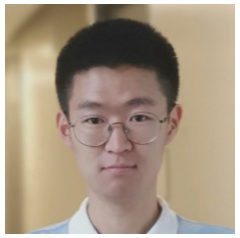
Reasoning Runtime Behavior of a Program with LLM: How Far Are We?

Junkai Chen*[1]

Zhiyuan Pan*[1]

Xing Hu[1]



Zhenhao Li[2]

Ge Li[3]

Xin Xia[1]

* Equal Contribution

[1] Zhejiang University, [2] York University, [3] Peking University

Benchmarking Code Reasoning

*Task: Predicting code execution behaviors **without** executing the code.*

```python
def f(var):
    if var.isdigit():
        return "int"
    elif var.replace('.', '', 1).isdigit():
        return "float"
    elif var.count(' ') == len(var) - 1:
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    else:
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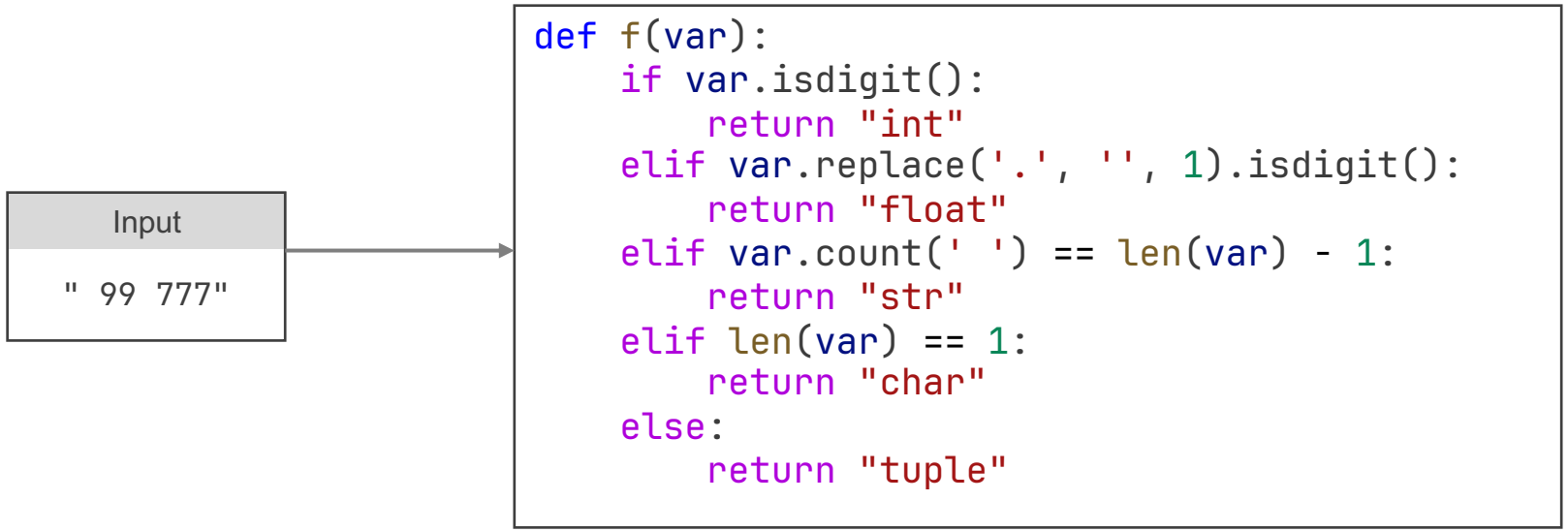

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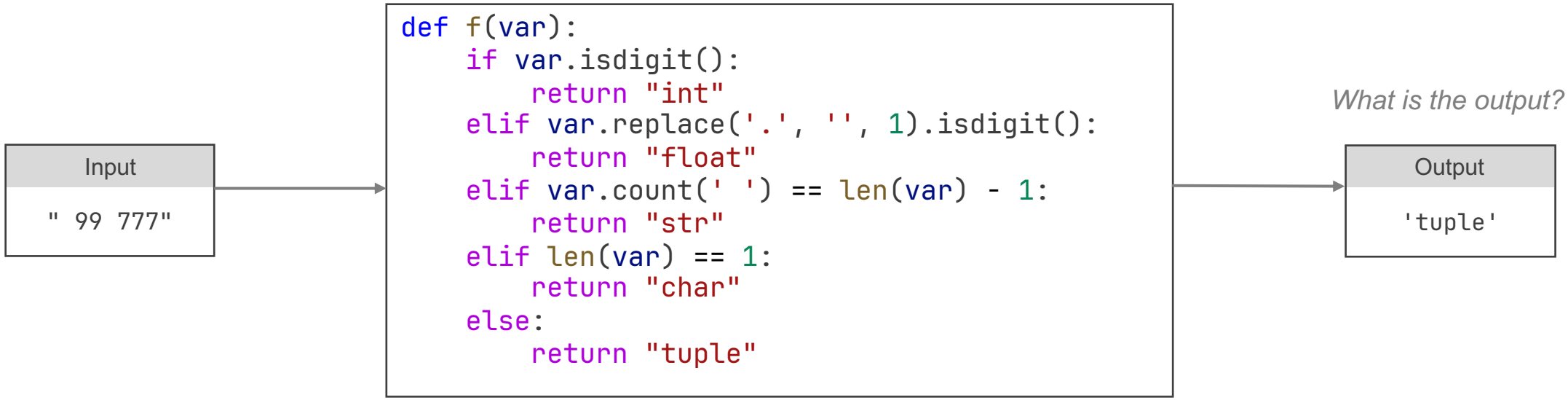

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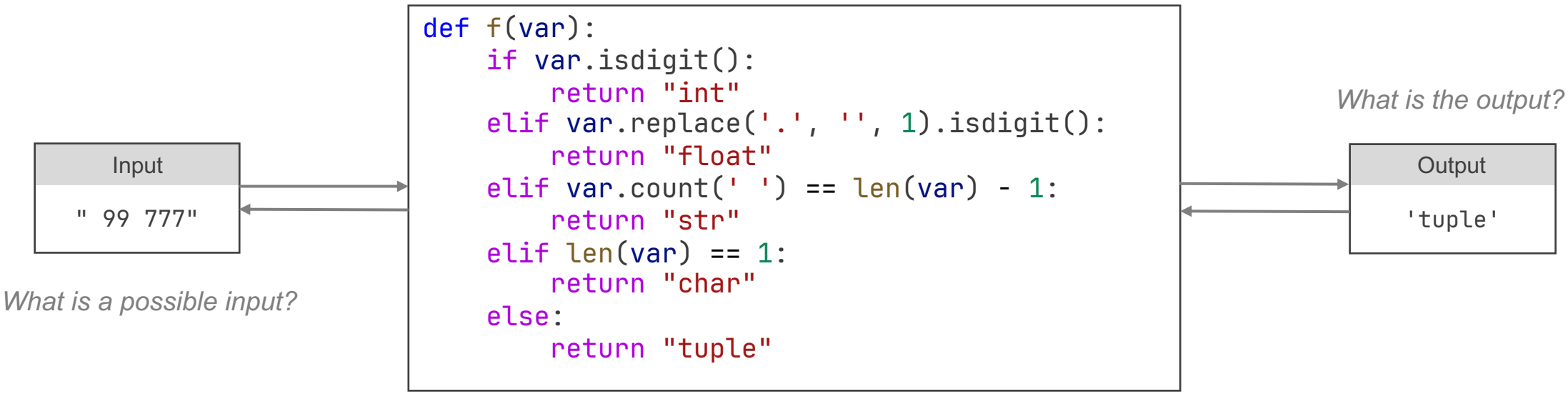

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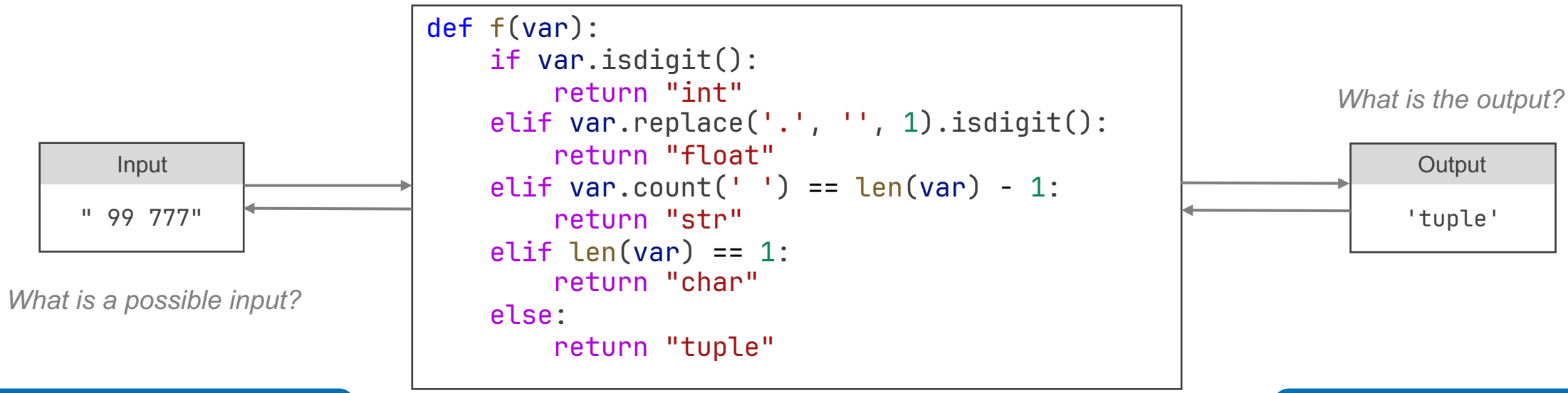

Previous benchmark[1]: Pre-/Post-Execution Information

