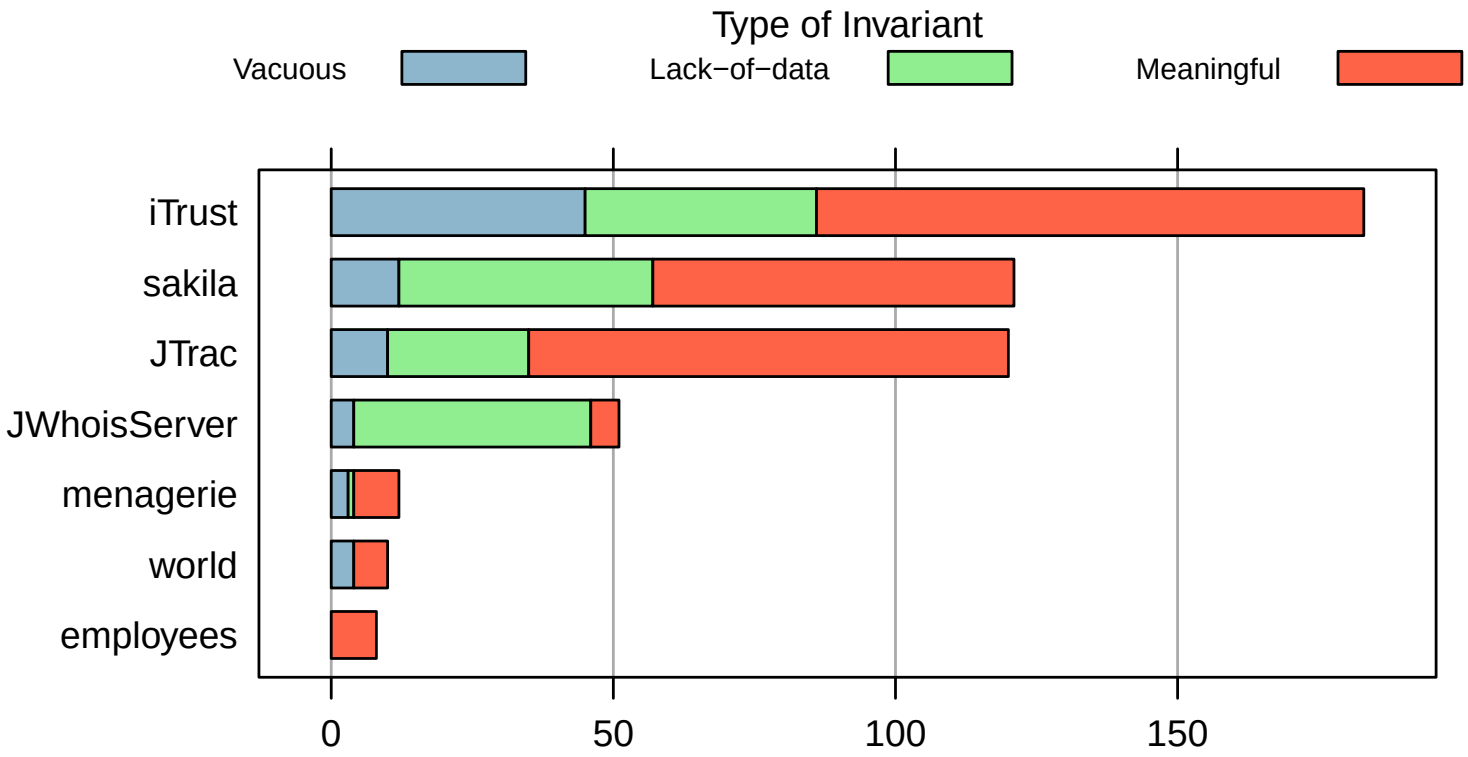


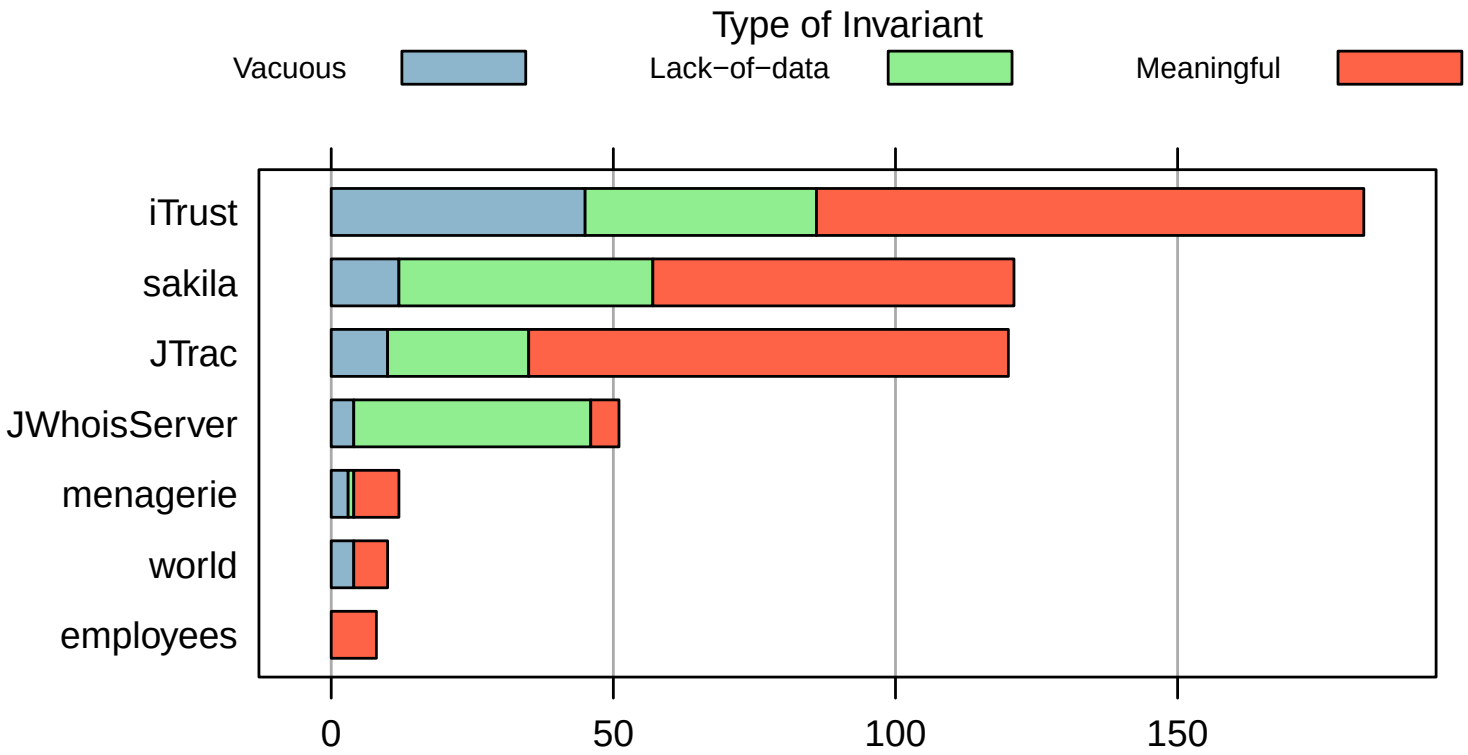
The majority of detected dynamic invariants are not spurious

Invariant Quality



employees' invariants are meaningful due to wealth of data

Invariant Quality



JWhoisServer's few meaningful invariants suggests poor tests

Schema Modification

Using Dynamic Invariants

- Some invariants can be enforced by the schema definition
- Schema enforcement:
  - Provides a stronger assurance of data integrity than application enforcement
  - Enables easy long-term maintenance of the program and the relational database
- Analyze enforceable invariants:
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Schema Modification

Schema Enforced

Invariant	Schema Definition
`employees.gender one of { "F", "M" }`	`ENUM('F','M')`
`countrylanguage.IsOfficial one of { "F", "T" }`	`ENUM('F','T')`
`customer.active one of { 0, 1 }`	`TINYINT(1)`
`inventory.film_id >= 1`	`SMALLINT(5) UNSIGNED`
`spaces.guest_allowed one of { 0, 1 }`	`BIT(1)`

Reverse engineered many constraints already enforced by the schema

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Schema Enforceable

Invariant	Schema	Modification
`isnull(message.message) != null`	`TEXT`	`NOT NULL`
`isnull(film_text.description) != null`	`TEXT`	`NOT NULL`
`isnull(history.time_stamp) != null`	`DATETIME`	`NOT NULL`
`user_space_roles.user_id >= 1`	`BIGINT(20)`	`UNSIGNED`
`pet.sex one of { "f", "m" }`	`CHAR(1)`	`ENUM('m','f')`
`country.Population >= 0`	`INT(11)`	`UNSIGNED`
`isnull(titles.to_date) != null`	`DATE`	`NOT NULL`

Many detected constraints can easily be added to the schema

Schema Modification

Schema Enforceable

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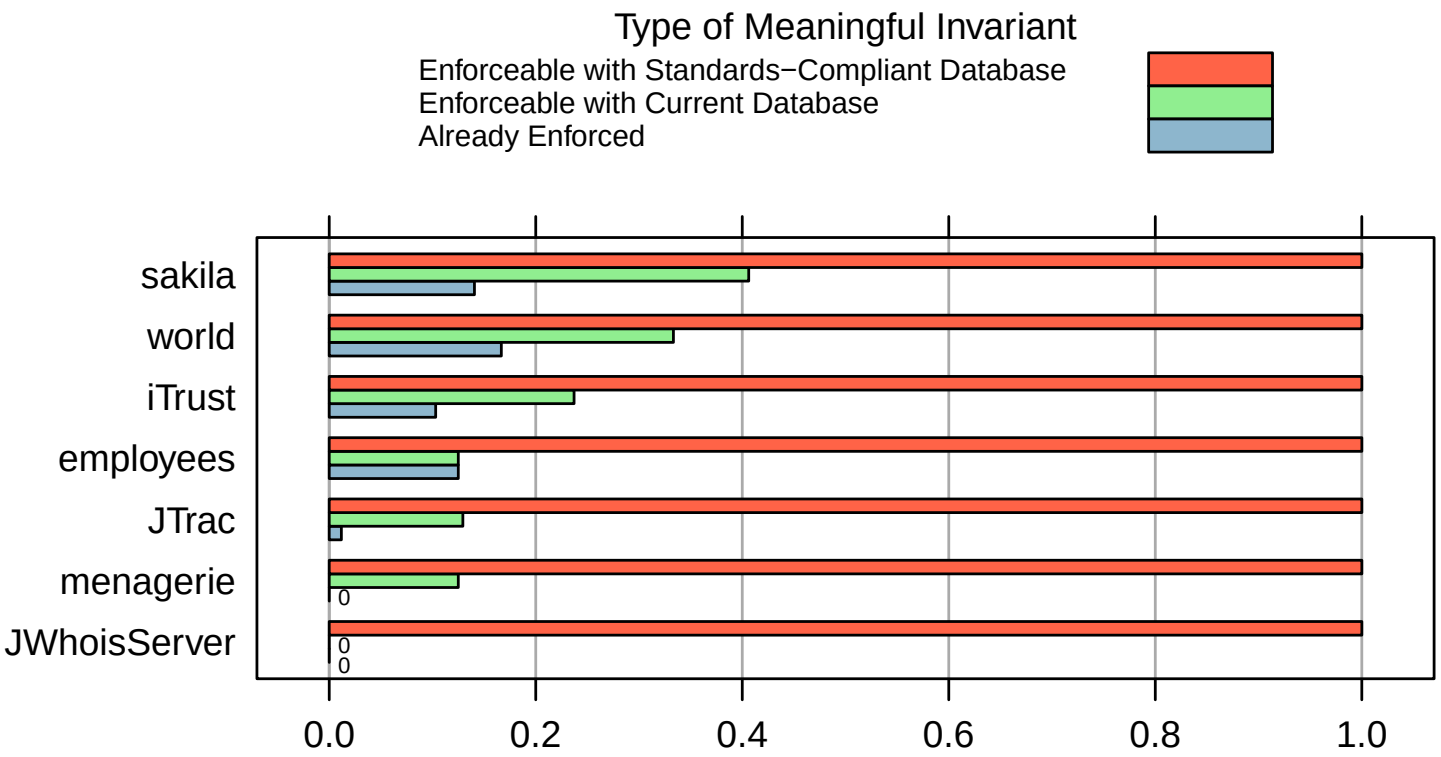
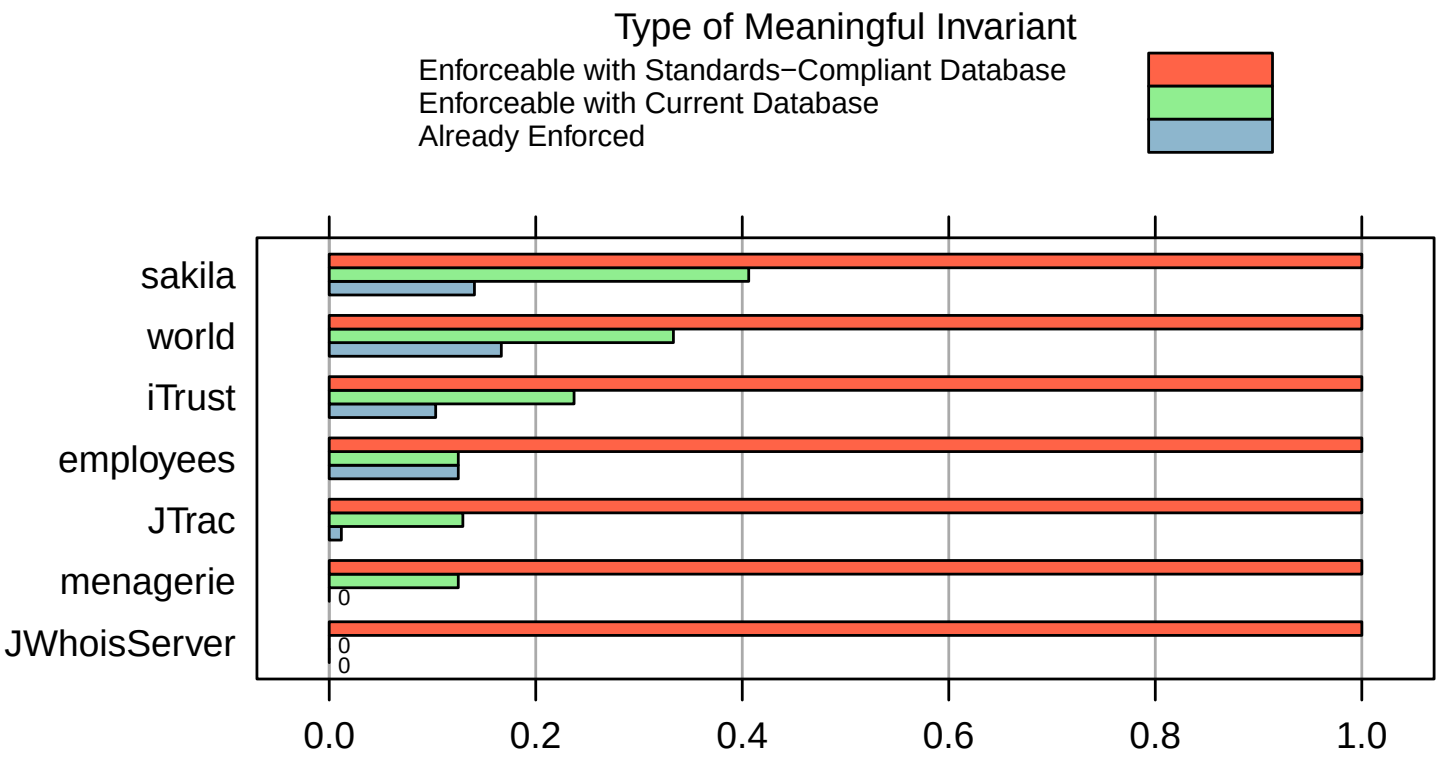
Many detected constraints can easily be added to the schema

