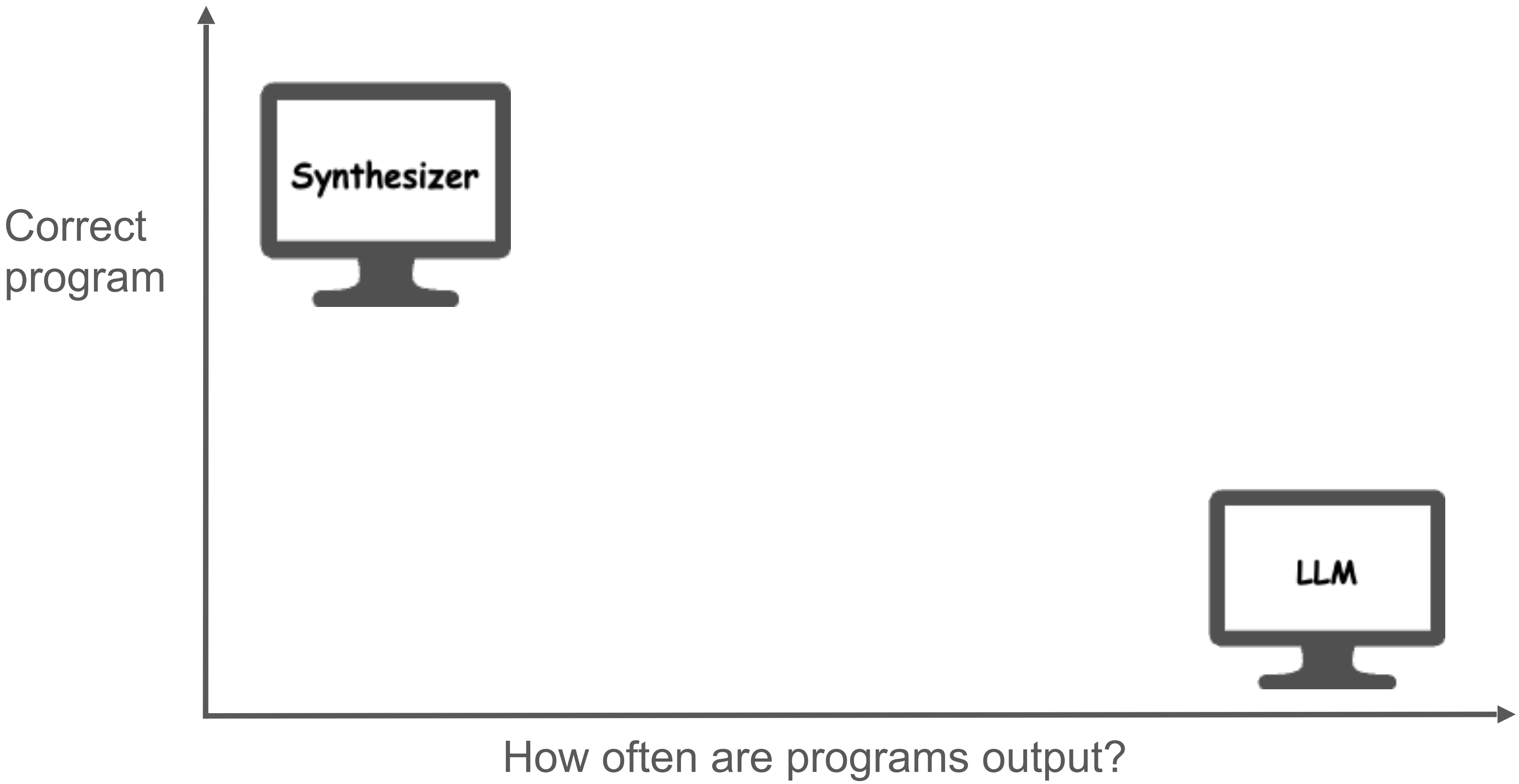
SYNVER: Towards Automated Verification of LLM-Synthesized C Programs