1. Gu et al. "CRUXEval: A Benchmark for Code Reasoning, Understanding and Execution." *ICML 2024*.

Benchmarking Code Reasoning

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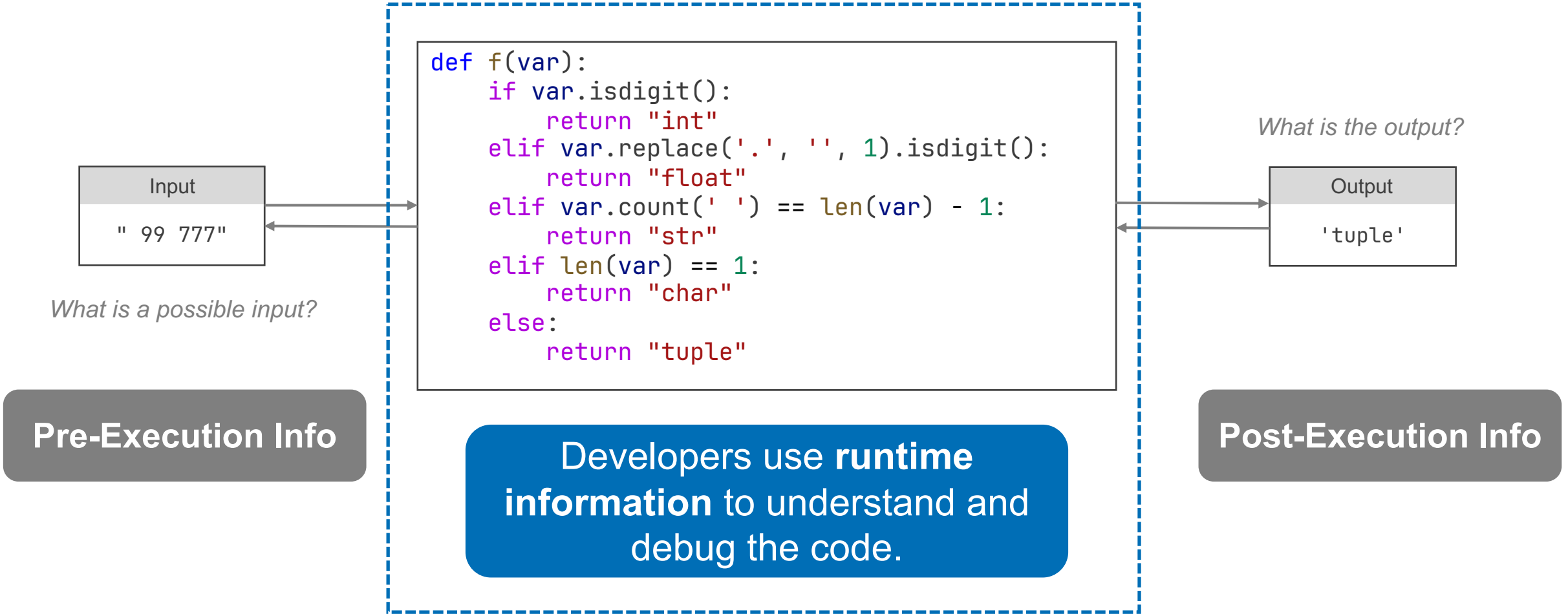

Benchmarking Code Reasoning

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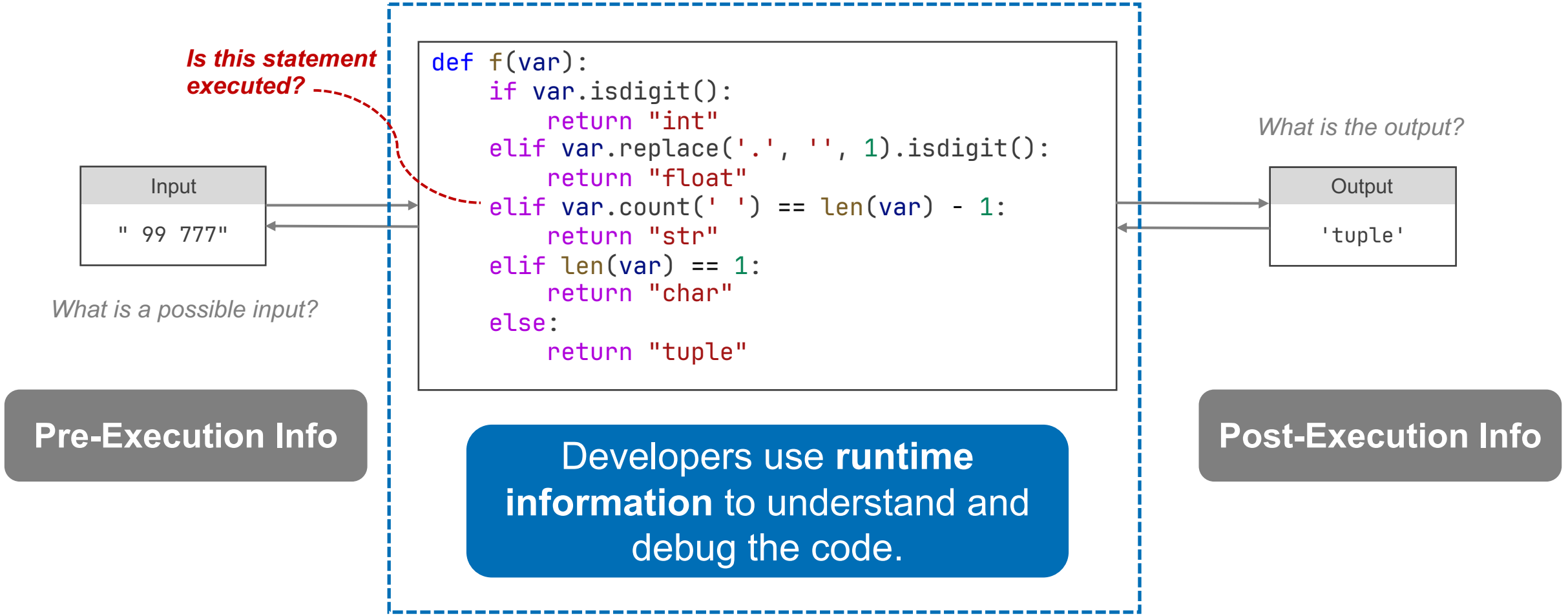

Benchmarking Code Reasoning

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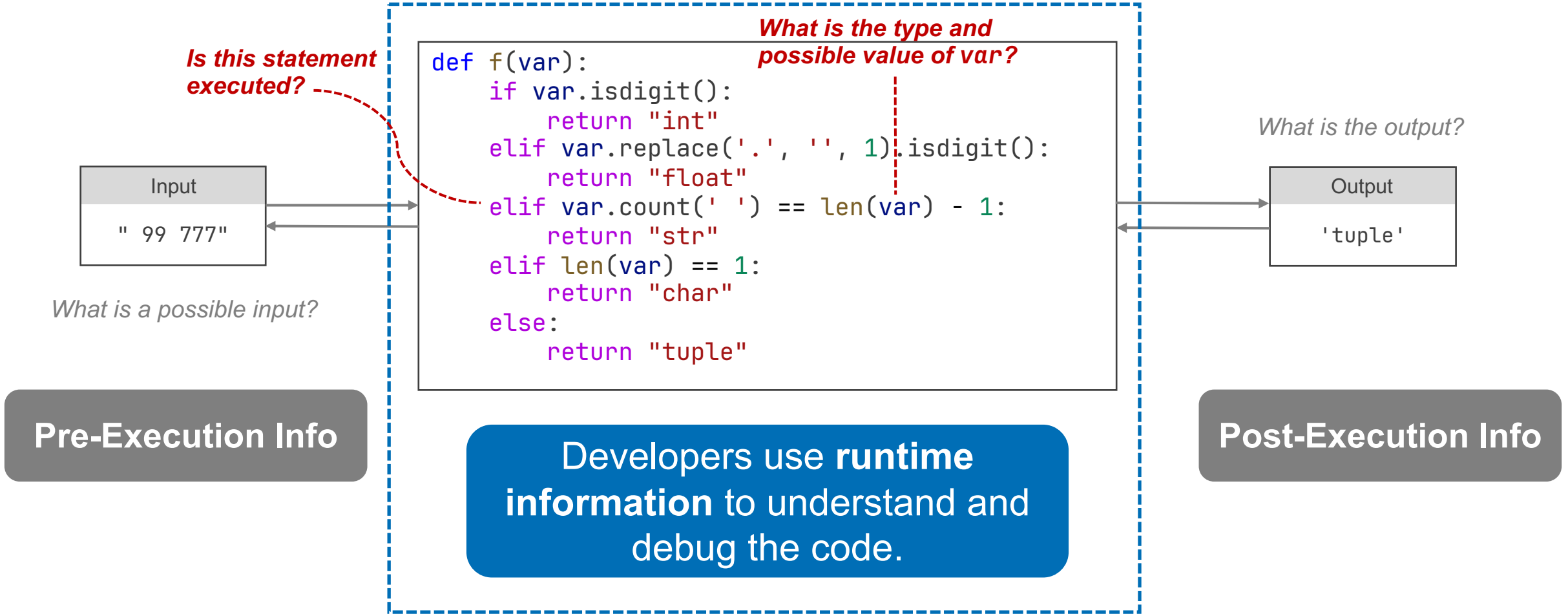

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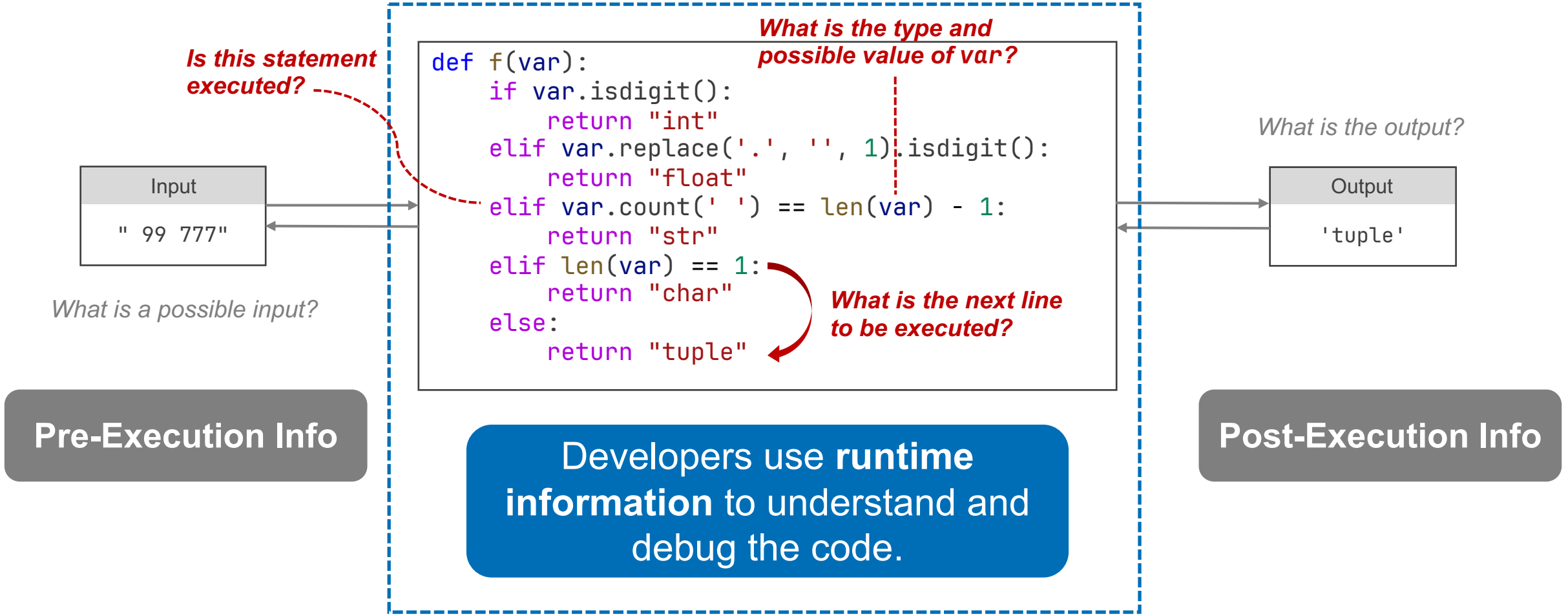

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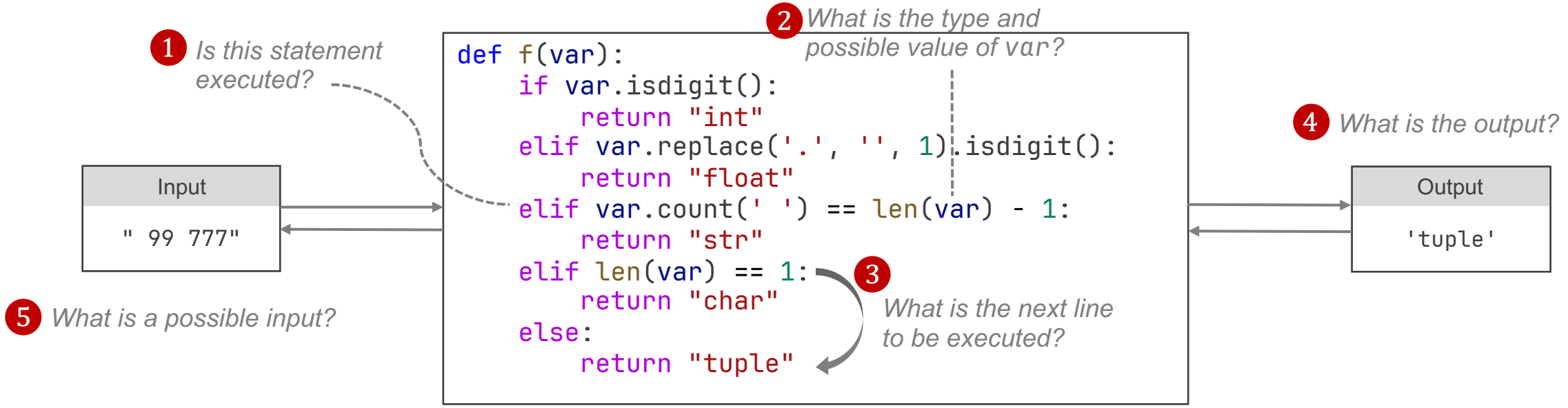


Previous[1]: 4 5

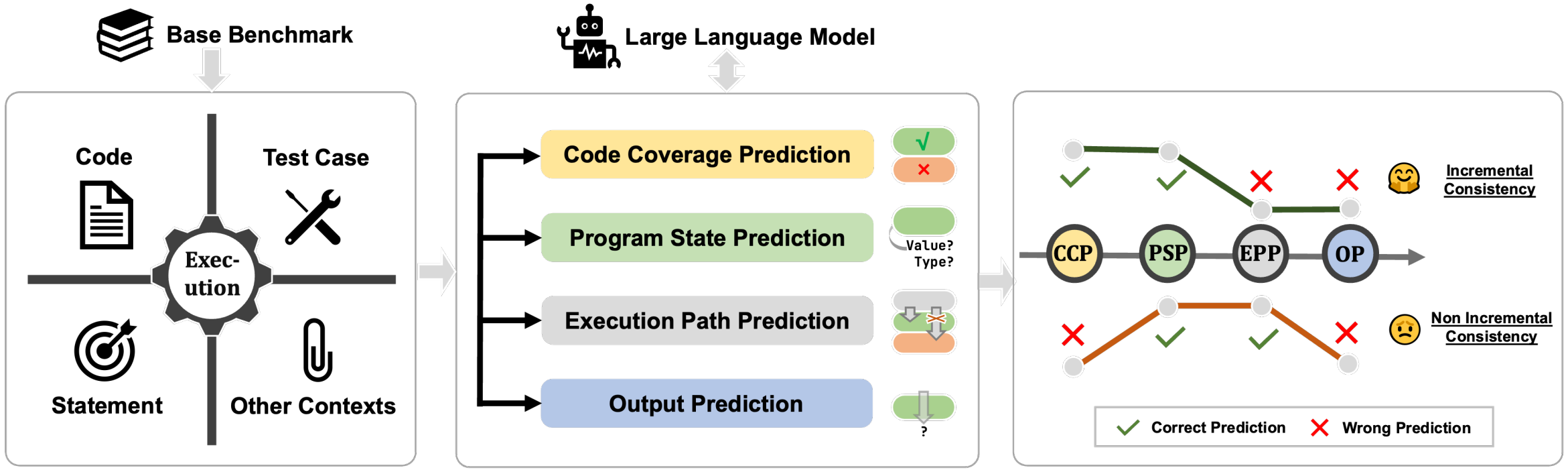
Pre-/Post- Execution Information **Only**

REval (Ours): 1 ▸ 2 ▸ 3 ▸ 4

With **Runtime Information & Consistency**

1. Gu et al. "CRUXEval: A Benchmark for Code Reasoning, Understanding and Execution." *ICML 2024*.

REval Framework



1: Runtime Behavior Reasoning

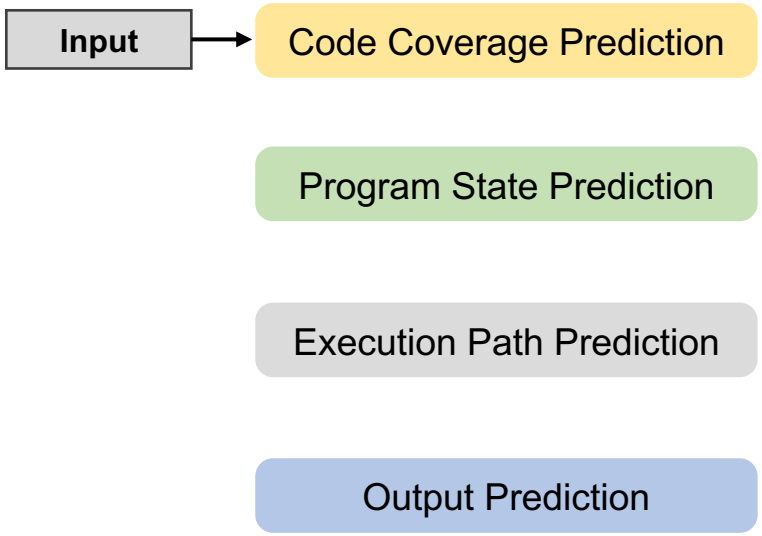
2: *Incremental Consistency* Evaluation

Reason about **four kinds of runtime behavior**.