Schema Modification



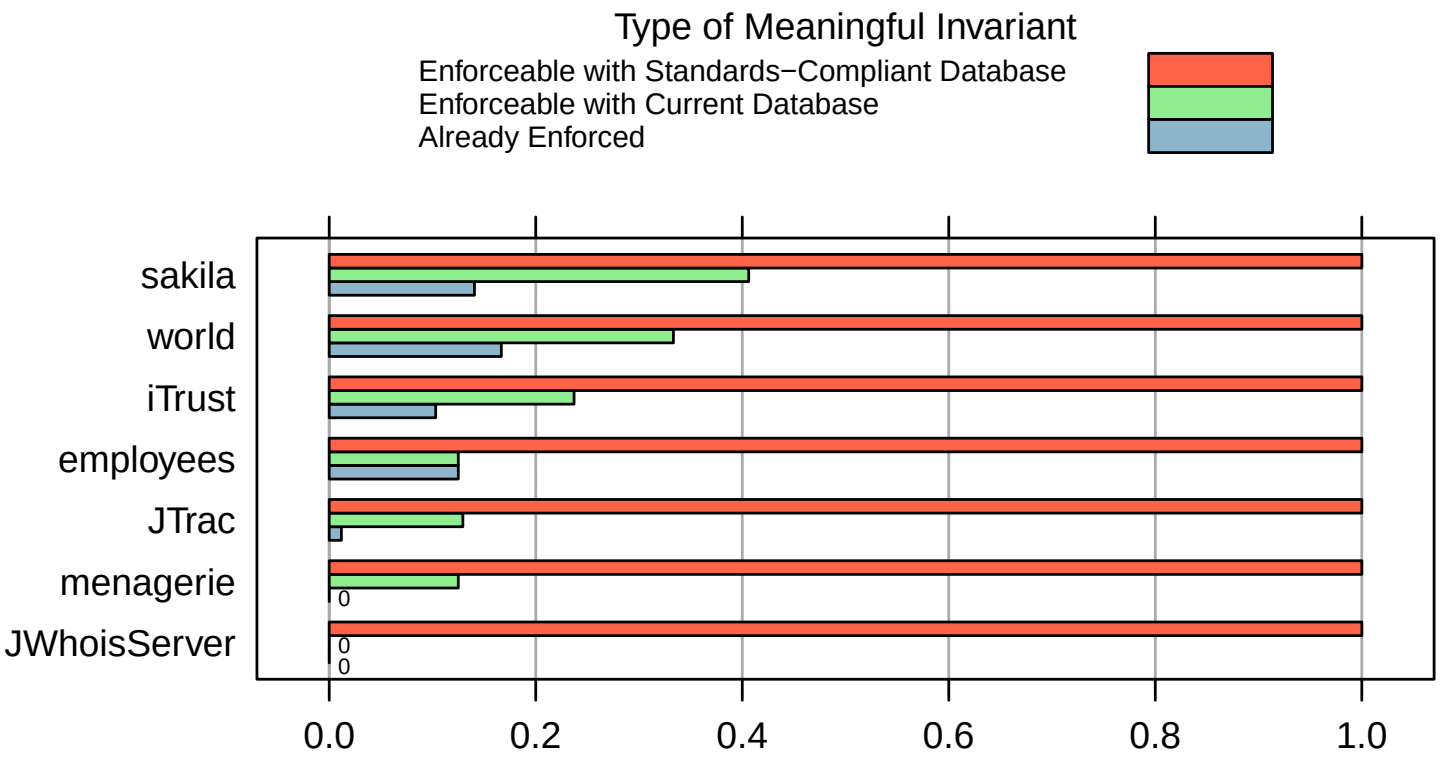
Percentages relative to the total number of non-spurious invariants

Schema Modification



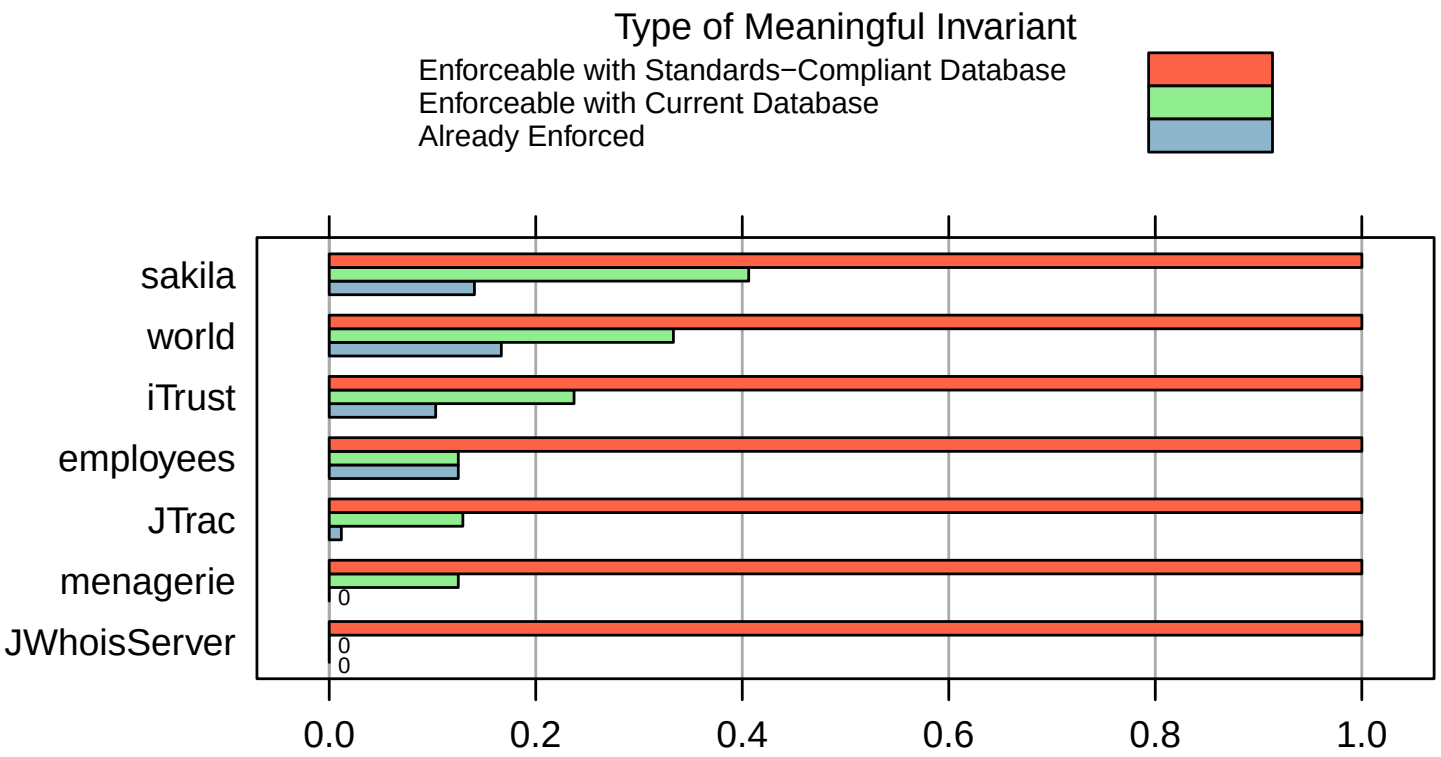
All constraints enforceable by a standards-compliant database

Schema Modification



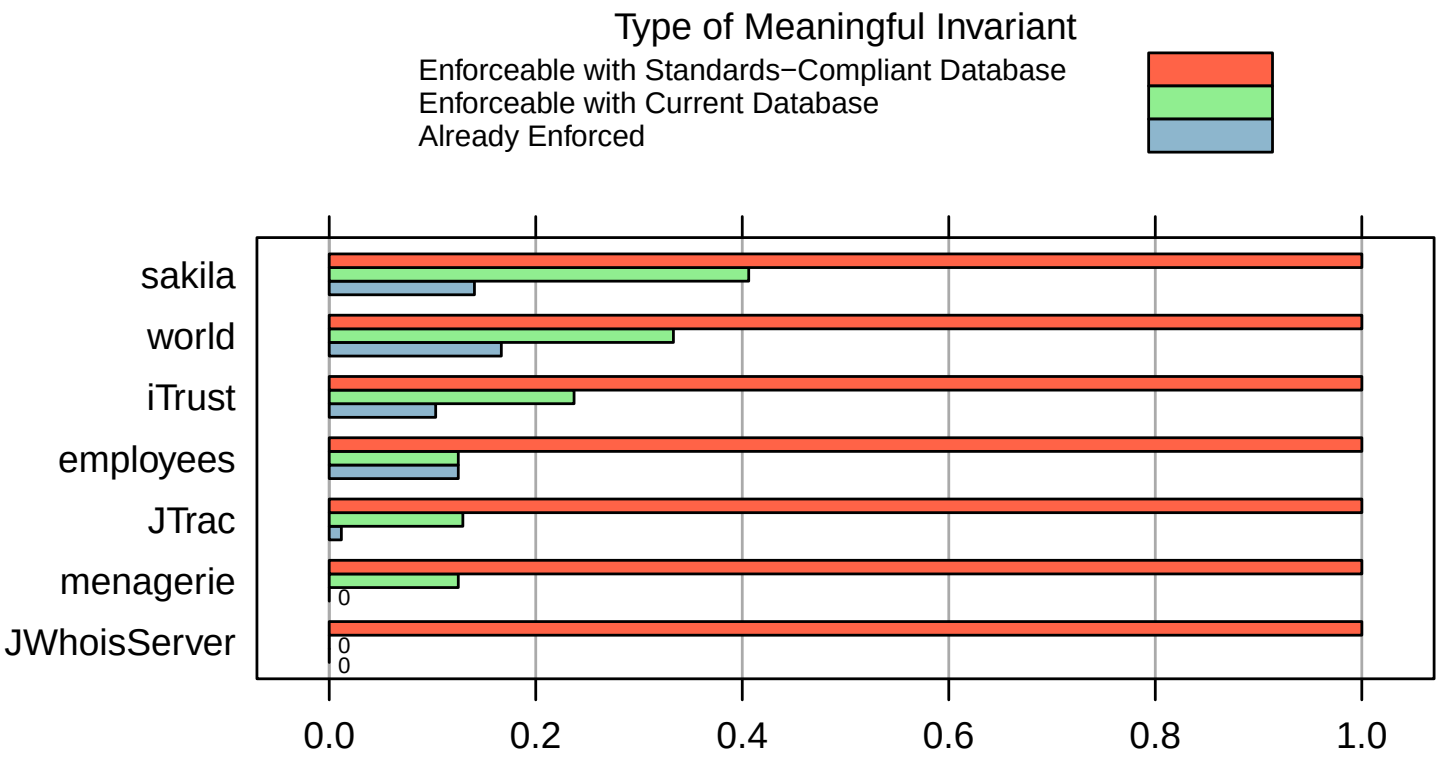
Three schemas can be enhanced with many new constraints

Schema Modification



menagerie did not already enforce any of the meaningful invariants

Schema Modification



JWhoisServer's MySQL doesn't support constraint enforcement

Empirical Conclusions and Future Research

Conclusions

- Meaningful invariants may be mined from both relational databases and database applications
- Invariant quality depends on existence of diverse data
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Future Research

- Invariants between multiple tables
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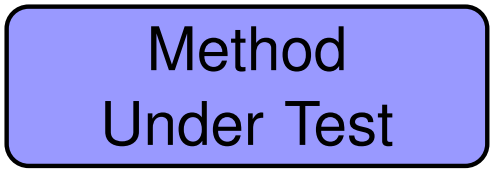

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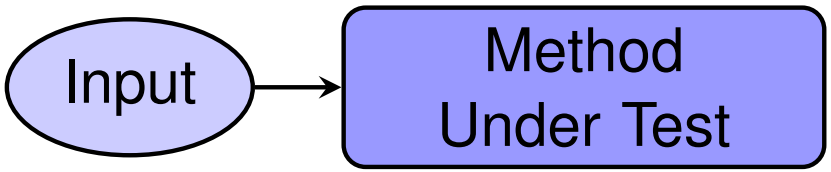

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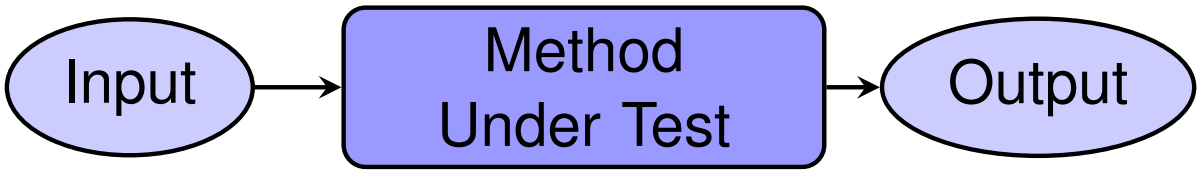

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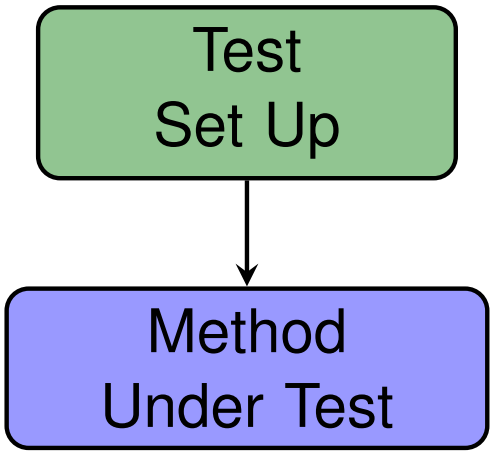

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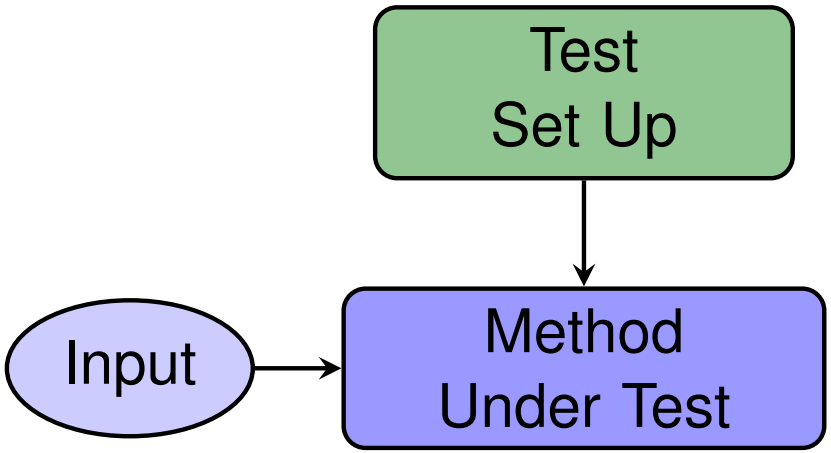

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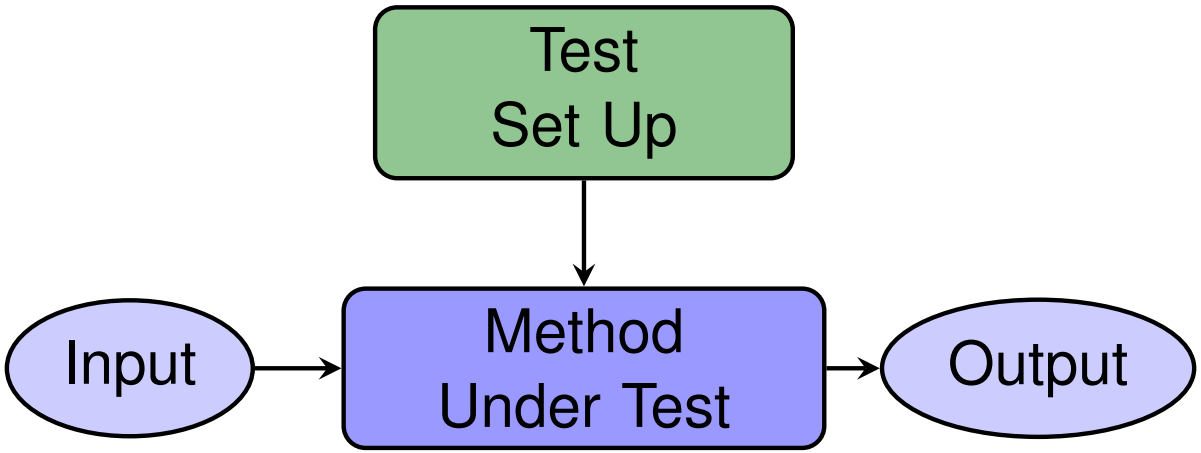