Prasita Mukherjee and Benjamin Delaware

CoqPL 2025

Program Synthesis: Present Scenario



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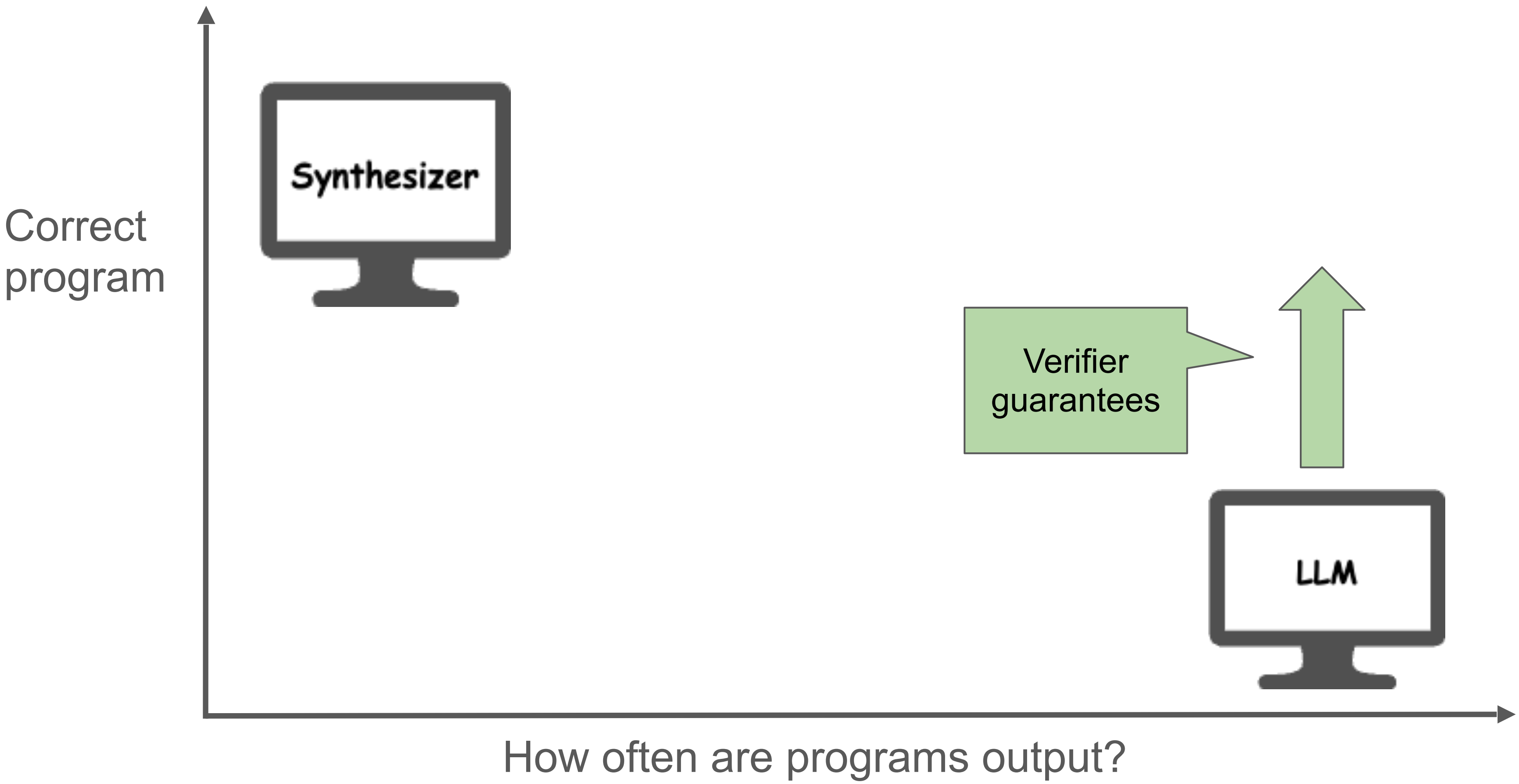

Synthesizing programs: LLMs

$$\forall a, b\ (max(a,b) = a \wedge a \geq b)$$
$$\vee\ (max(a,b) = b \wedge b > a)$$

$$Definition\ fi2 := fun\ x => x =?\ 2$$
$$listrep\ l\ h\ \ * listrep\ (filter\ fi2\ l)\ a$$

....

$$listrep\ [1; l; 2]\ h$$

struct sll *addf(..)
struct sll *addb(..)