Evaluate **consistency** with a sequence of previous results.

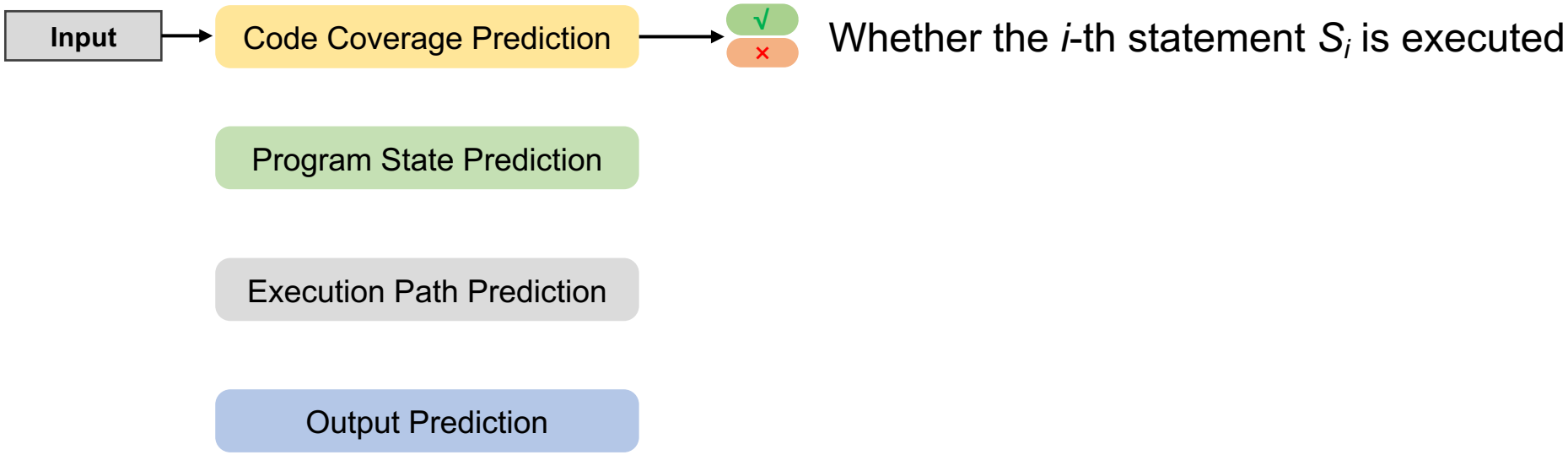
Task Definition & Metrics

Component I: Runtime Behavior Reasoning



Task Definition & Metrics

Component I: Runtime Behavior Reasoning



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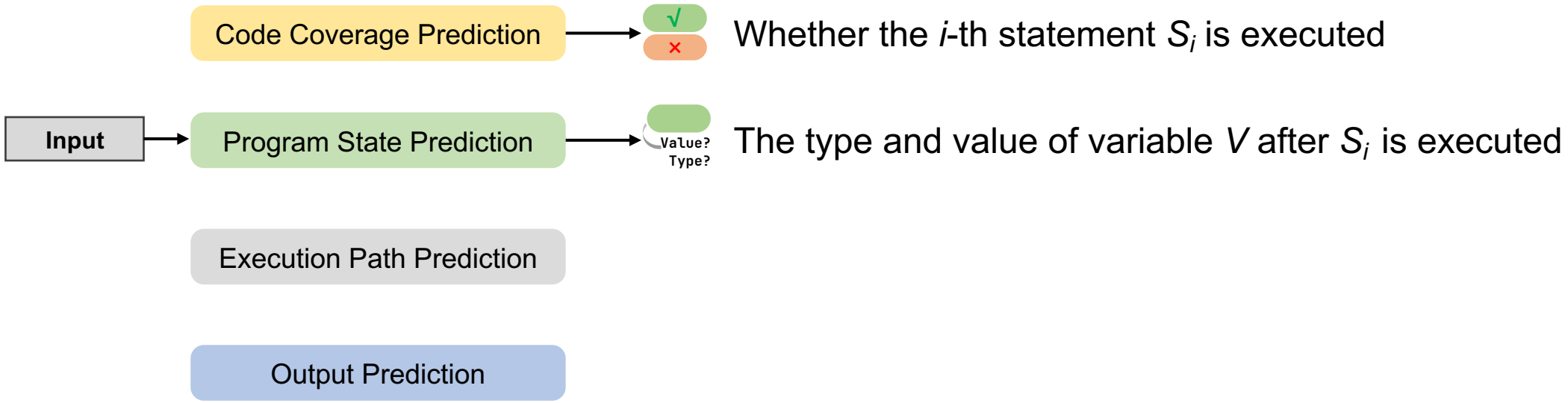

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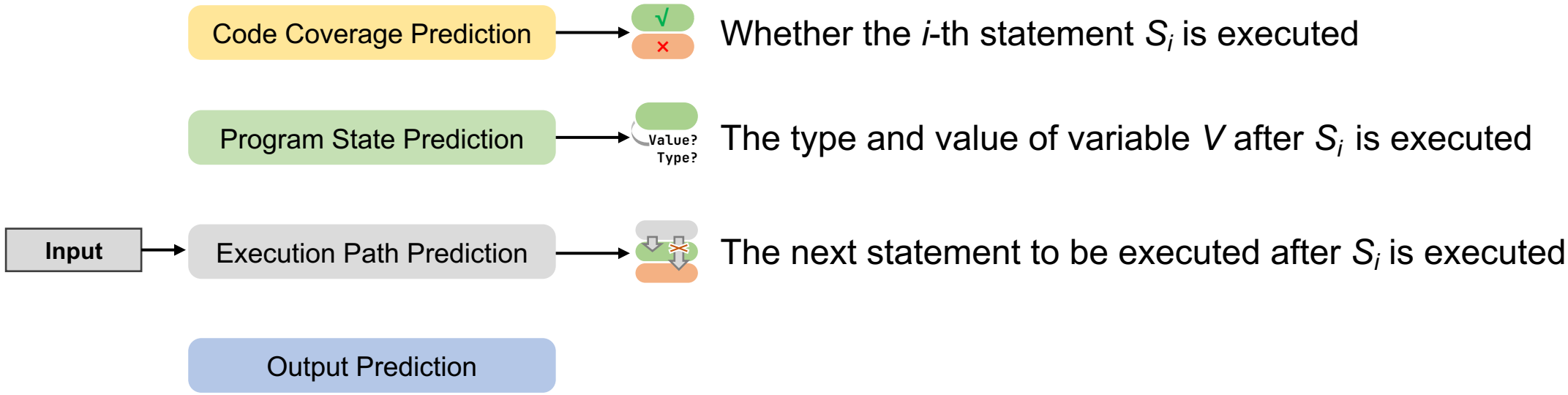

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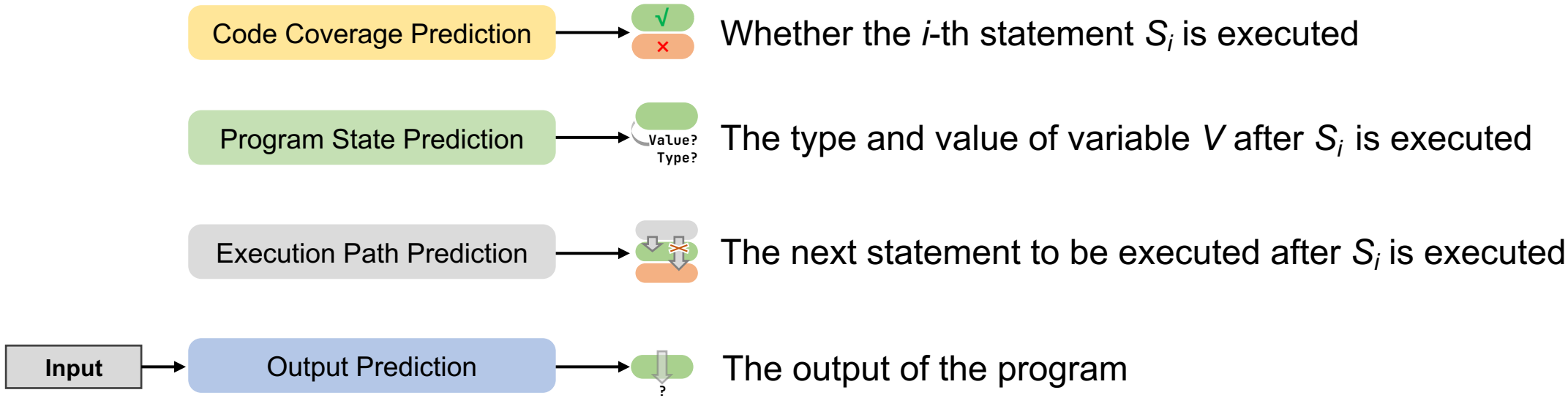

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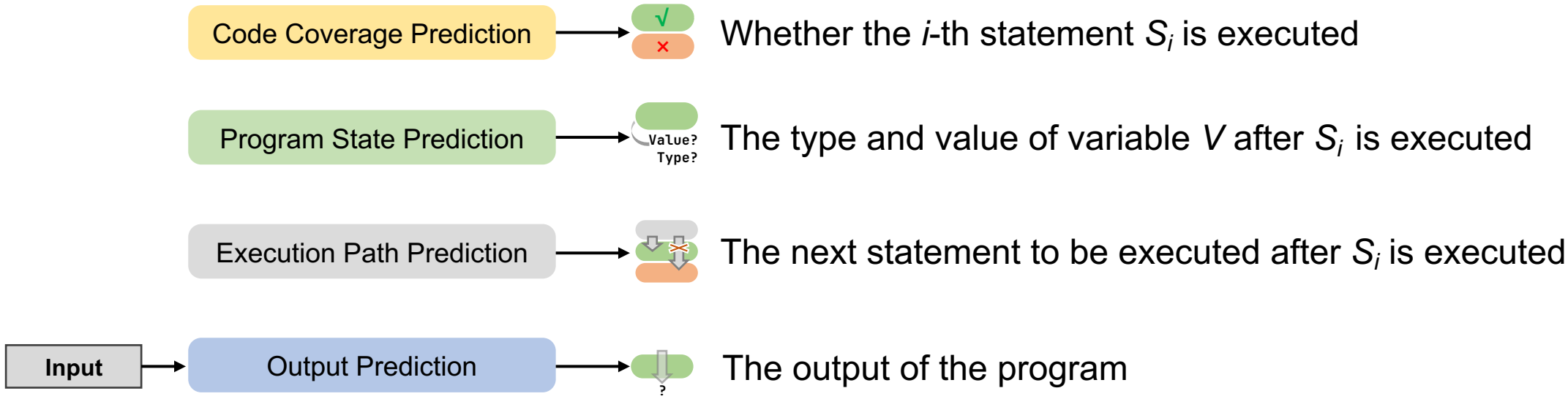
Component I: Runtime Behavior Reasoning



Whether the *i*-th statement S_i is executed

The type and value of variable *V* after S_i is executed

The next statement to be executed after S_i is executed

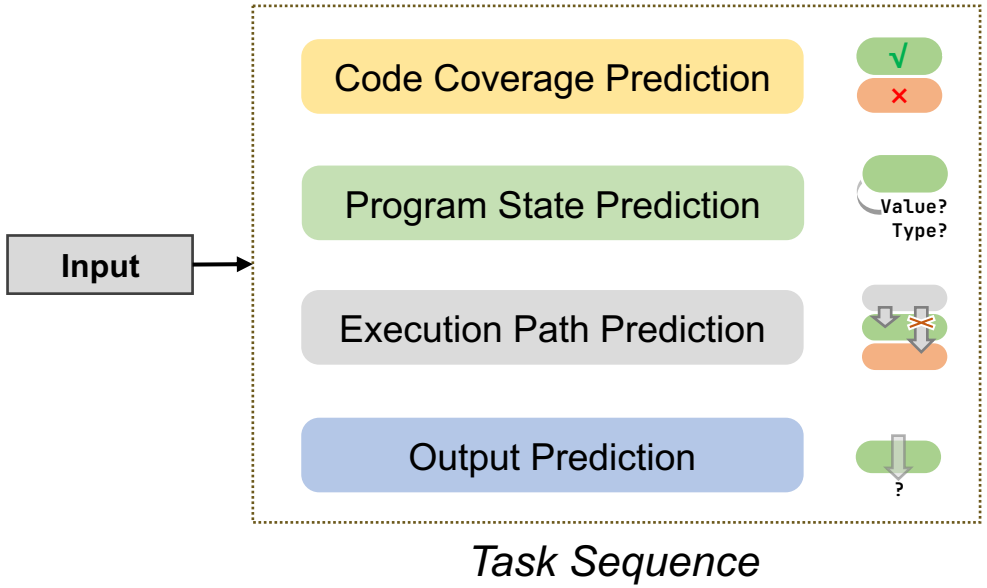
The output of the program

Evaluation Metric(s)

- **Accuracy**: Percentage of correct predictions
- **F1 Score** (Additional for Code Coverage Prediction)

Task Definition & Metrics

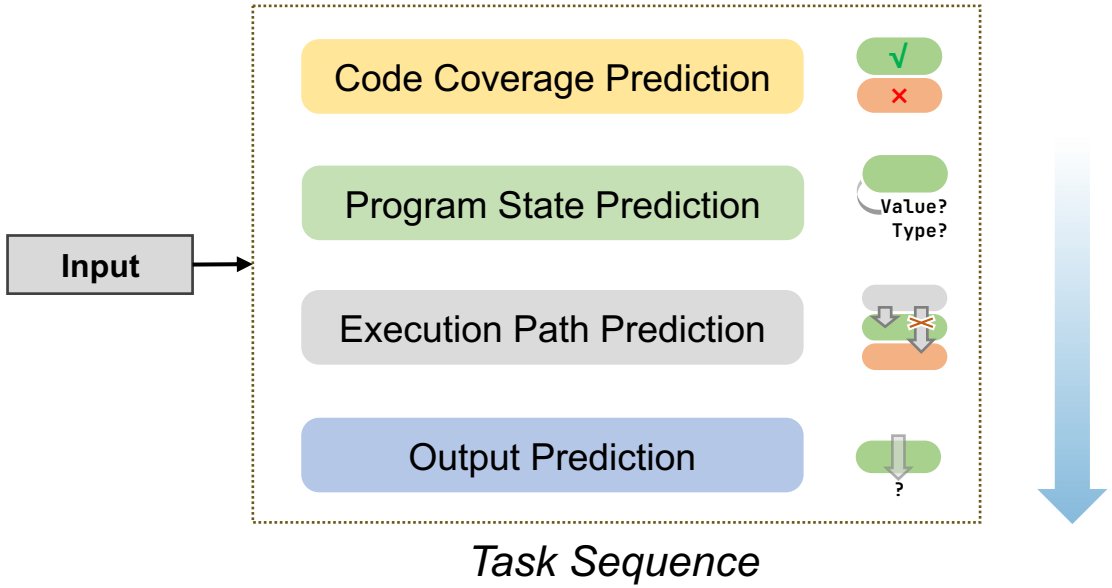