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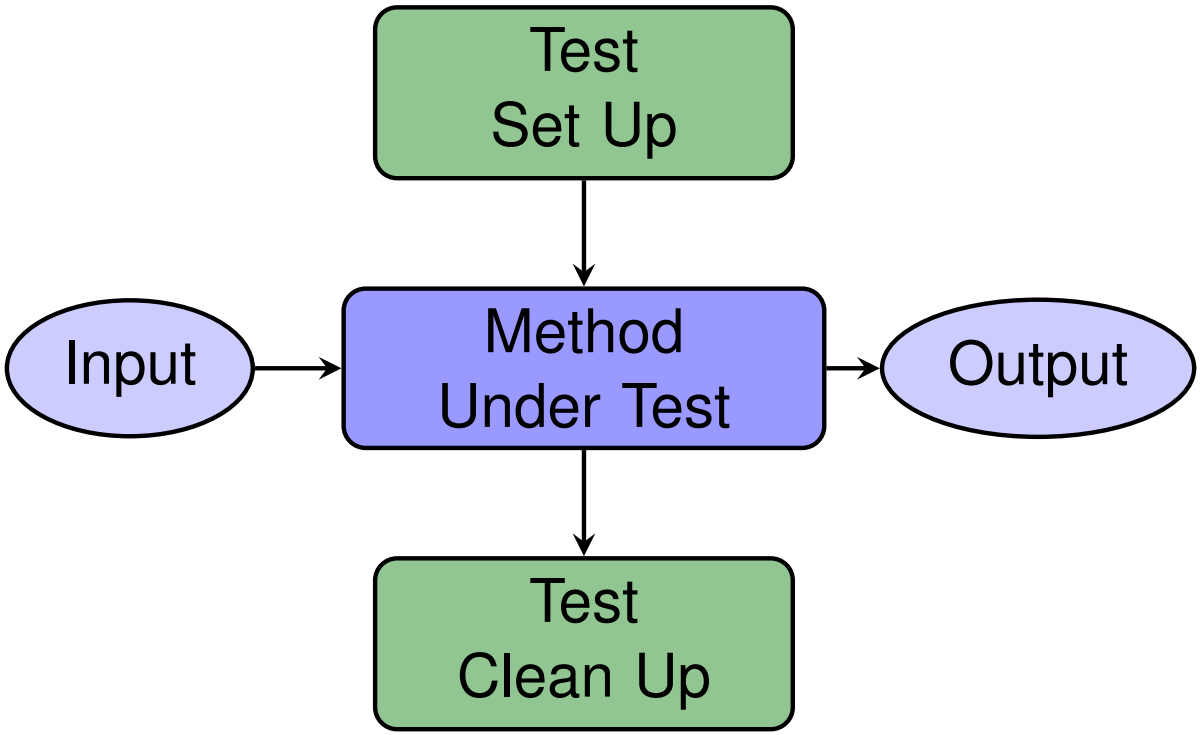

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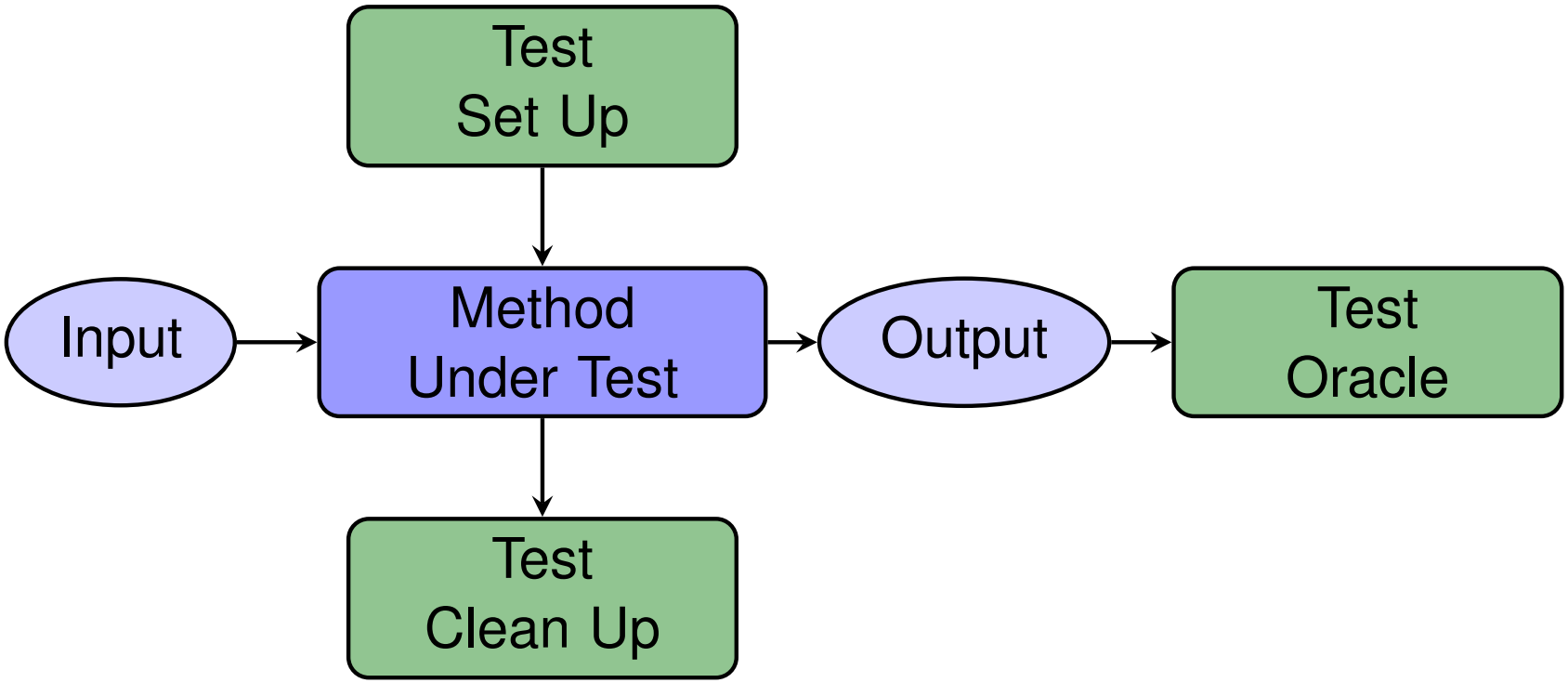

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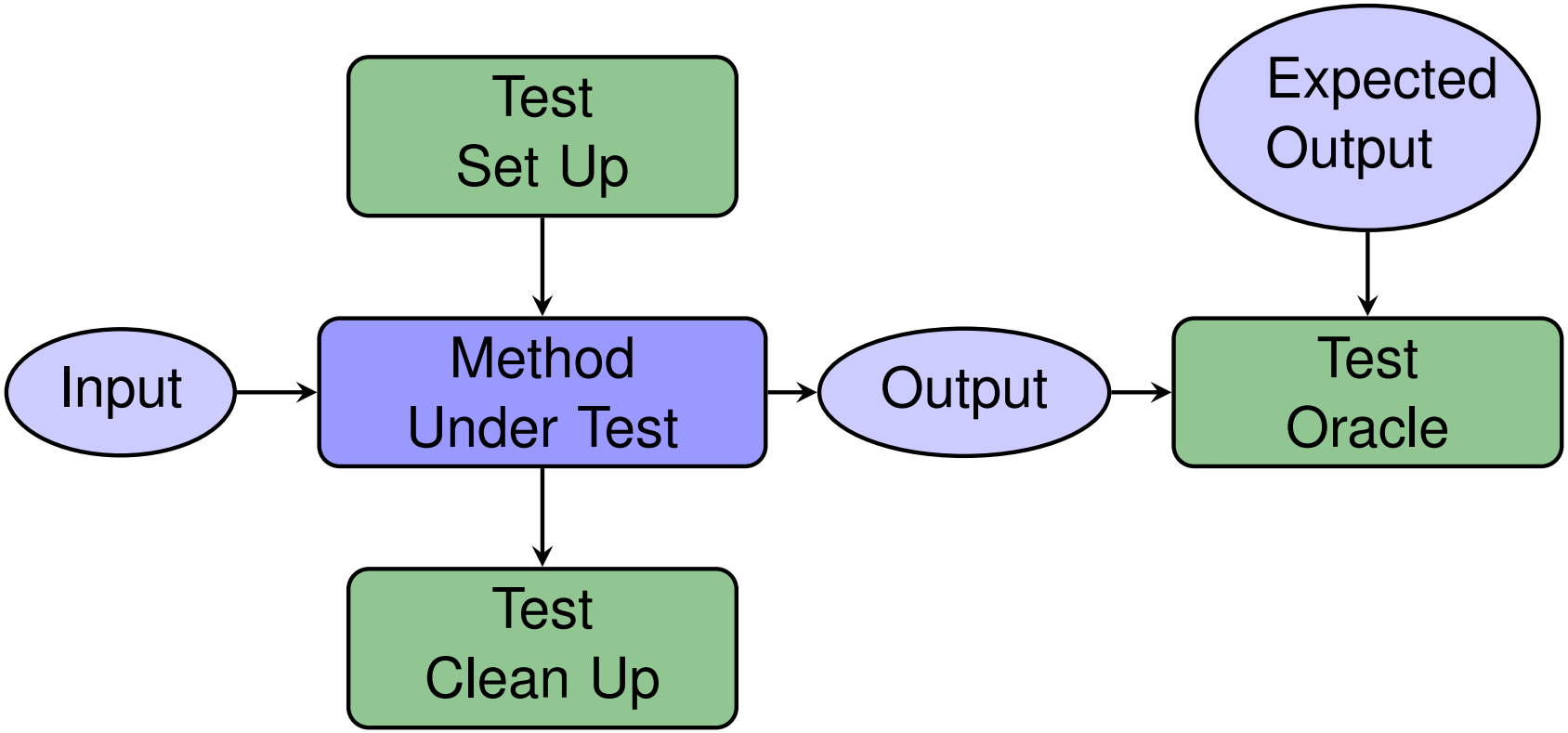

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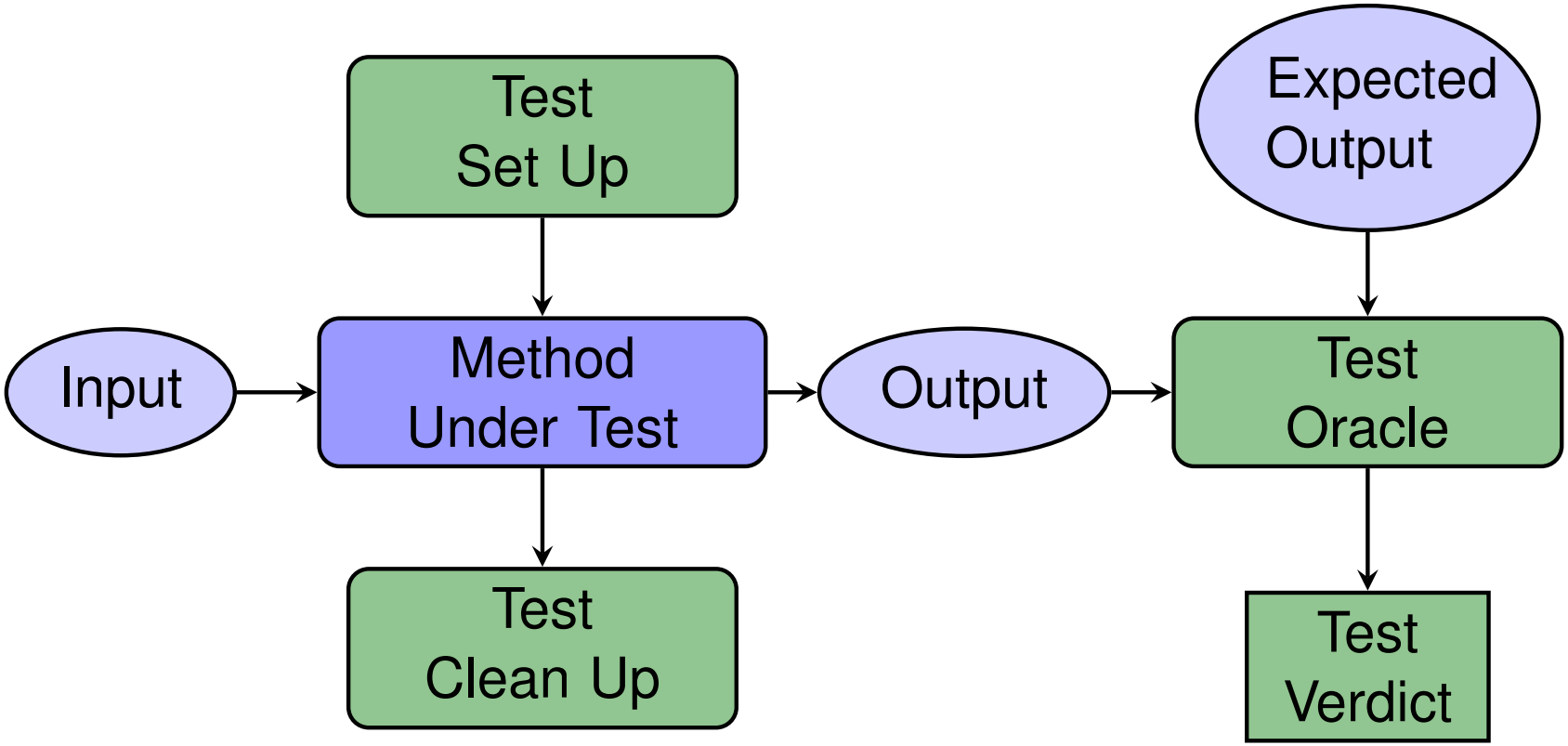

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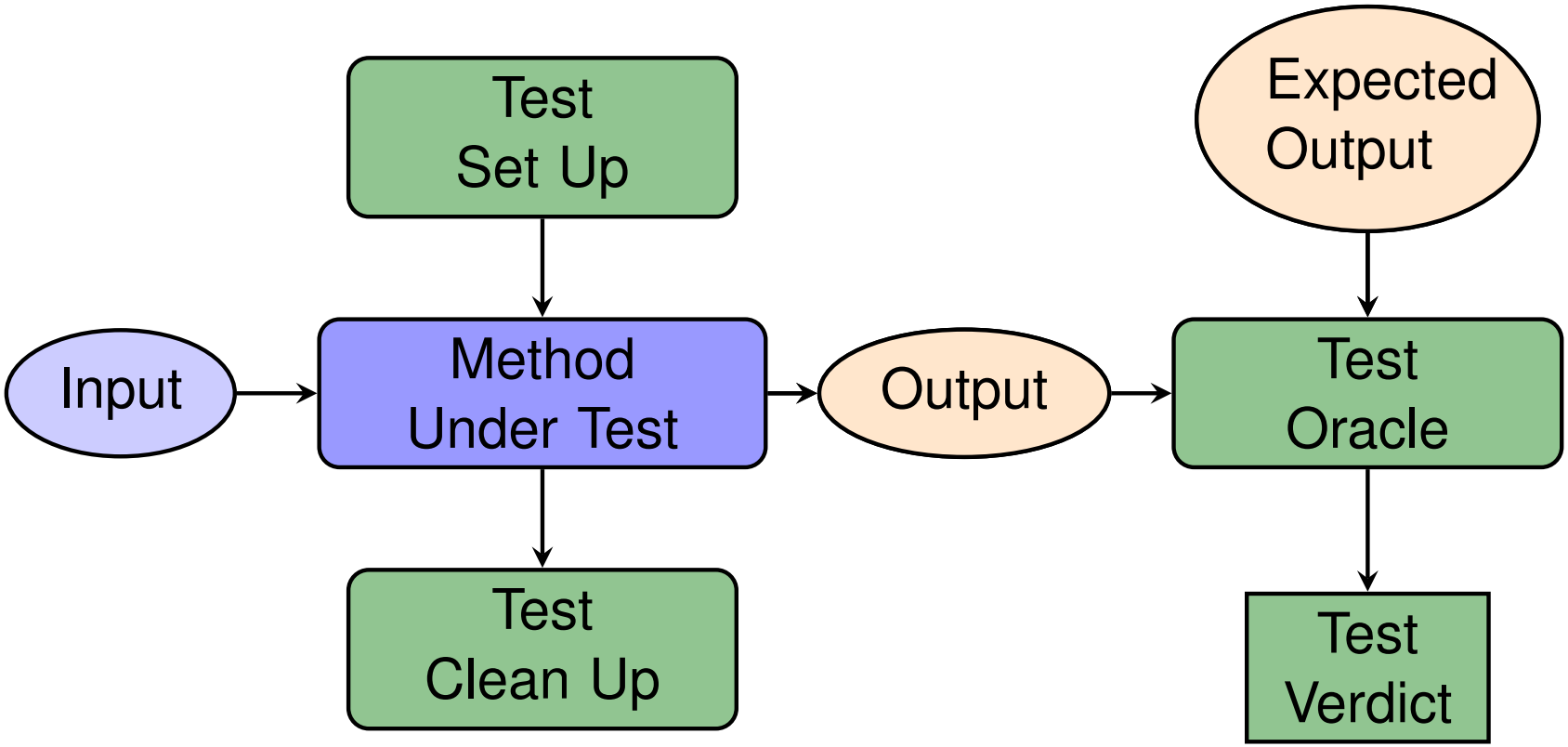