Component II: “Incremental Consistency”



Task Sequence

Task Definition & Metrics

Component II: “Incremental Consistency”

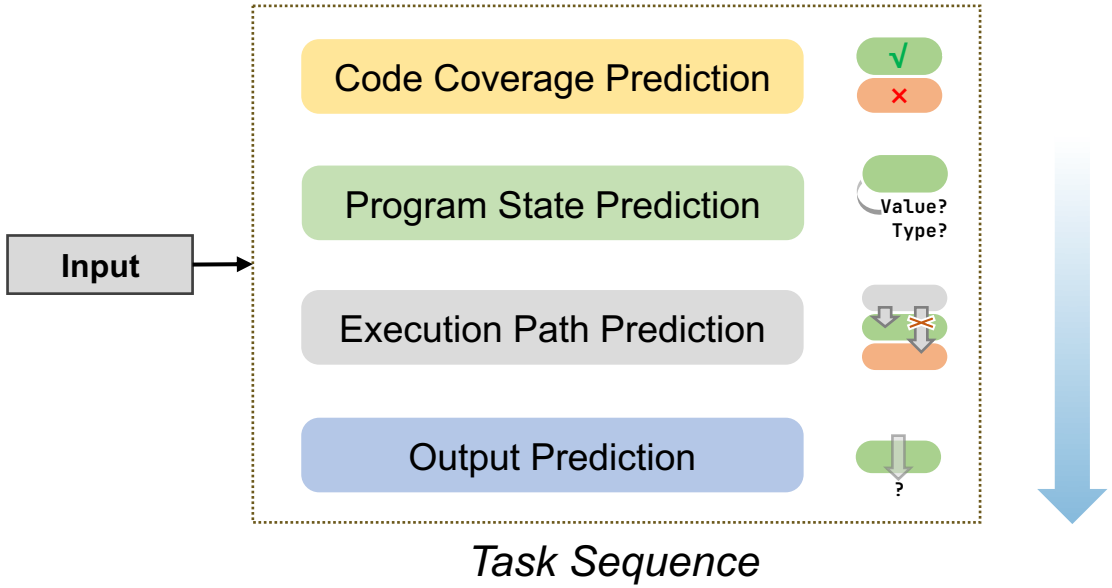


Incremental **knowledge required**

With *incremental* difficulty

Task Definition & Metrics

Component II: “Incremental Consistency”



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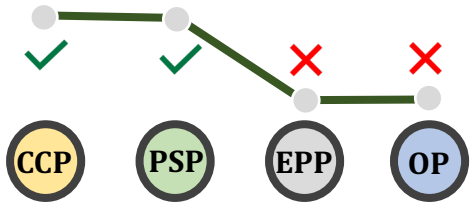

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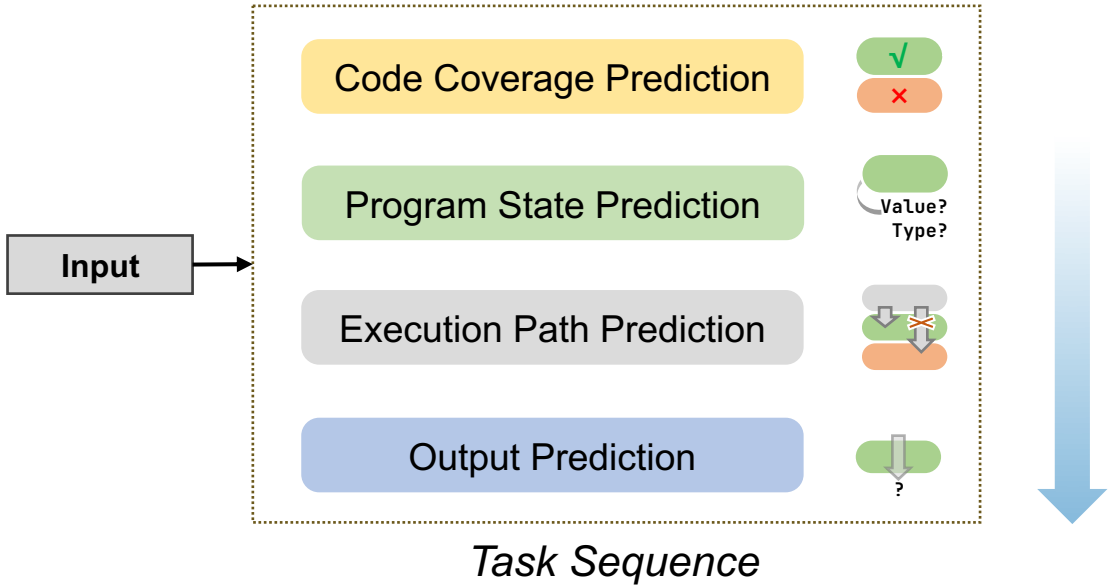

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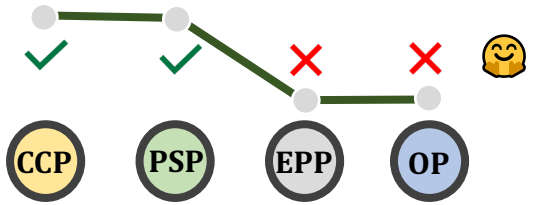

$\{1, 1, 0, 0\}$

Task Definition & Metrics

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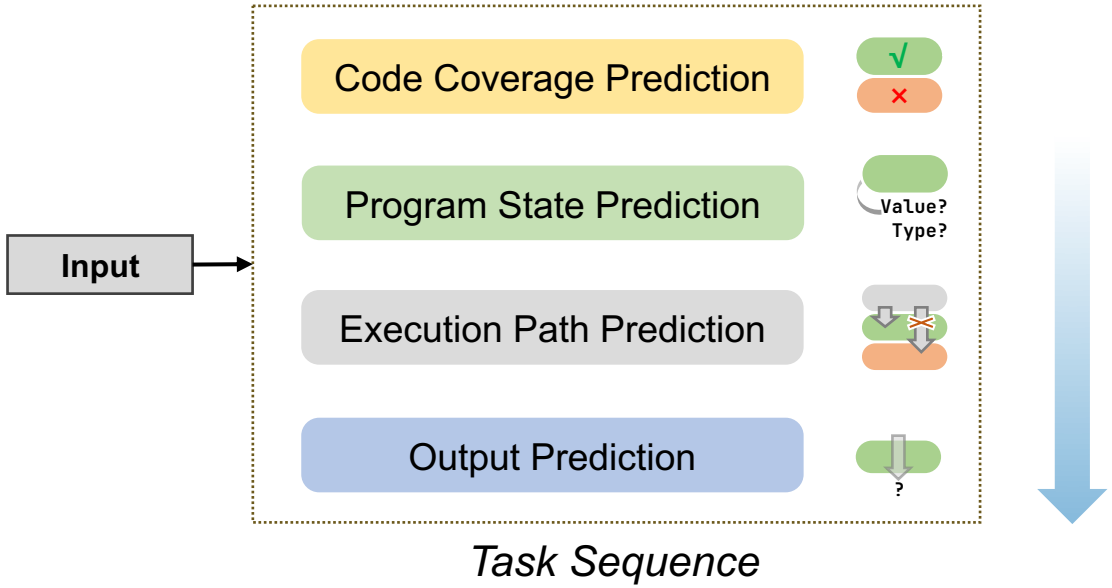

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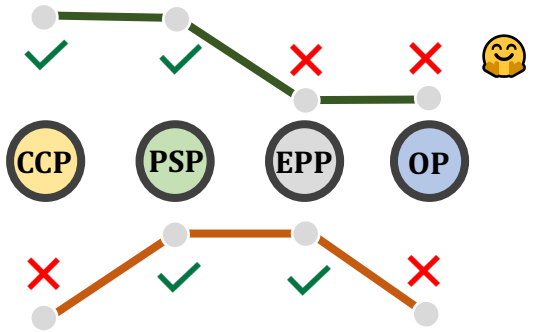

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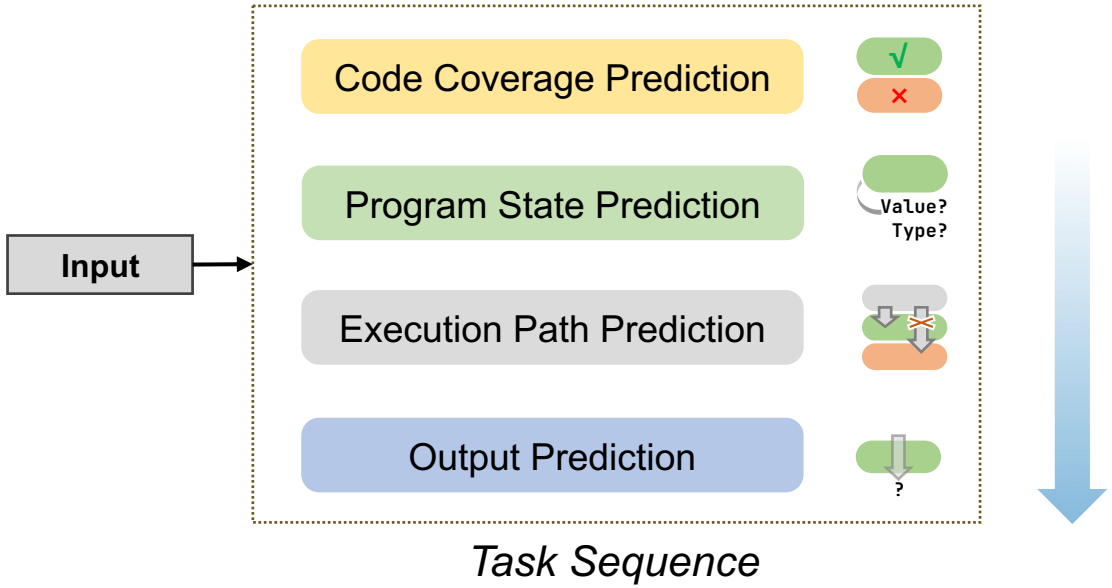

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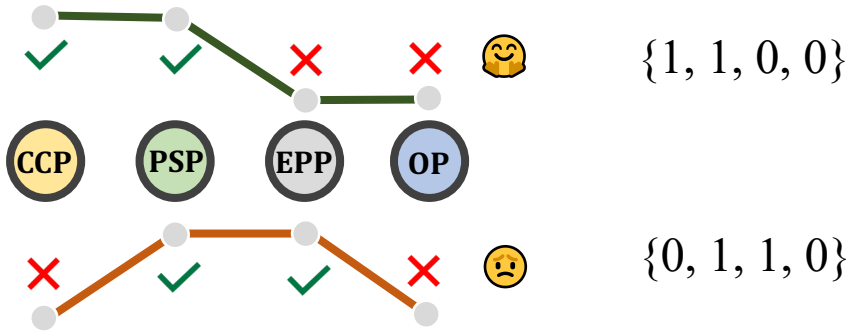

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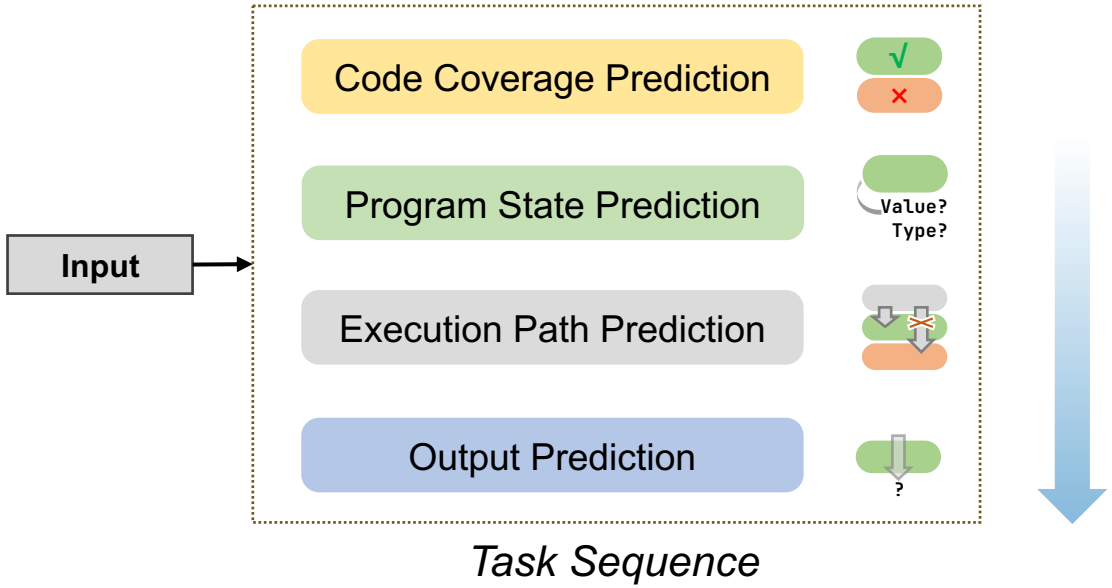

Task Sequence

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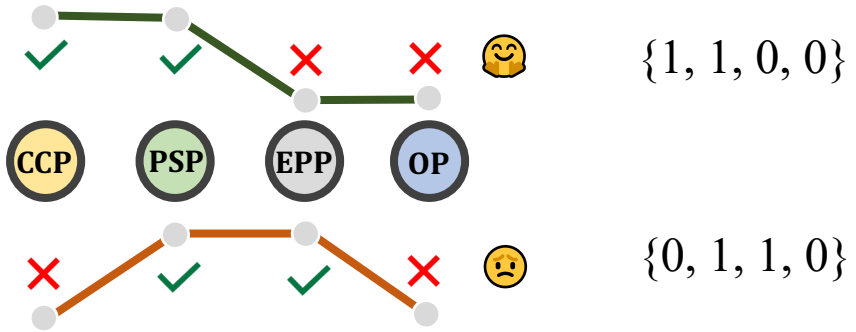

Evaluation Metric:

$$\text{IC Score} = \frac{100}{N}\sum_{i=1}^{N}\text{IC Score}_i,$$

$$\text{IC Score}_i = \begin{cases} \frac{1}{2^{j-1}}, & \text{if } \mathbf{R}_i = \mathbf{S}_j, j \in \{1,2,3,4\} \\ 0, & \text{otherwise} \end{cases}$$

Result sequences *S* with *"Incremental Consistency"*:

$$\{\{1,1,1,1\},\{1,1,1,0\},\{1,1,0,0\},\{1,0,0,0\}\}$$

Benchmark Construction

A. **Problem Construction: How to build the problems?**

B. **Runtime Behavior Extraction: How to get the ground truth?**

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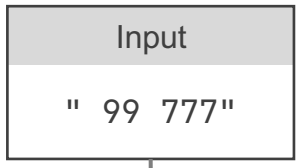
A. Using **canonical solutions** in code generation benchmarks

Benchmark Construction



A. From **test cases** in original benchmarks

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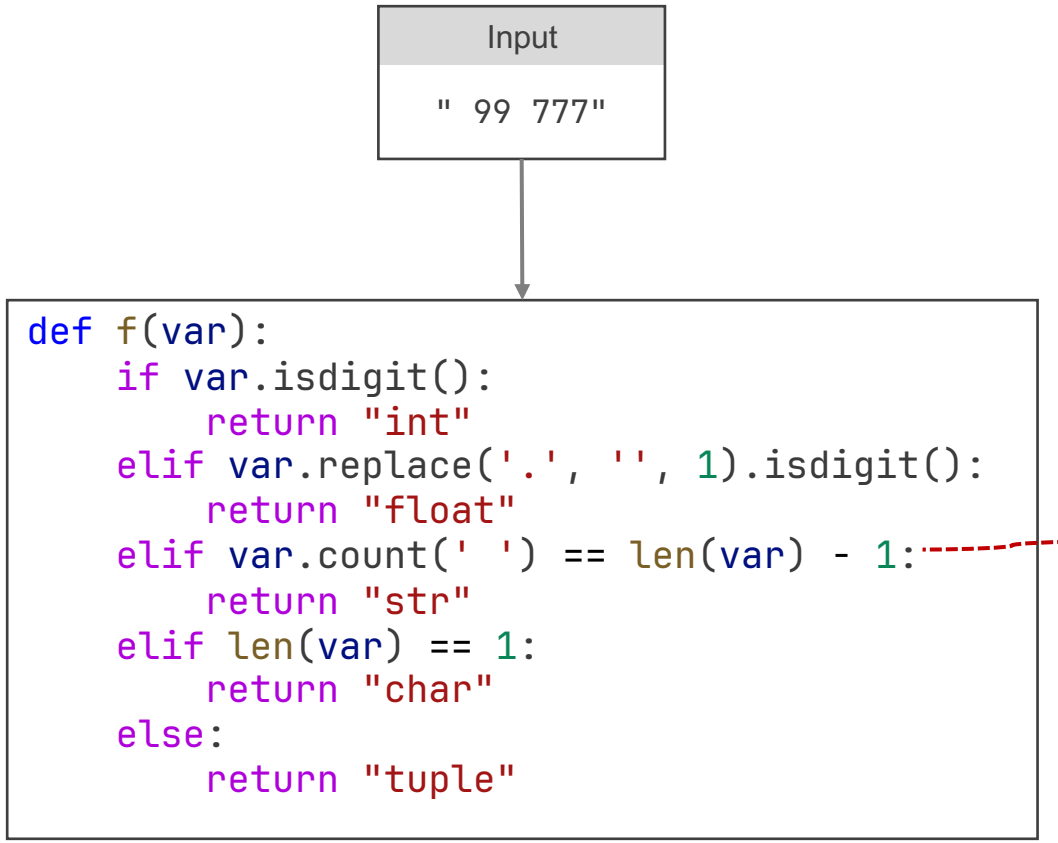

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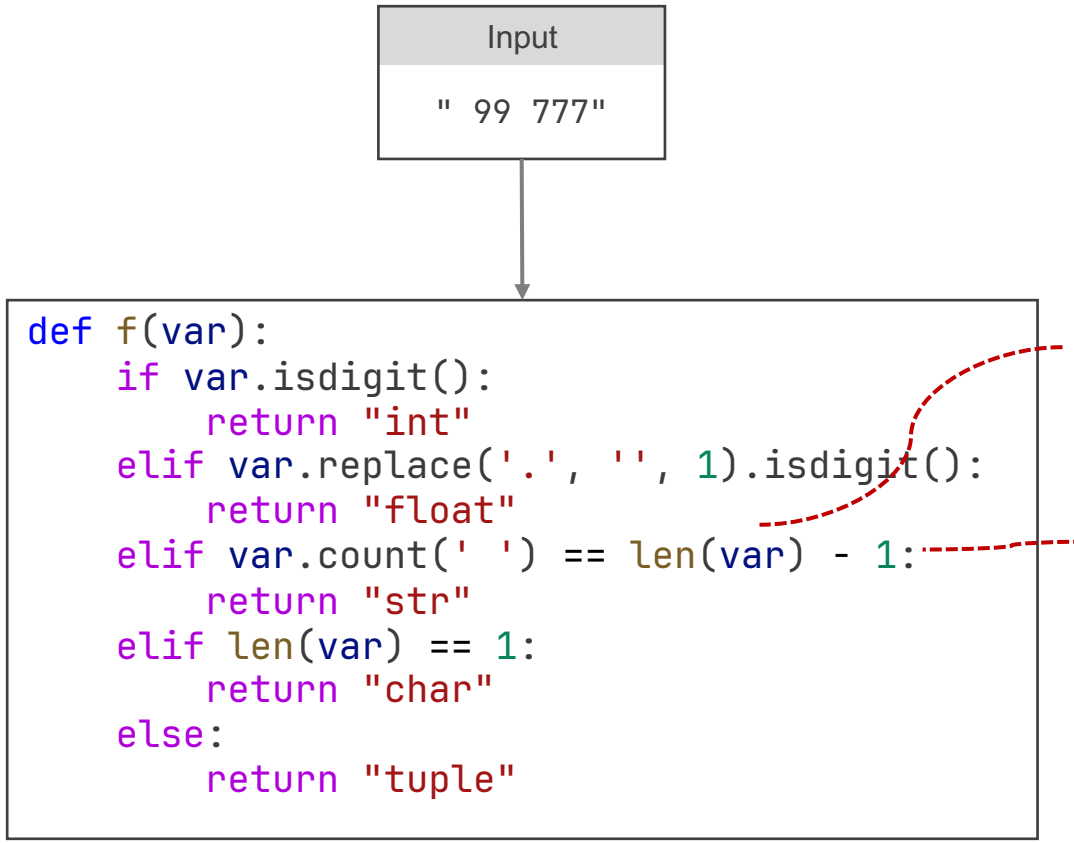
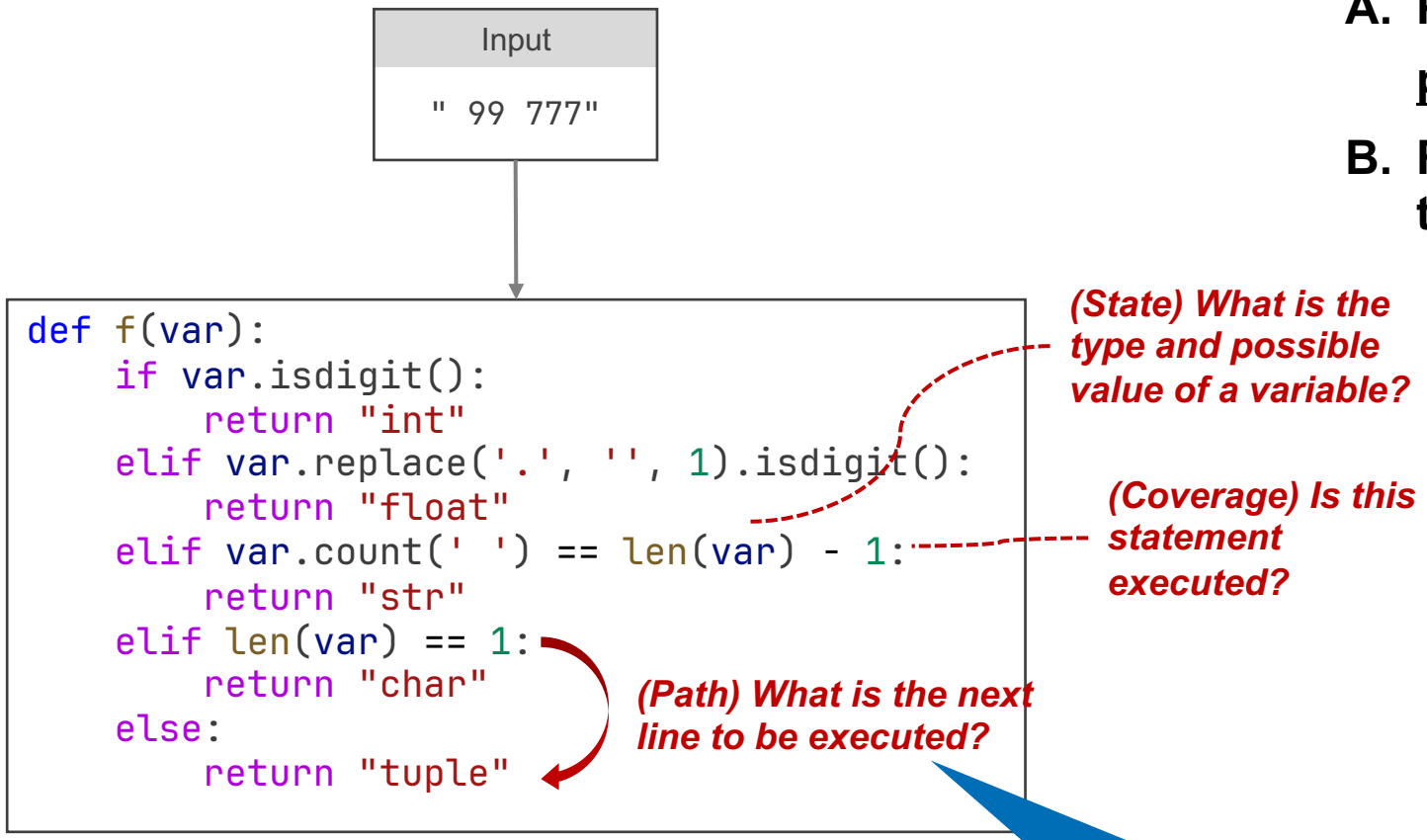


A. **Problem Construction: How to build the problems?**