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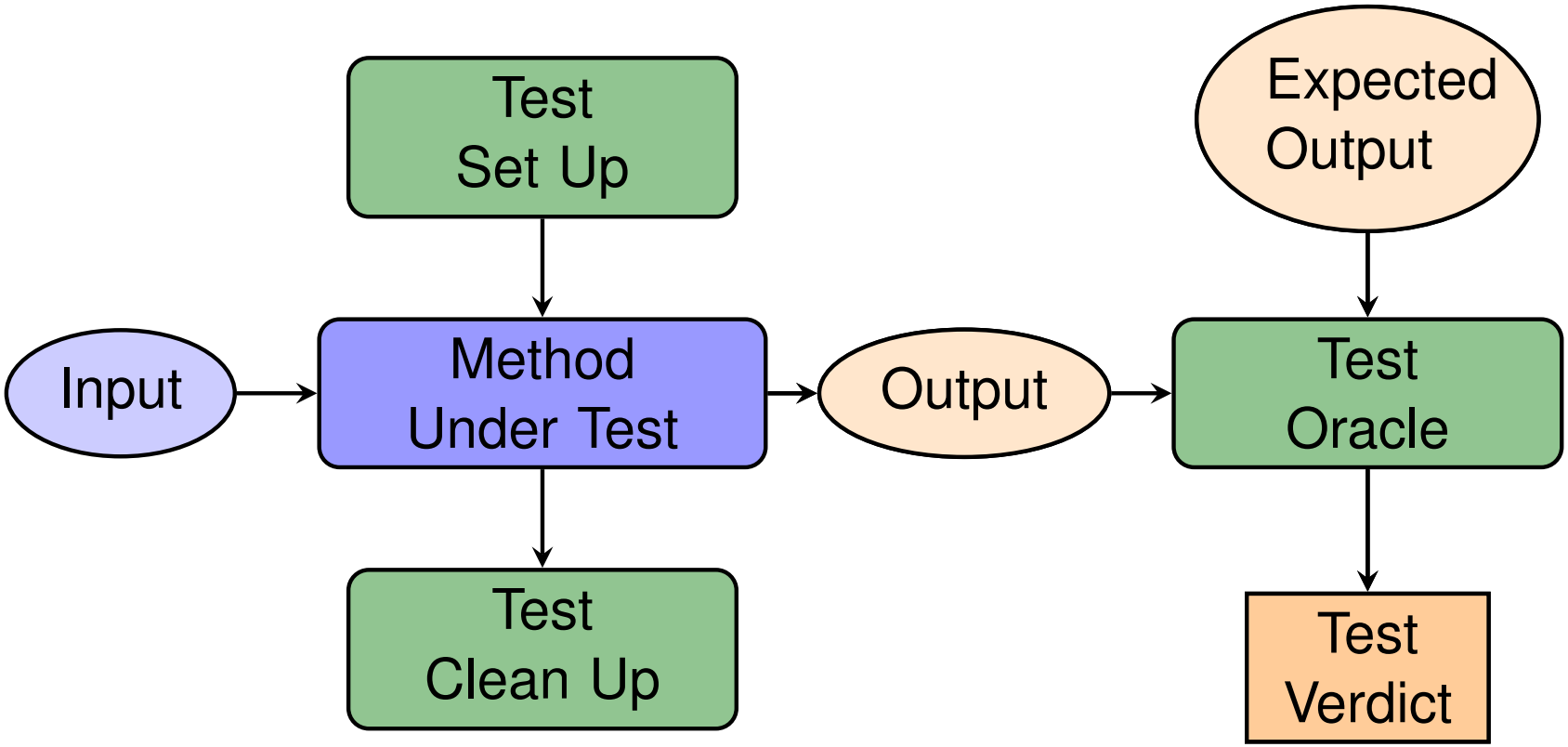

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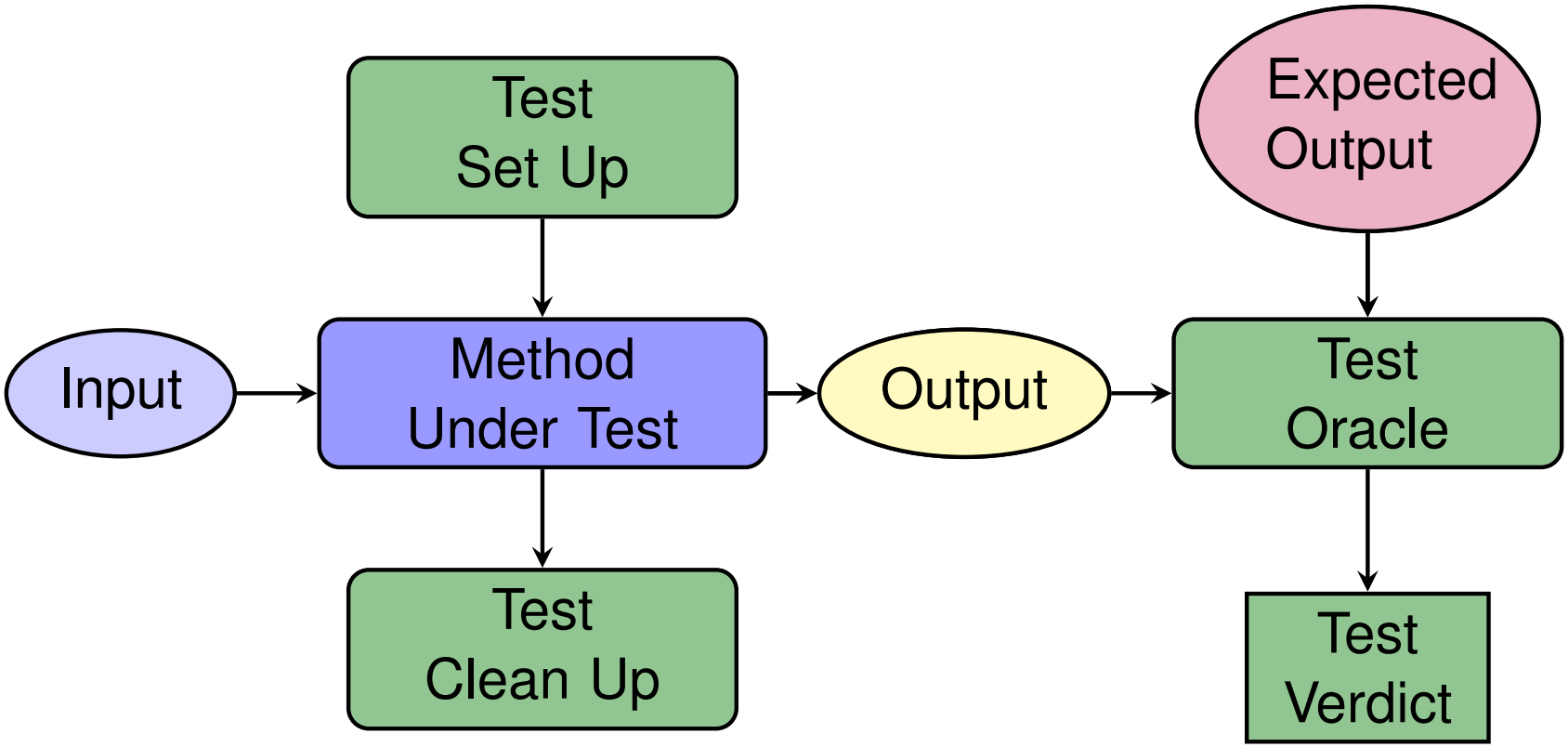

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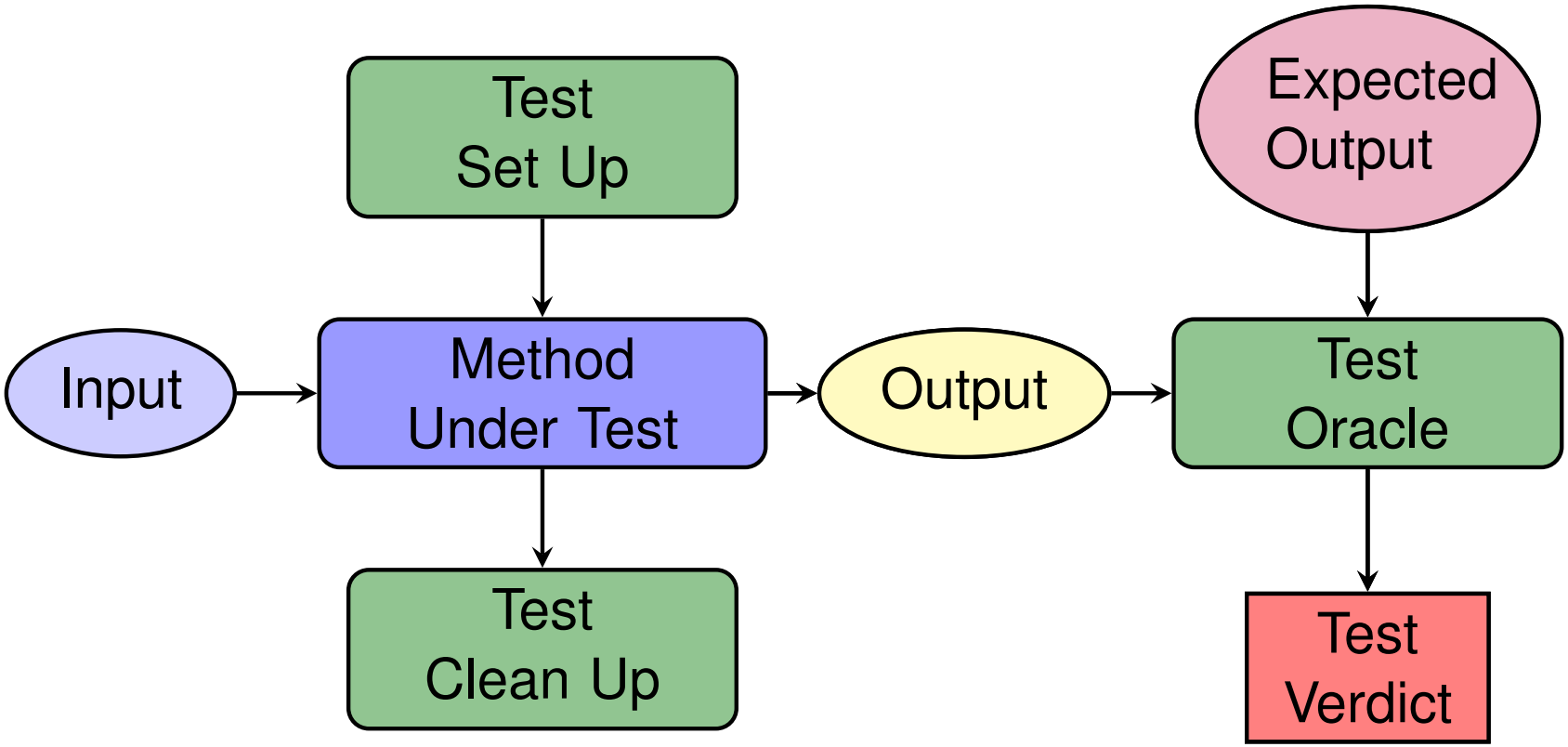

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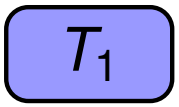

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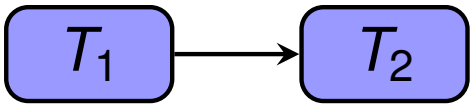

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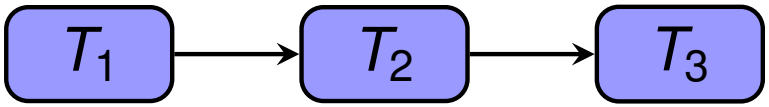

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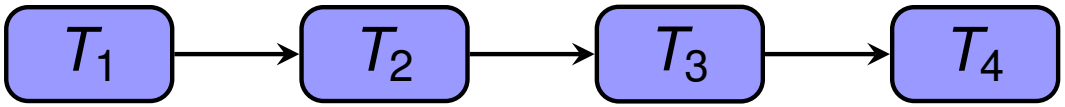

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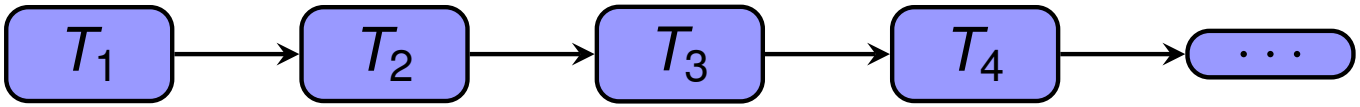

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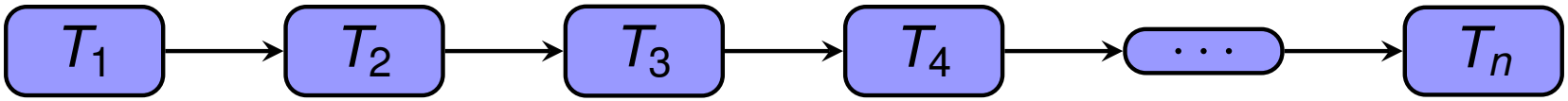
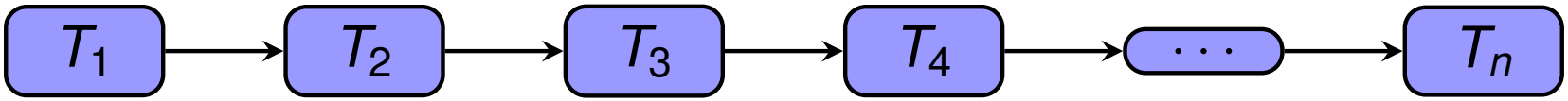


What is a Test Suite?

Organize the Test Cases into a Test Suite



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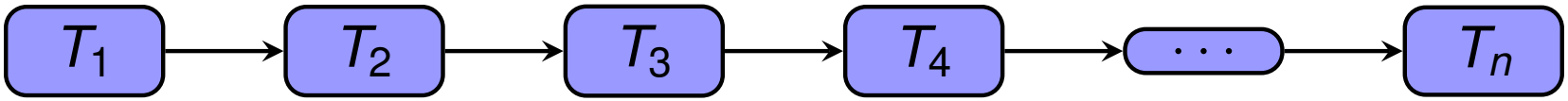

Tool Support for Software Testing?

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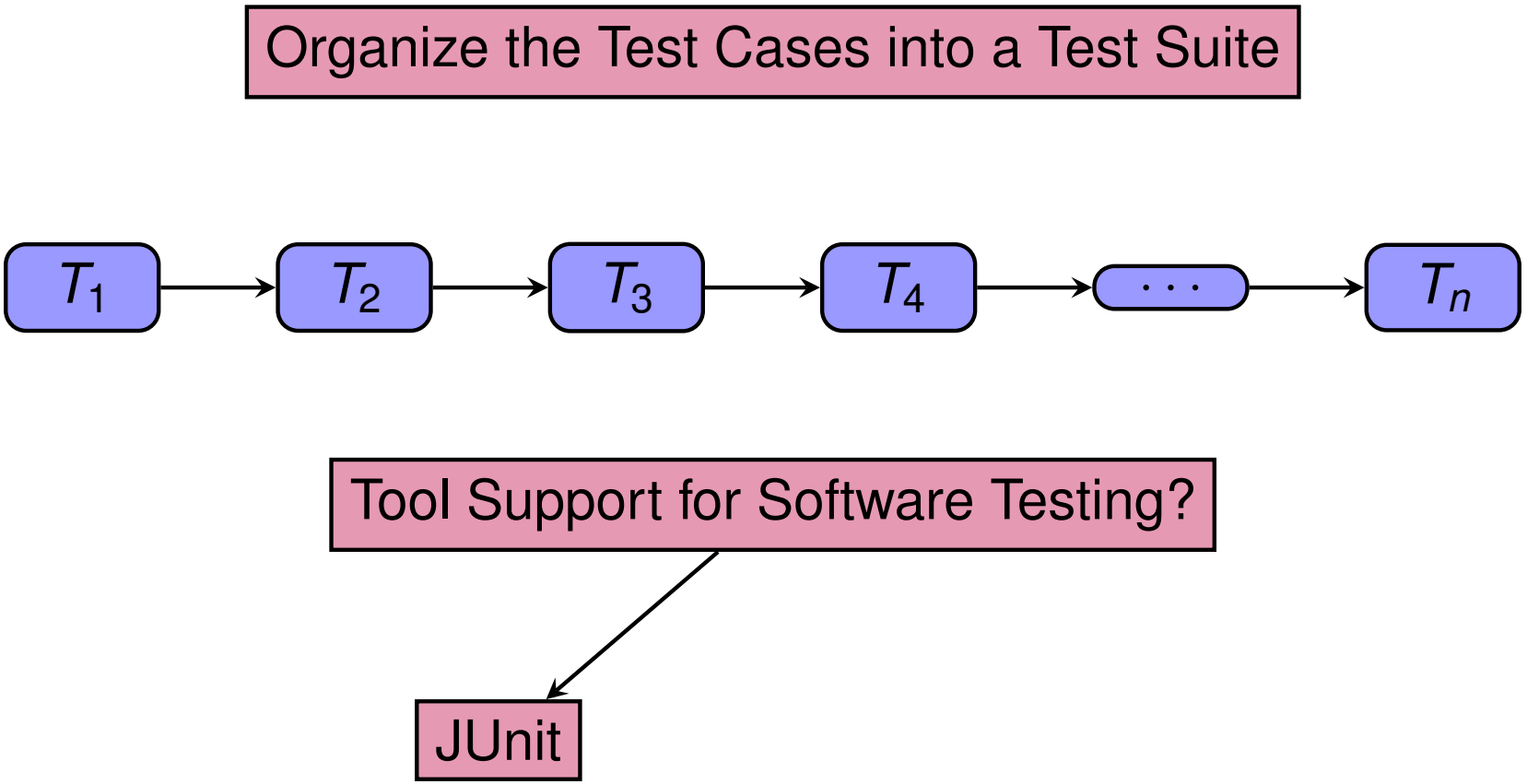