B. **Runtime Behavior Extraction: How to get the ground truth?**

A. Locate variables in assignment and return, and variables with modified value
B. Inspect runtime frames

Benchmark Construction



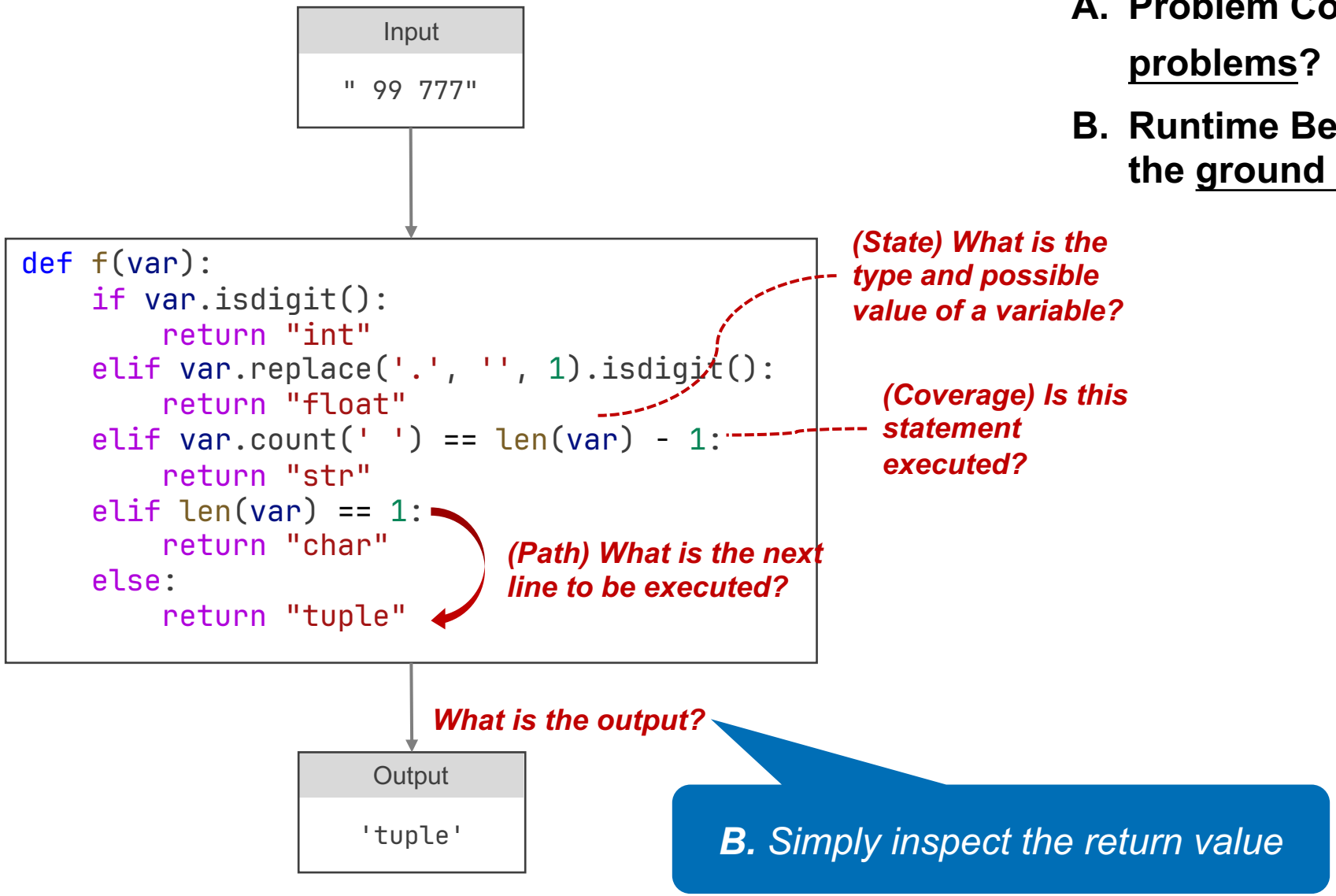
A. **Problem Construction: How to build the problems?**

B. **Runtime Behavior Extraction: How to get the ground truth?**

A. Use the same line numbers in previous tasks

B. Inspect code execution trace

Benchmark Construction



A. **Problem Construction: How to build the problems?**

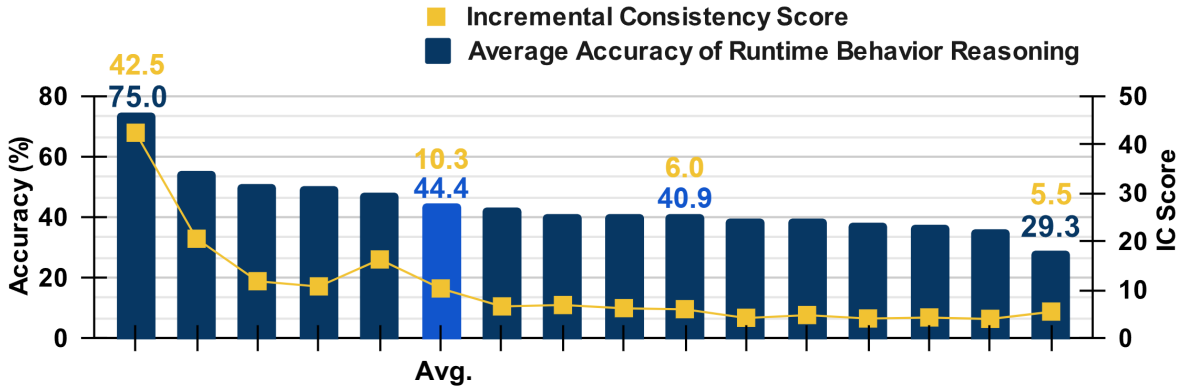
B. **Runtime Behavior Extraction: How to get the ground truth?**

B. *Simply inspect the return value*

Results

*Performance on **Runtime Behavior Reasoning** and **Incremental Consistency Evaluation***

Model	CCP		PSP	EPP	OP	Acc. Avg.	IC
	Acc. (%)	F1	Acc. (%)	Acc. (%)	Acc. (%)	(%)	Score
CodeLlama-7B-Base	54.3±0.5	56.1±0.5	25.0±0.5	5.6±0.3	58.2±1.6	35.8	4.0±0.2
CodeLlama-7B-Python	55.5±0.7	62.7±0.6	31.3±1.0	8.7±0.7	62.3±1.0	39.4	4.8±0.2
CodeLlama-7B-Instruct	55.6±0.9	47.2±1.2	25.1±0.5	10.8±0.2	62.6±0.8	38.5	4.1±0.1
CodeLlama-13B-Instruct	61.0±0.7	66.4±0.6	32.5±0.4	14.4±0.4	64.5±1.1	43.1	6.6±0.3
CodeLlama-34B-Instruct	61.5±0.5	70.1±0.4	47.5±0.6	29.2±0.4	65.9±1.1	51.0	11.8±0.3
StarCoder2-3B	54.8±0.7	58.2±0.5	29.0±0.7	6.5±0.5	58.8±0.8	37.3	4.3±0.3
StarCoder2-7B	55.1±0.7	63.8±0.6	34.2±0.7	5.0±0.4	63.9±0.8	39.6	4.2±0.3
StarCoder2-15B	58.9±0.8	64.6±0.8	43.5±0.3	28.0±0.5	71.5±1.1	50.5	10.7±0.4
Magicoder-CL	58.7±1.4	61.2±1.8	30.1±0.5	15.5±1.1	60.4±1.4	41.2	6.2±0.3
Magicoder-S-CL	60.3±1.1	69.9±0.8	31.4±0.4	9.8±0.4	62.3±1.2	40.9	6.0±0.2
Gemma-2B-It	52.7±0.4	31.0±0.6	13.5±0.5	7.3±0.5	43.9±1.5	29.3	5.5±0.2
Gemma-7B-It	66.3±0.3	75.2±0.1	32.1±0.1	8.4±0.4	57.9±0.7	41.2	6.9±0.2
Mistral-7B-Instruct	69.5±0.2	75.9±0.2	35.2±0.3	35.8±0.4	51.5±0.7	48.0	16.3±0.3
GPT-3.5-Turbo	61.8	64.0	51.6	48.6	60.7	55.7	20.6
GPT-4-Turbo	**88.4**	**89.8**	**71.4**	**57.7**	**82.6**	**75.0**	**42.5**
Average	61.0	63.7	35.6	19.4	61.8	44.4	10.3
CodeLlama-7B-Instruct (CoT)	57.5	59.2	33.4	21.4	55.8	42.2	7.5



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1. As of March 2024

Case Study

```
def largest_prime_factor(n: int):
    """Return the largest prime factor of n.