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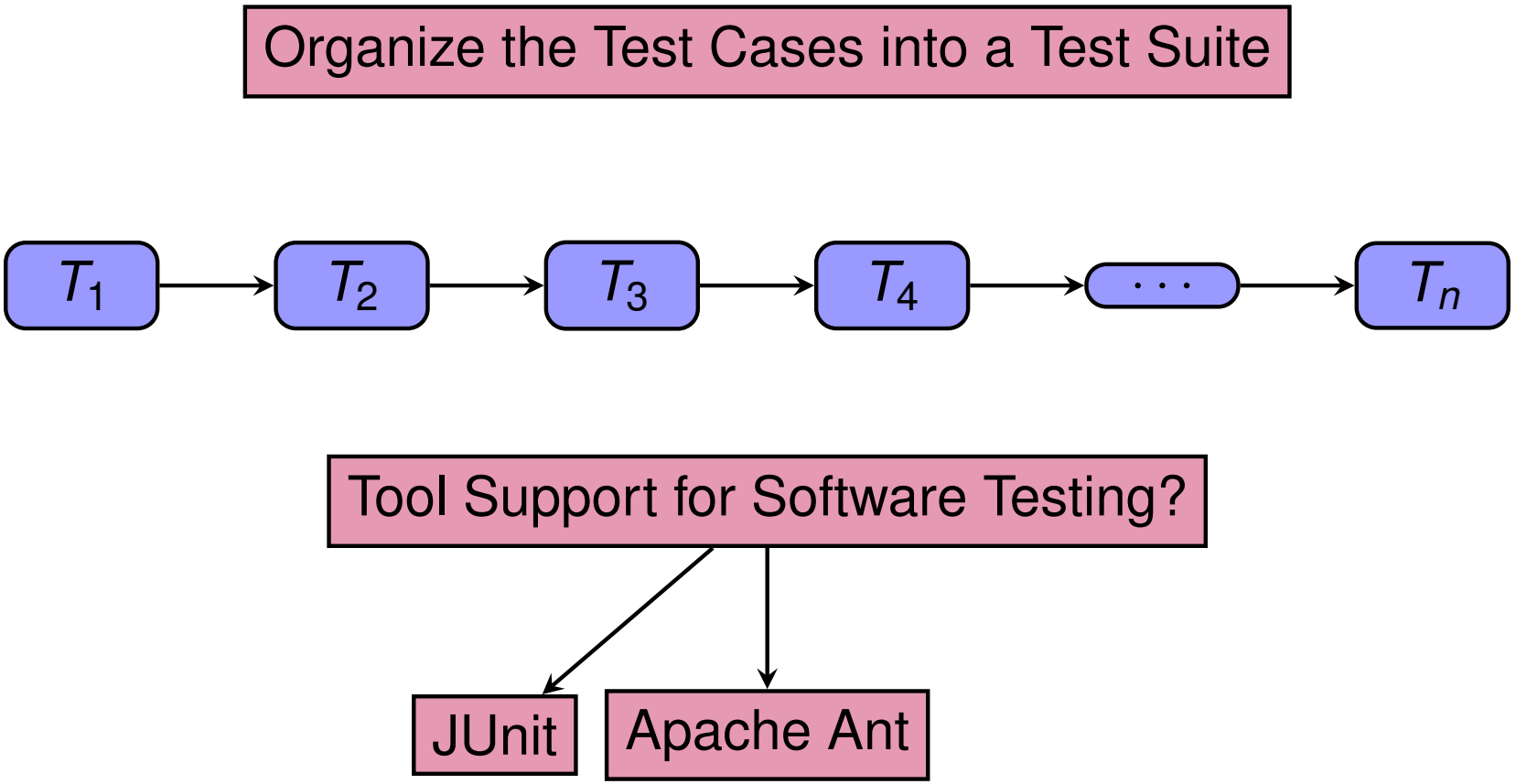

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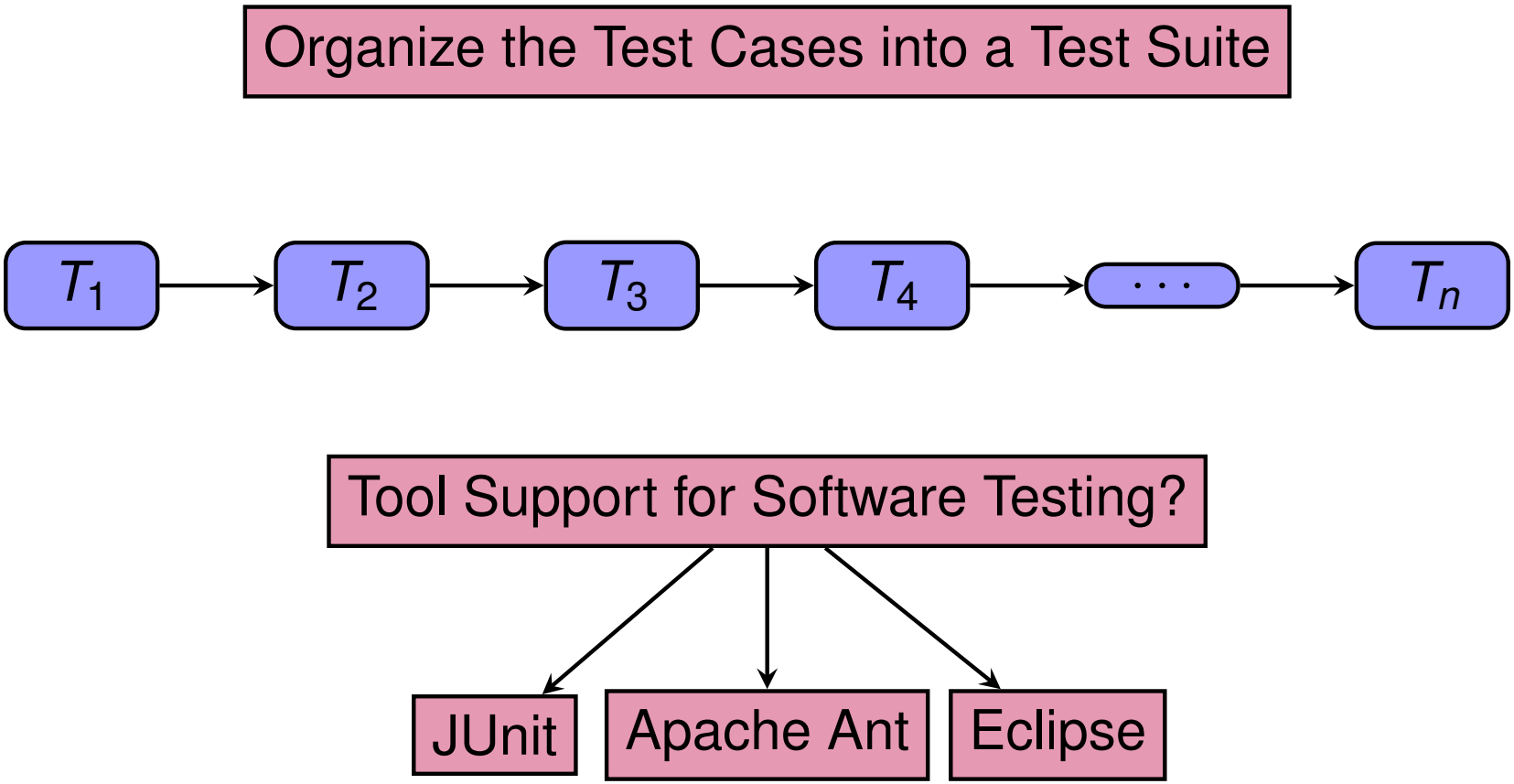

Test Suite Management

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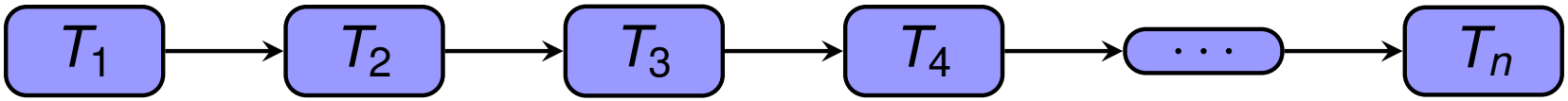

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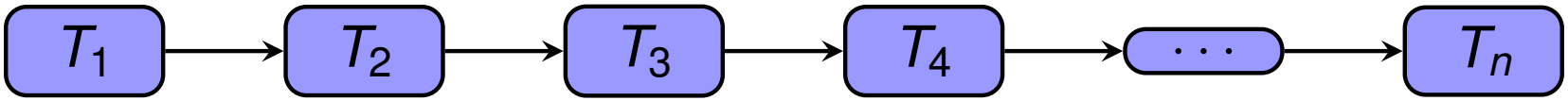
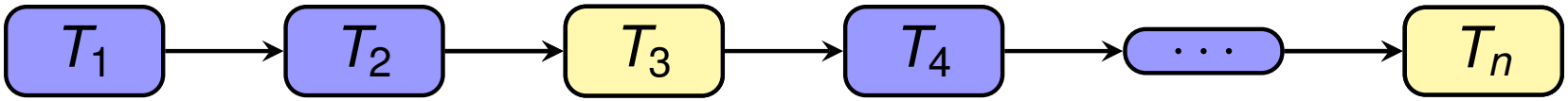


Regression Testing Technique

Test Suite Management

What if Some Test Cases are More Effective?



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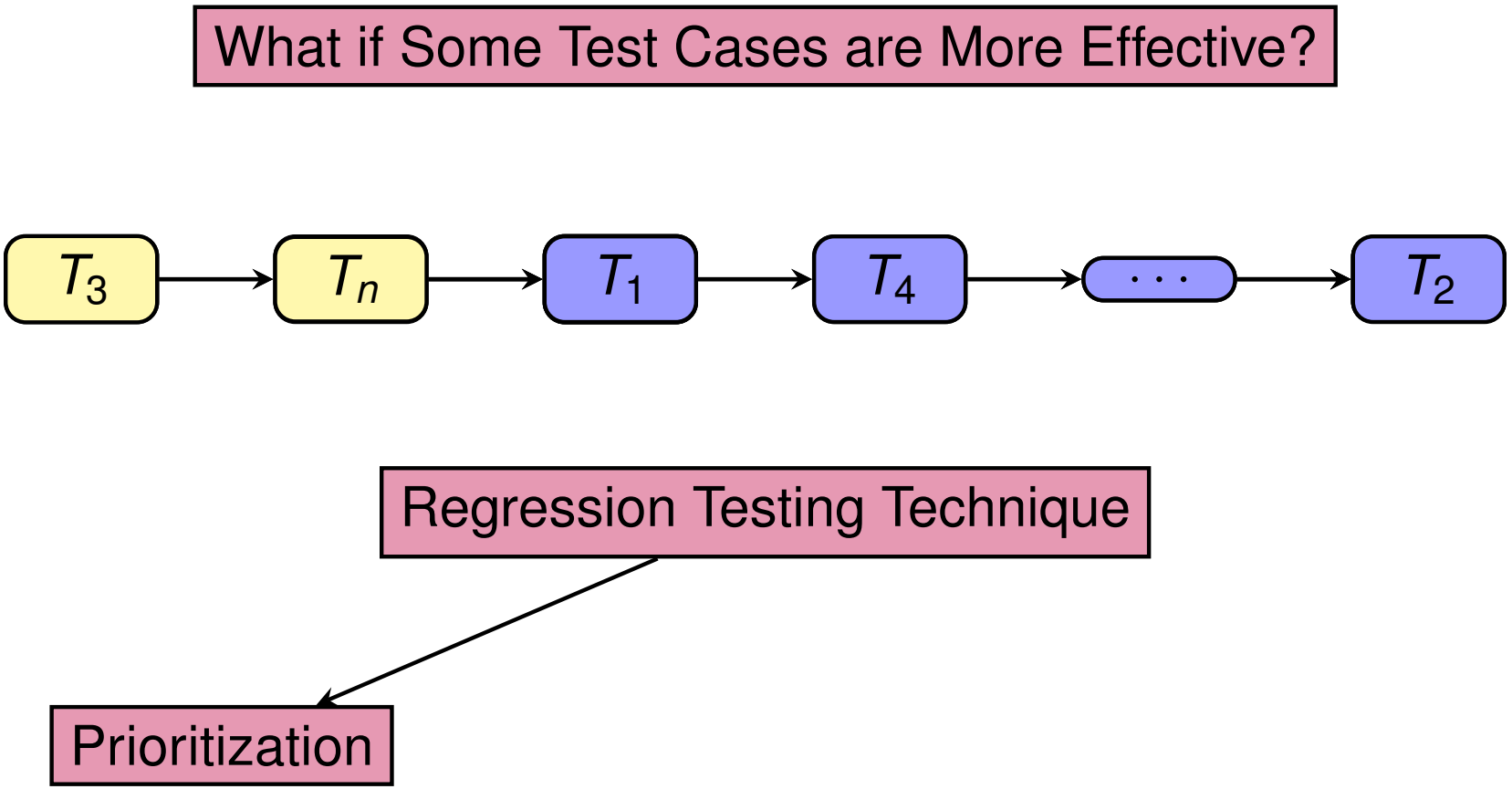

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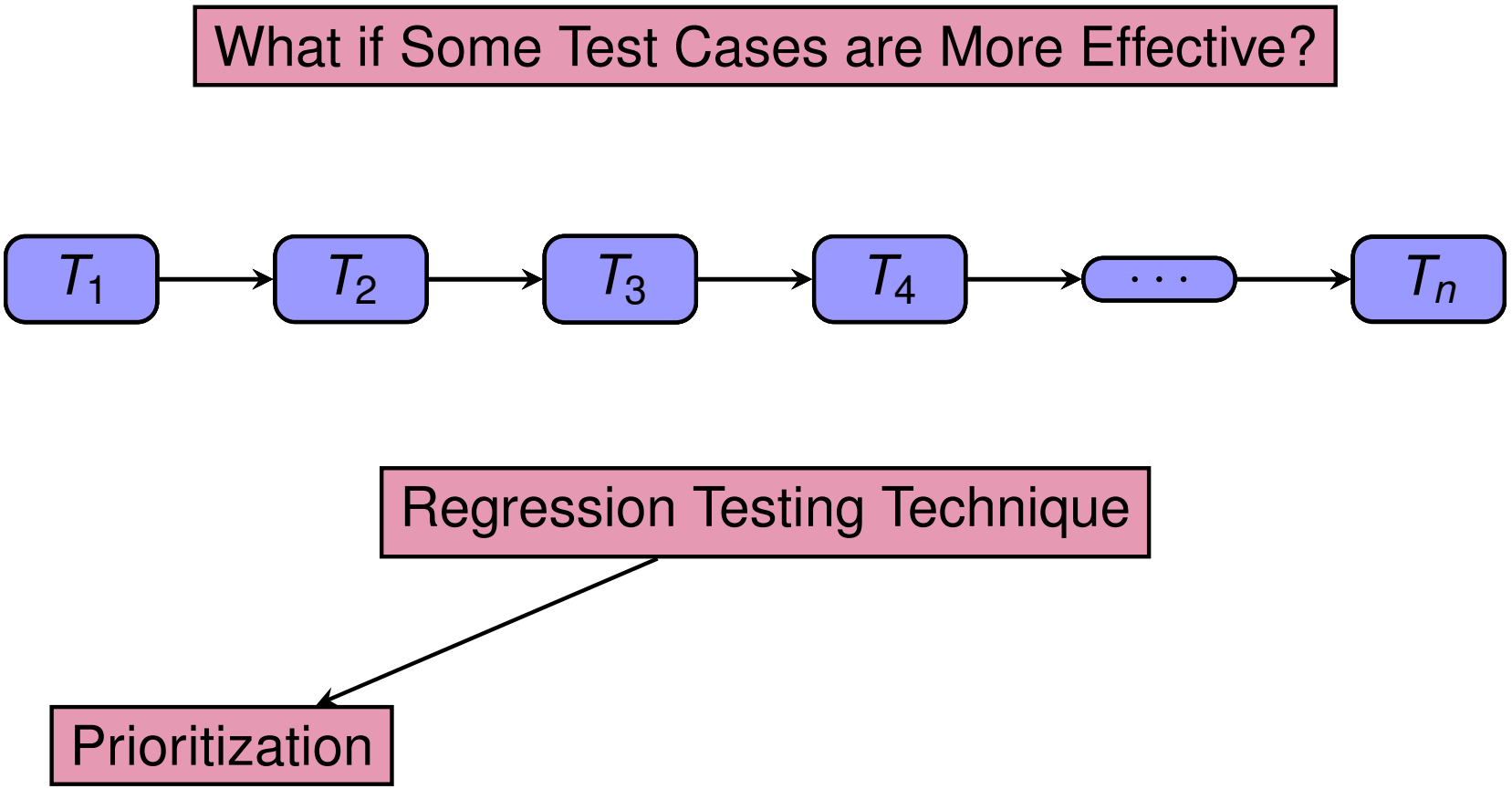

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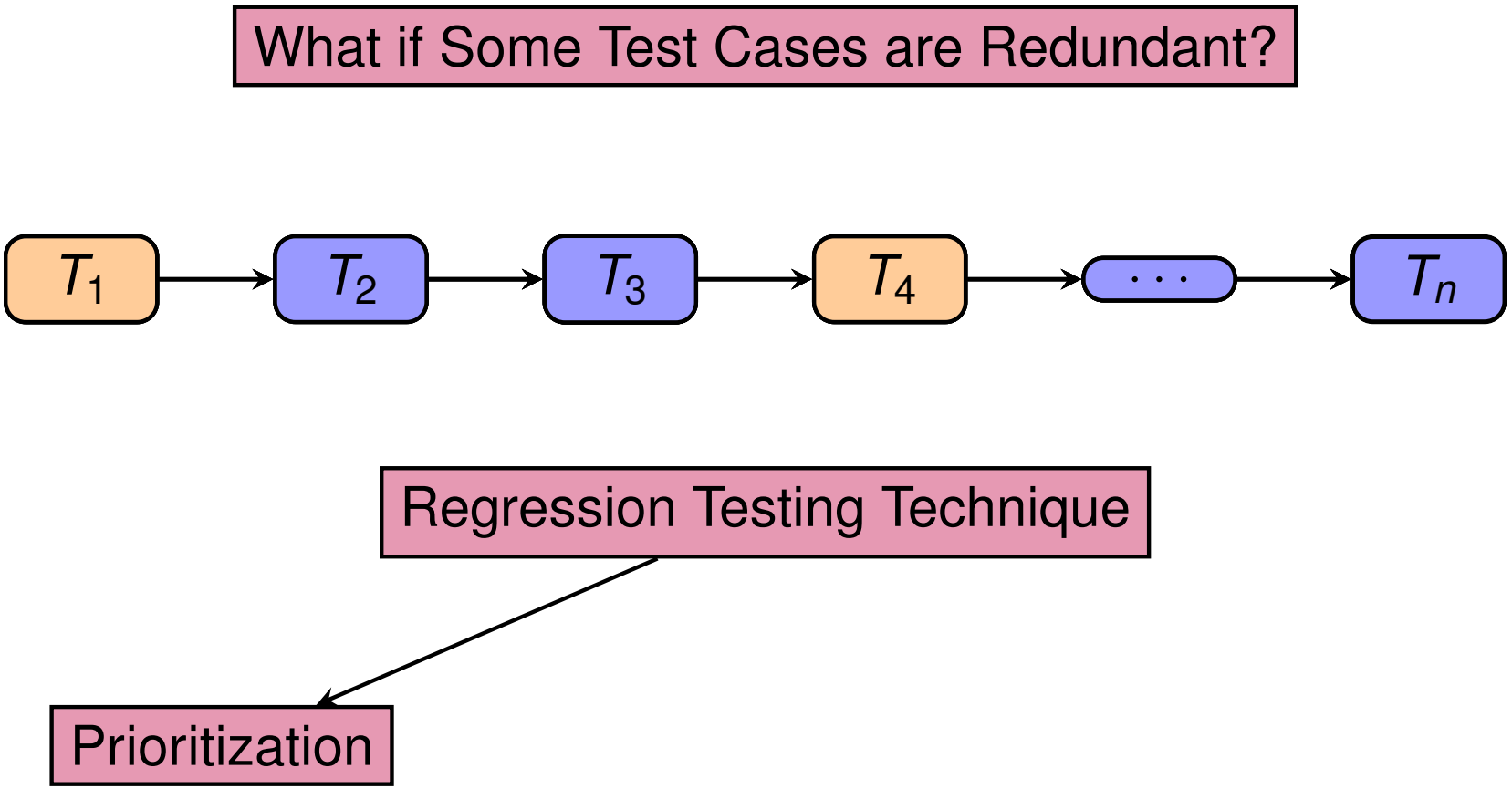

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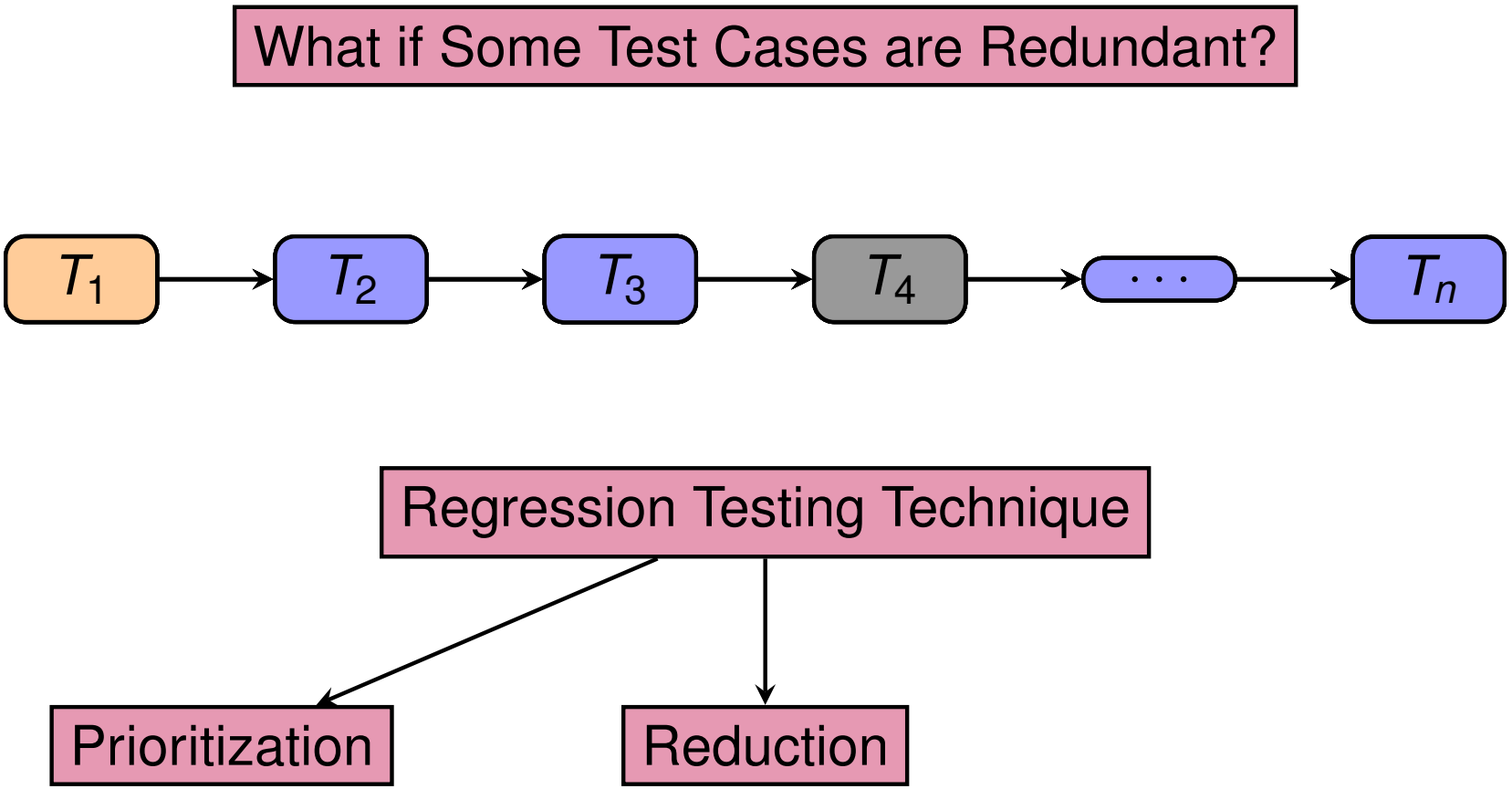

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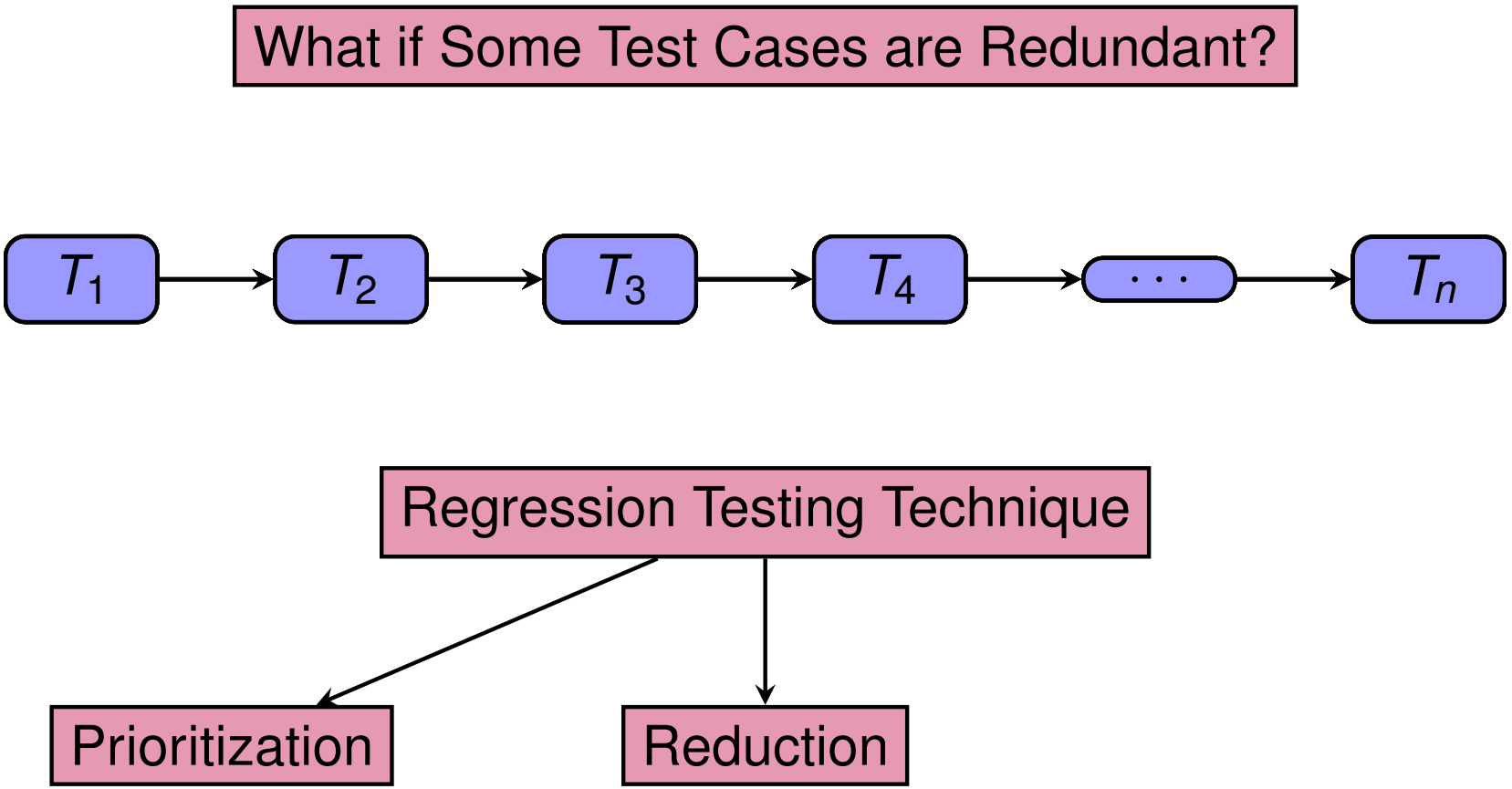

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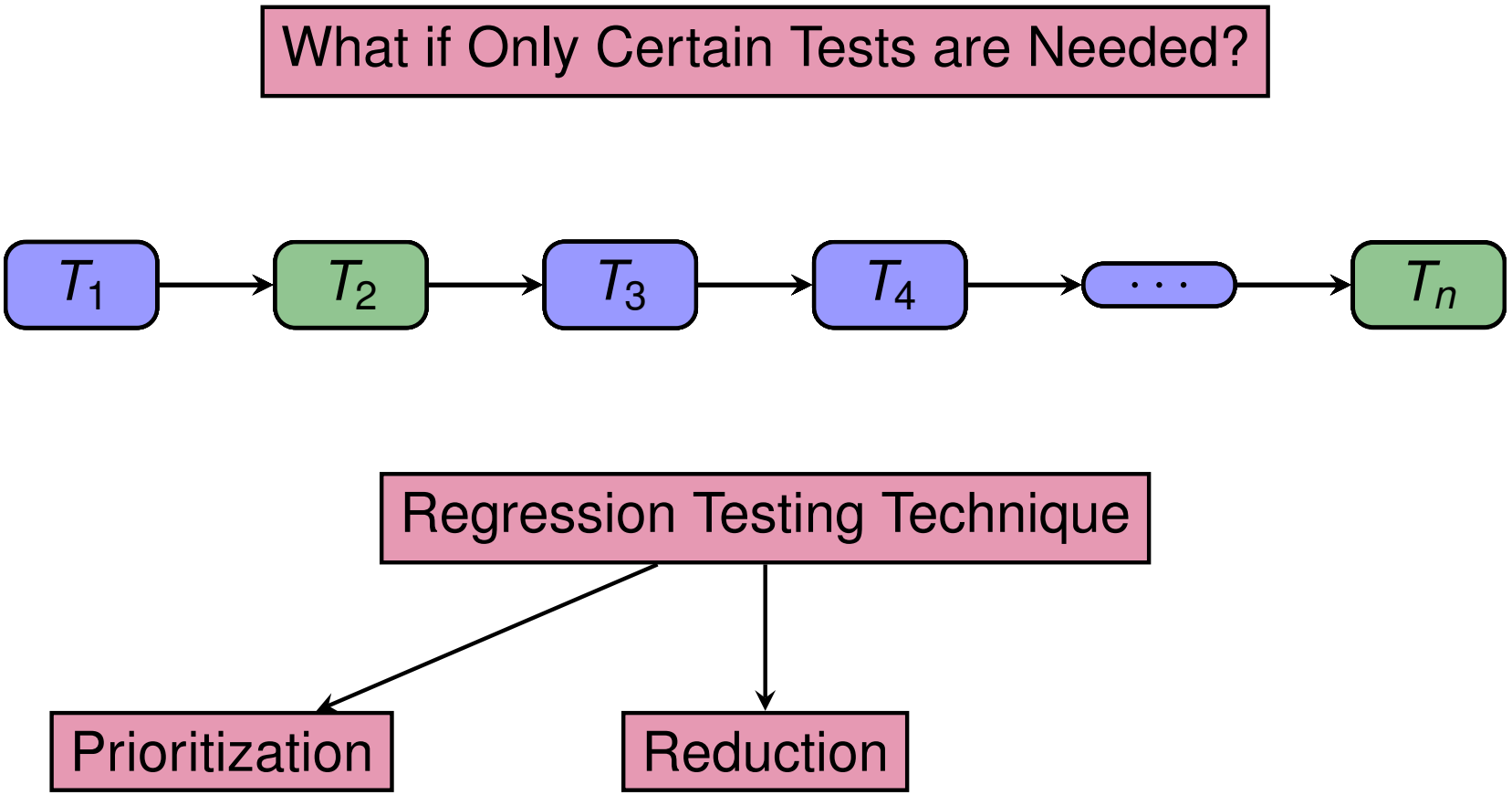