Assume n > 1 and is not a prime.
    >>> largest_prime_factor(13195)
    29
    >>> largest_prime_factor(2048)
    2
    """
    def is_prime(k):
        if k < 2:
            return False
        for i in range(2, k - 1):
            if k % i == 0:
                return False
        return True
    largest = 1
√   for j in range(2, n + 1):
        if n % j == 0 and is_prime(j):
            largest = max(largest, j)
×   return largest
```

GPT-4-Turbo

GPT-3.5-Turbo

CodeLlama-34B-Instruct

Input: 15

Question:
What is the next line to be executed after line "largest = max(largest, j)"?

Manual Analysis

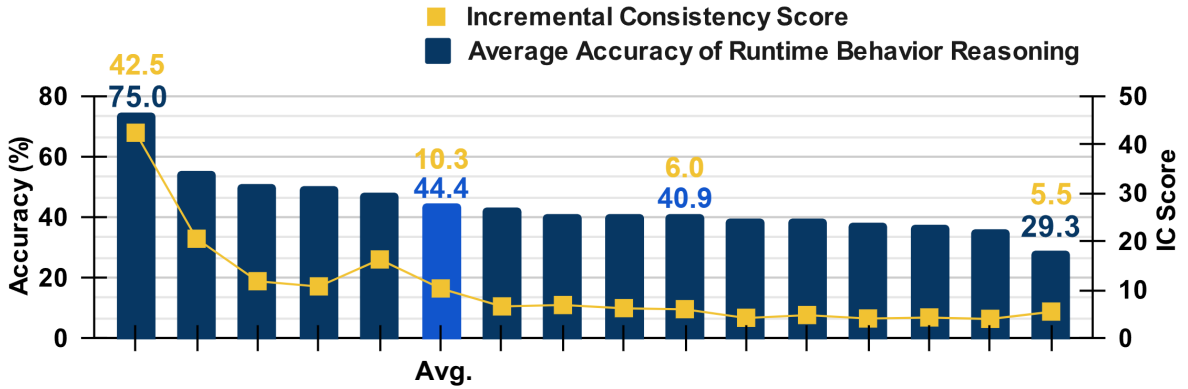
- Range of `j`: $[2, 15]$
- Possible value of j if `largest = max(largest, j)` can be executed: $\{3,\ 5\}$
- Loop is not terminated, if `largest = max(largest, j)` is be executed

Next Line is
`for j in range(2, n + 1):`

Results

*Performance on **Runtime Behavior Reasoning** and **Incremental Consistency Evaluation***

Model	CCP		PSP	EPP	OP	Acc. Avg.	IC
	Acc. (%)	F1	Acc. (%)	Acc. (%)	Acc. (%)	(%)	Score
CodeLlama-7B-Base	54.3±0.5	56.1±0.5	25.0±0.5	5.6±0.3	58.2±1.6	35.8	4.0±0.2
CodeLlama-7B-Python	55.5±0.7	62.7±0.6	31.3±1.0	8.7±0.7	62.3±1.0	39.4	4.8±0.2
CodeLlama-7B-Instruct	55.6±0.9	47.2±1.2	25.1±0.5	10.8±0.2	62.6±0.8	38.5	4.1±0.1
CodeLlama-13B-Instruct	61.0±0.7	66.4±0.6	32.5±0.4	14.4±0.4	64.5±1.1	43.1	6.6±0.3
CodeLlama-34B-Instruct	61.5±0.5	70.1±0.4	47.5±0.6	29.2±0.4	65.9±1.1	51.0	11.8±0.3
StarCoder2-3B	54.8±0.7	58.2±0.5	29.0±0.7	6.5±0.5	58.8±0.8	37.3	4.3±0.3
StarCoder2-7B	55.1±0.7	63.8±0.6	34.2±0.7	5.0±0.4	63.9±0.8	39.6	4.2±0.3
StarCoder2-15B	58.9±0.8	64.6±0.8	43.5±0.3	28.0±0.5	71.5±1.1	50.5	10.7±0.4
Magicoder-CL	58.7±1.4	61.2±1.8	30.1±0.5	15.5±1.1	60.4±1.4	41.2	6.2±0.3
Magicoder-S-CL	60.3±1.1	69.9±0.8	31.4±0.4	9.8±0.4	62.3±1.2	40.9	6.0±0.2
Gemma-2B-It	52.7±0.4	31.0±0.6	13.5±0.5	7.3±0.5	43.9±1.5	29.3	5.5±0.2
Gemma-7B-It	66.3±0.3	75.2±0.1	32.1±0.1	8.4±0.4	57.9±0.7	41.2	6.9±0.2
Mistral-7B-Instruct	69.5±0.2	75.9±0.2	35.2±0.3	35.8±0.4	51.5±0.7	48.0	16.3±0.3
GPT-3.5-Turbo	61.8	64.0	51.6	48.6	60.7	55.7	20.6
GPT-4-Turbo	**88.4**	**89.8**	**71.4**	**57.7**	**82.6**	**75.0**	**42.5**
Average	61.0	63.7	35.6	19.4	61.8	44.4	10.3
CodeLlama-7B-Instruct (CoT)	57.5	59.2	33.4	21.4	55.8	42.2	7.5



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1. As of March 2024

Benchmarking Code Reasoning

*Task: Predicting code execution behaviors **without** executing the code.*

REval Framework

Base Benchmark

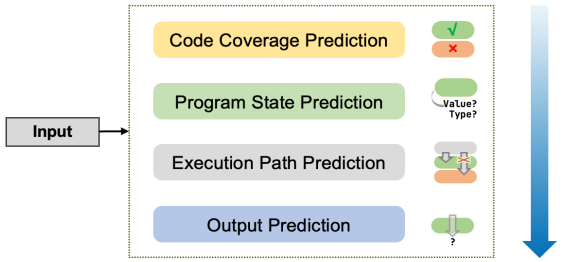
Large Language Model

Paper, Code & Leaderboard

https://r-eval.github.io

Task Definition & Metrics

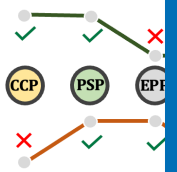
Component II: "Incremental Consistency"



Task Sequence

***Incremental* knowledge**

With *incremental* difficu



Evaluation Metric:

$$\text{IC Score} = \frac{100}{N}\sum_{i=1}^{N}\text{IC Score}_i,$$

$$\text{IC Score}_i = \begin{cases} \frac{1}{2^{j-1}}, & \text{if } \mathbf{R}_i = \mathbf{S}_j, j \in \{1,2,3,4\} \\ 0, & \text{otherwise} \end{cases}$$

Result seque

$\{\{1,1,1,1\},\{$

r Reasoning* and *Incremental Consistency Evaluation

	EPP	OP	Acc. Avg.	IC
	Acc. (%)	Acc. (%)	(%)	Score
	5.6±0.3	58.2±1.6	35.8	4.0±0.2
	8.7±0.7	62.3±1.0	39.4	4.8±0.2
	10.8±0.2	62.6±0.8	38.5	4.1±0.1
	14.4±0.4	64.5±1.1	43.1	6.6±0.3
	29.2±0.4	65.9±1.1	51.0	11.8±0.3
	6.5±0.5	58.8±0.8	37.3	4.3±0.3
	5.0±0.4	63.9±0.8	39.6	4.2±0.3
	28.0±0.5	71.5±1.1	50.5	10.7±0.4
	15.5±1.1	60.4±1.4	41.2	6.2±0.3
	9.8±0.4	62.3±1.2	40.9	6.0±0.2
	7.3±0.5	43.9±1.5	29.3	5.5±0.2
	8.4±0.4	57.9±0.7	41.2	6.9±0.2
	35.8±0.4	51.5±0.7	48.0	16.3±0.3
	48.6	60.7	55.7	20.6
	57.7	**82.6**	**75.0**	**42.5**
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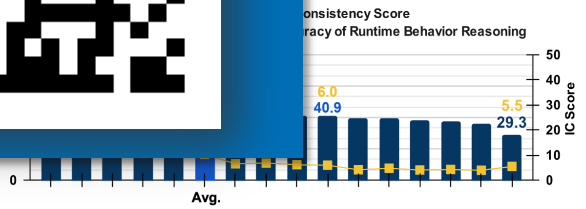

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