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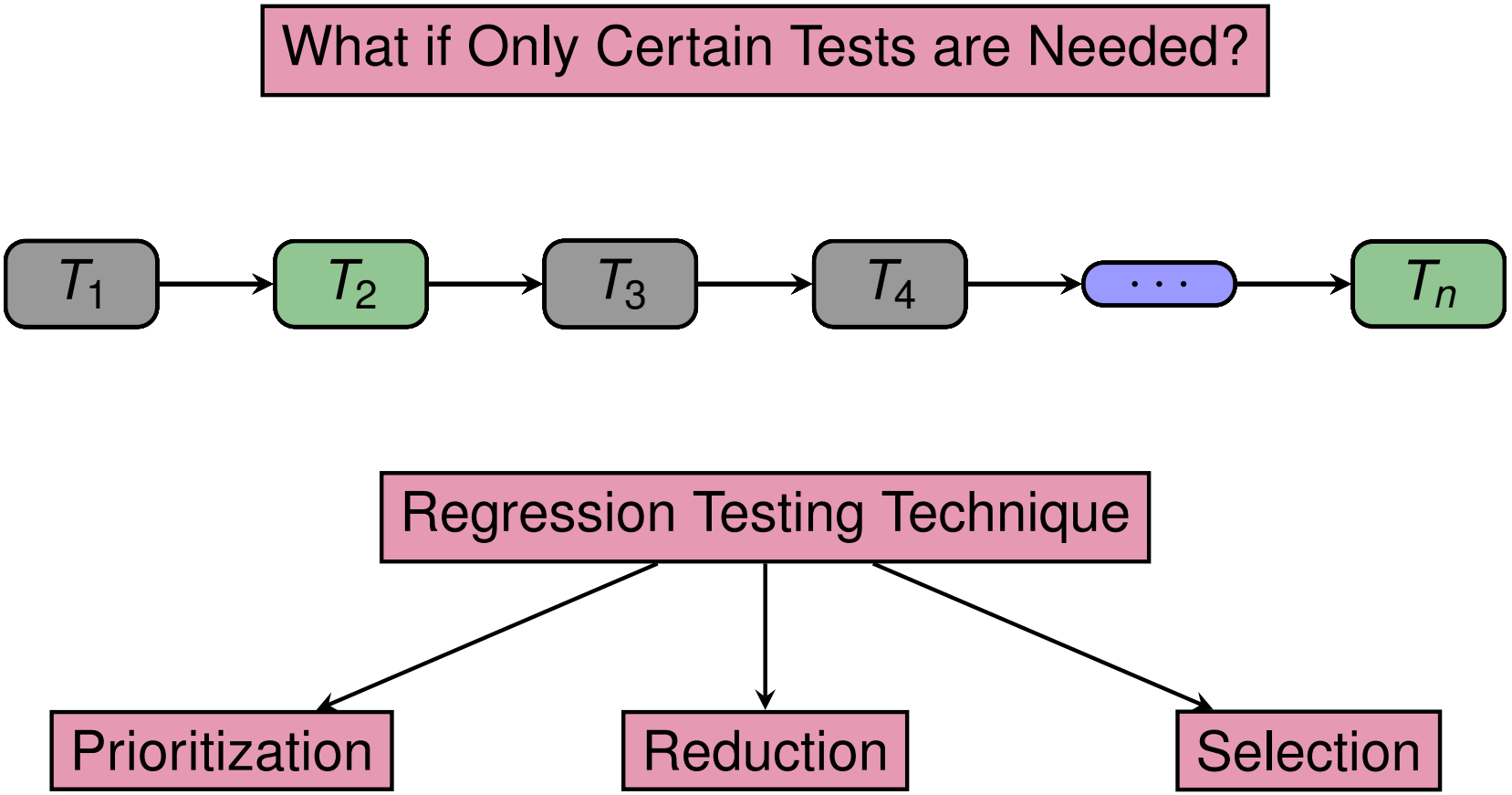

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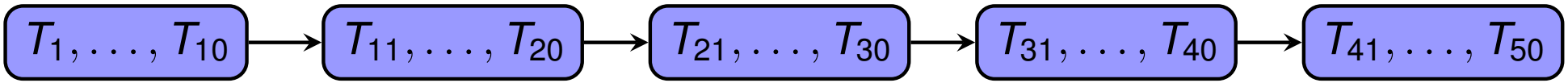

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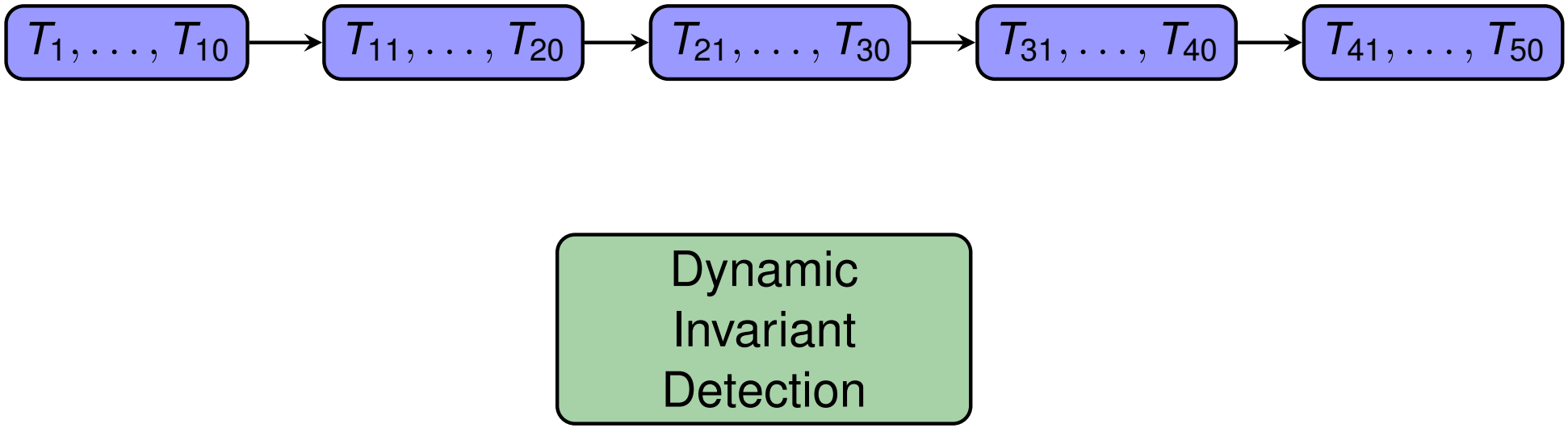

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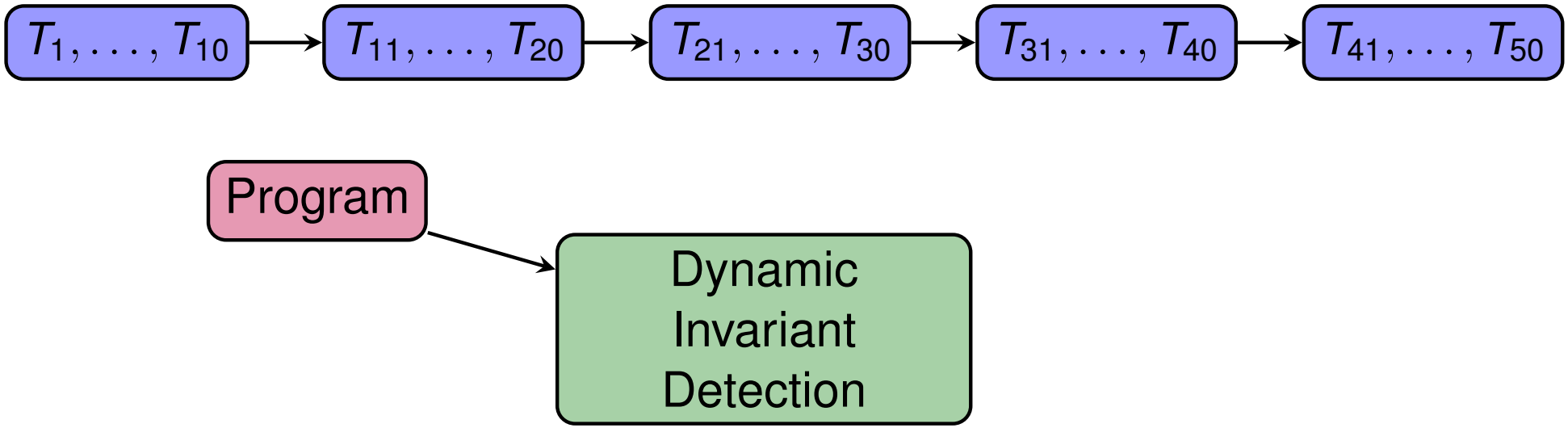

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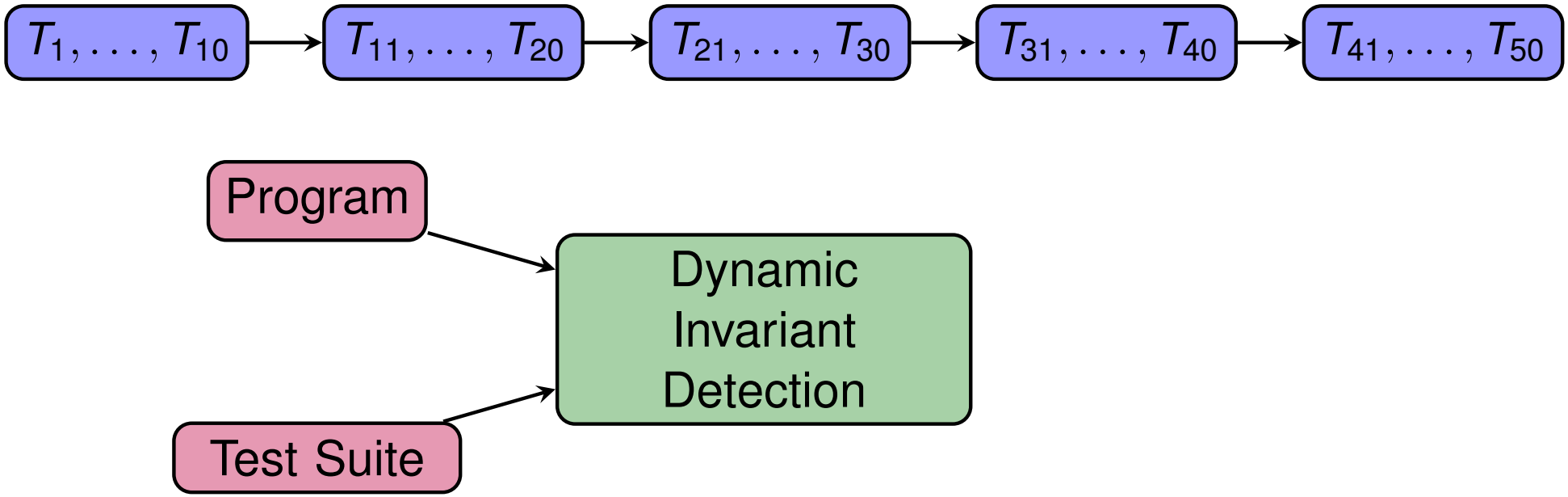

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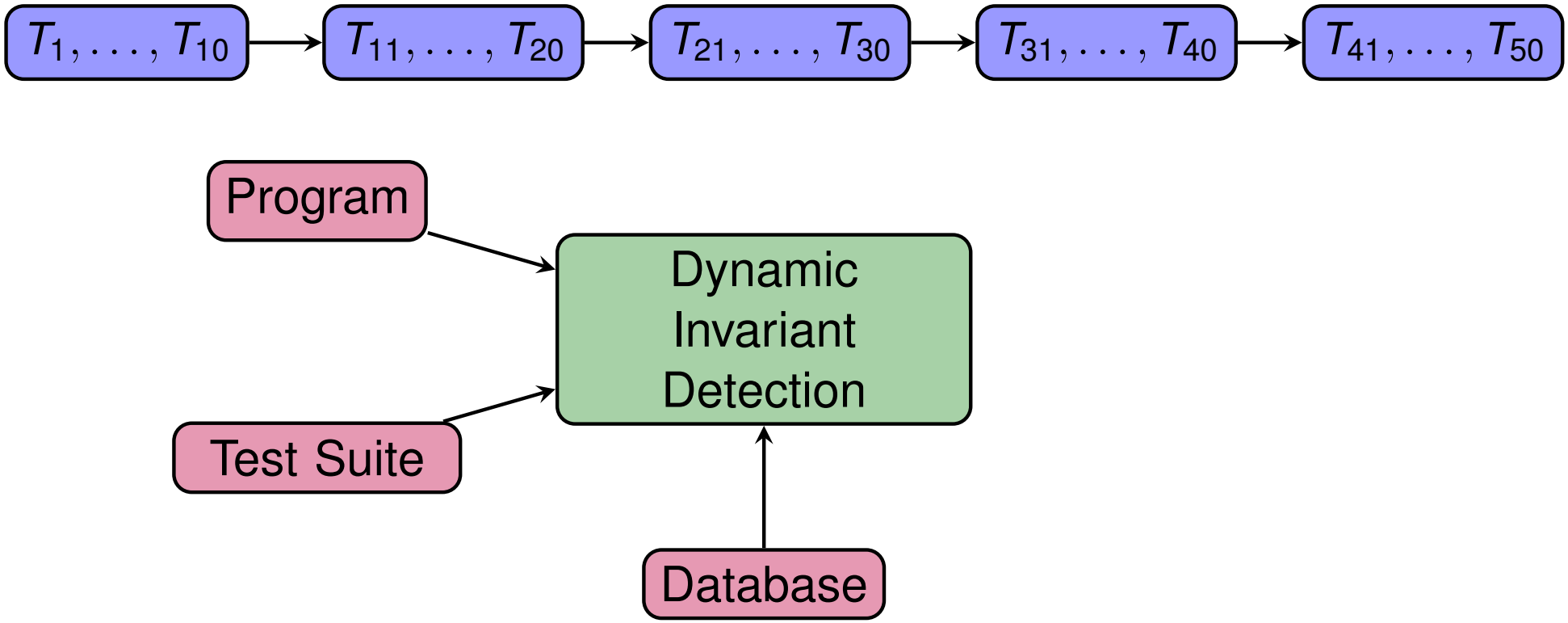

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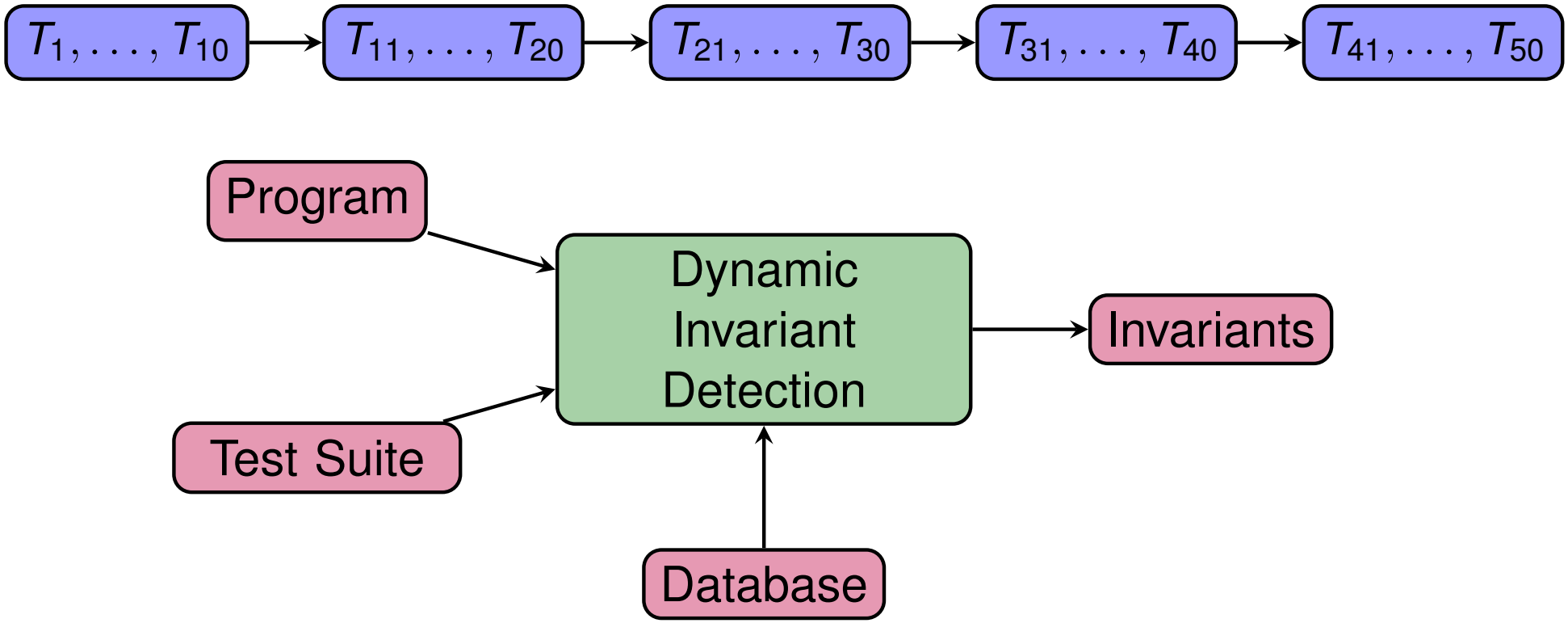

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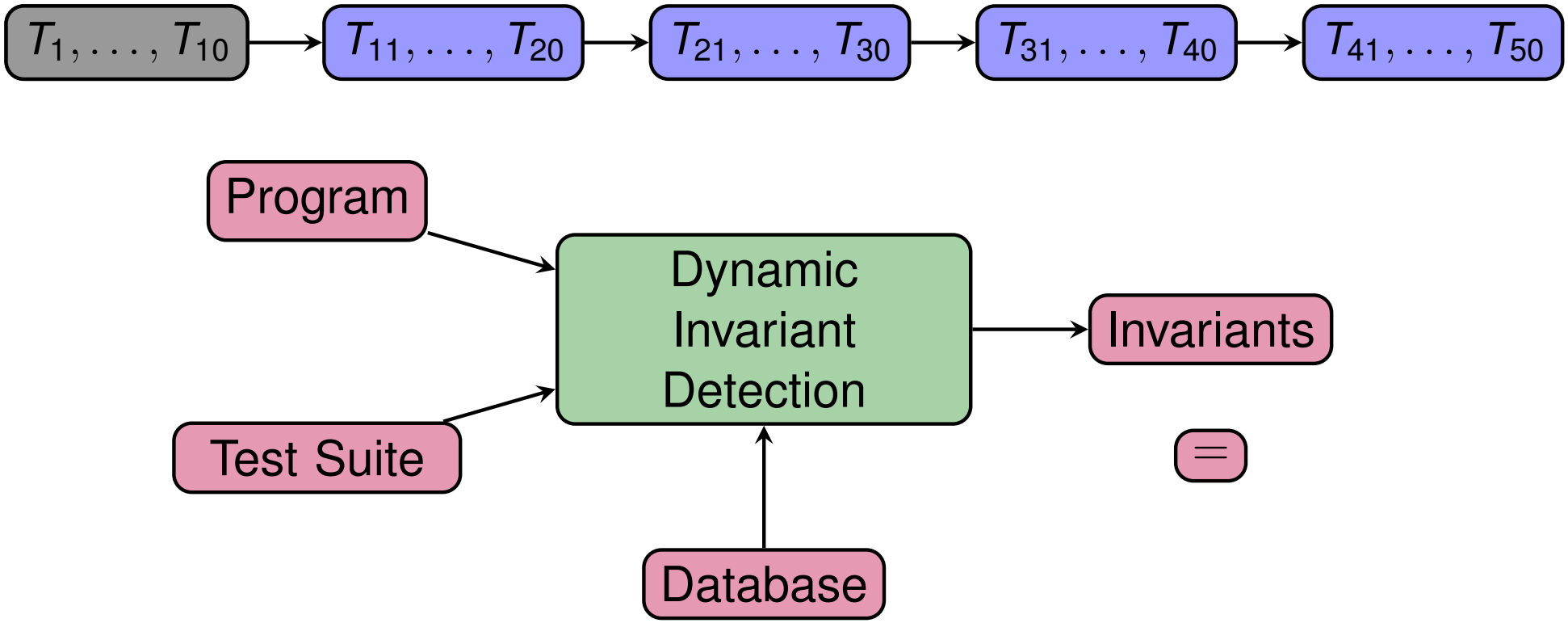

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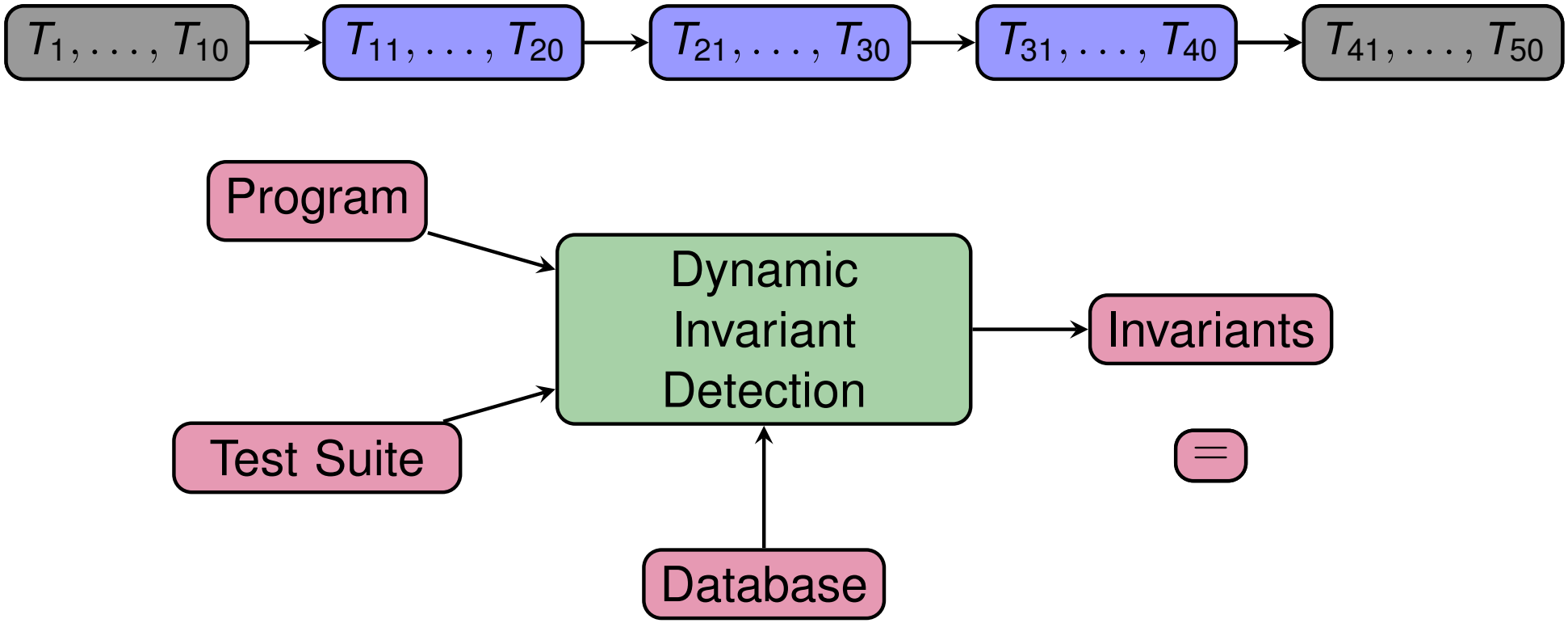

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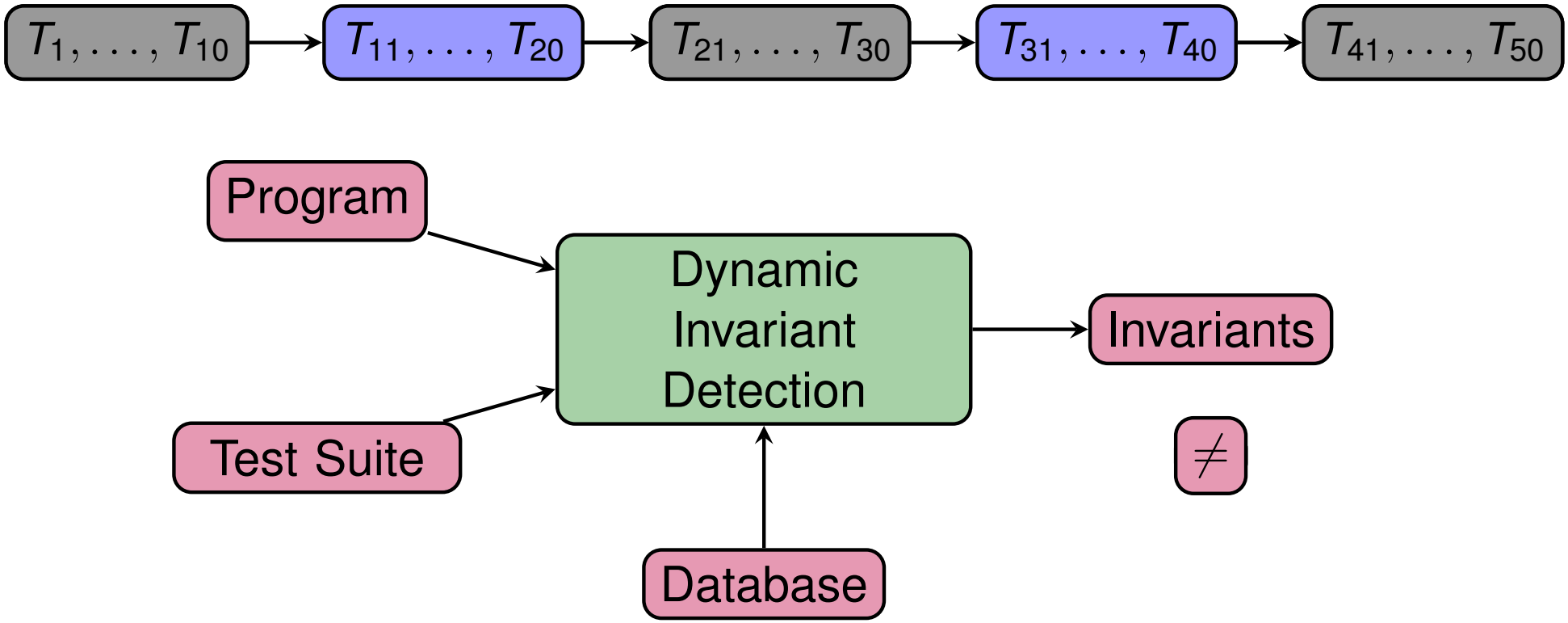

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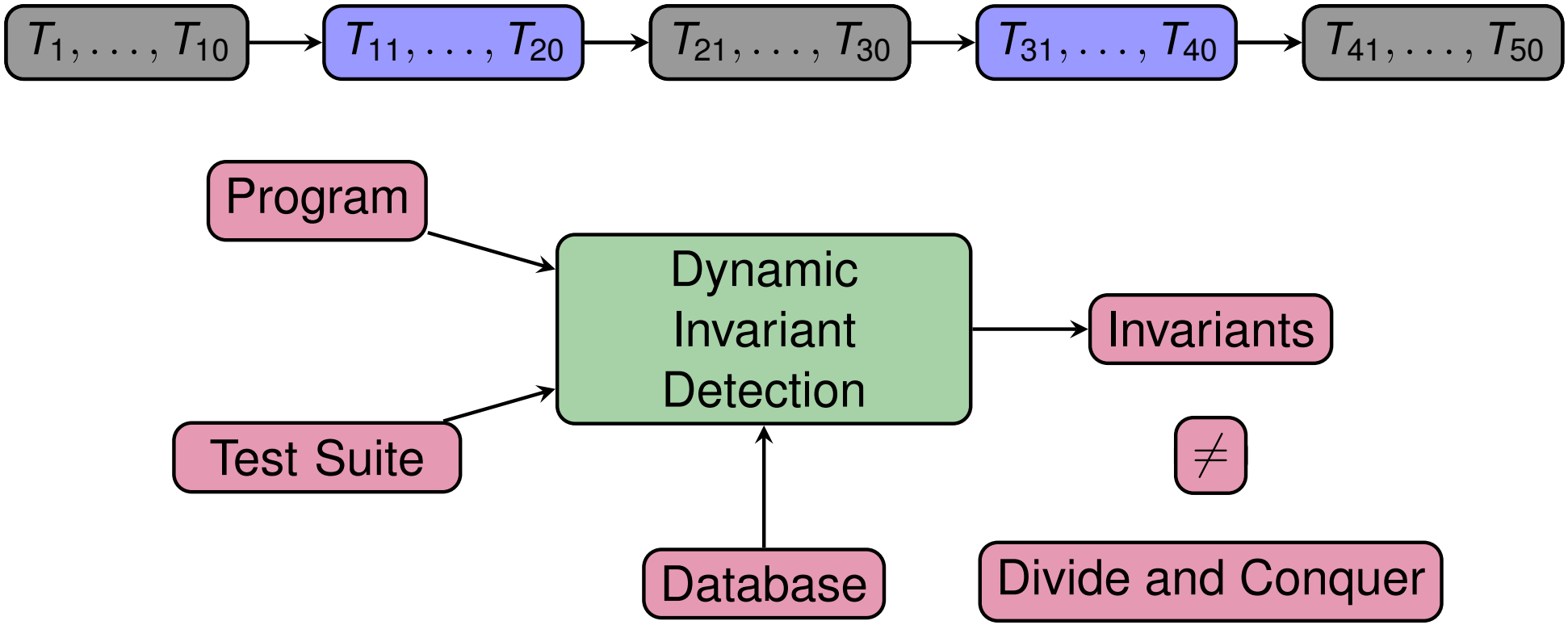

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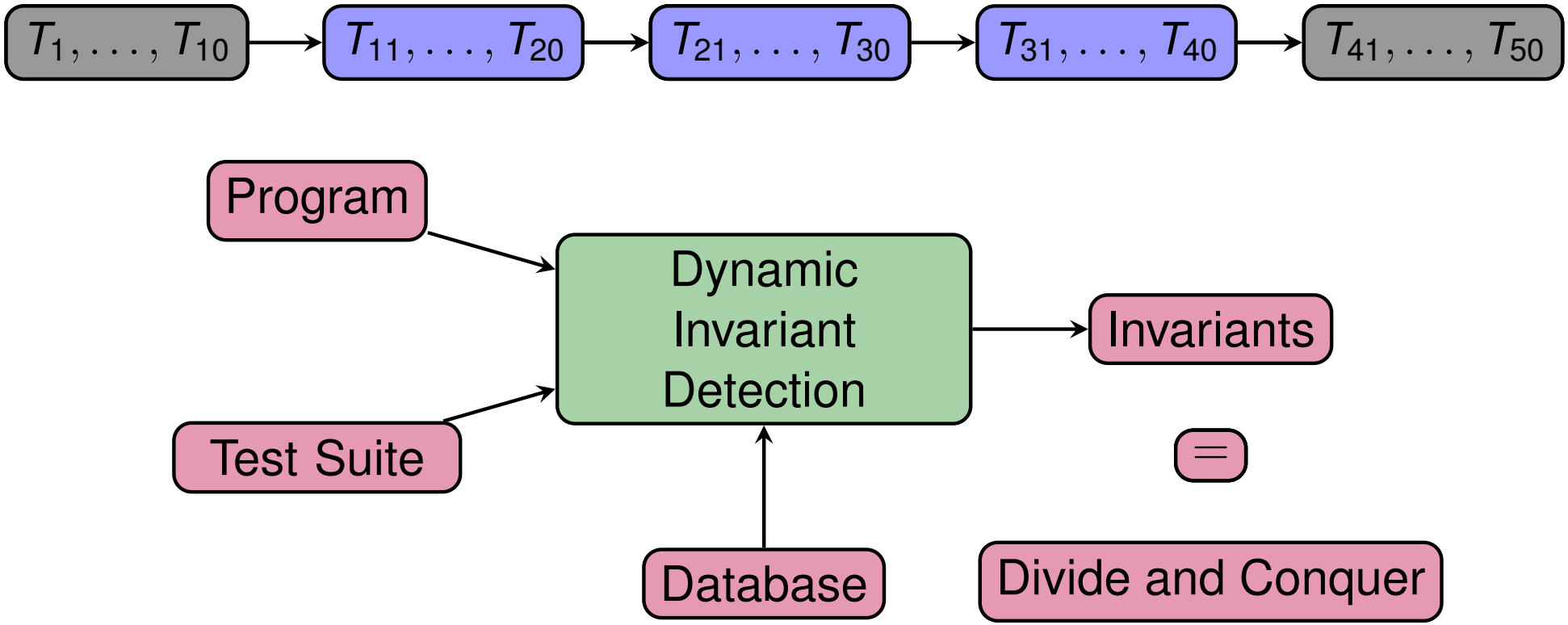

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Using Dynamic Invariant Detection to Support the Testing and Analysis of Database Applications

Gregory M. Kapfhammer

Department of Computer Science
Allegheny College
http://www.cs.allegheny.edu/~gkapfham/

Thank you for your attention!
I welcome your questions and comments.

ALLEGHENY COLLEGE