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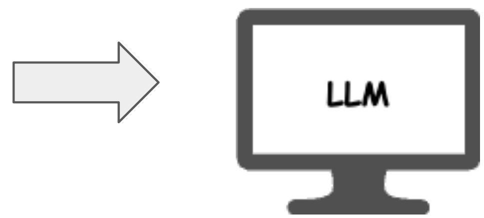


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Significant verification effort needed

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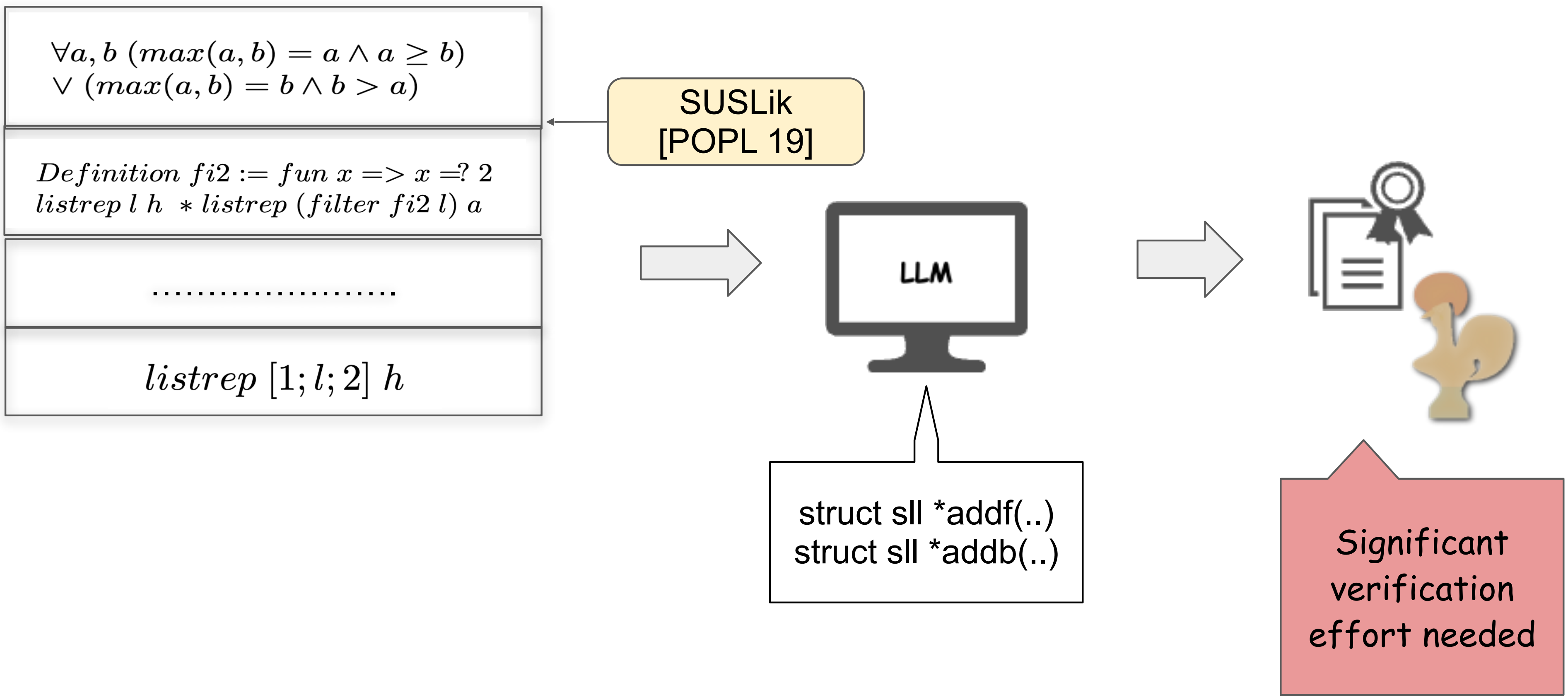

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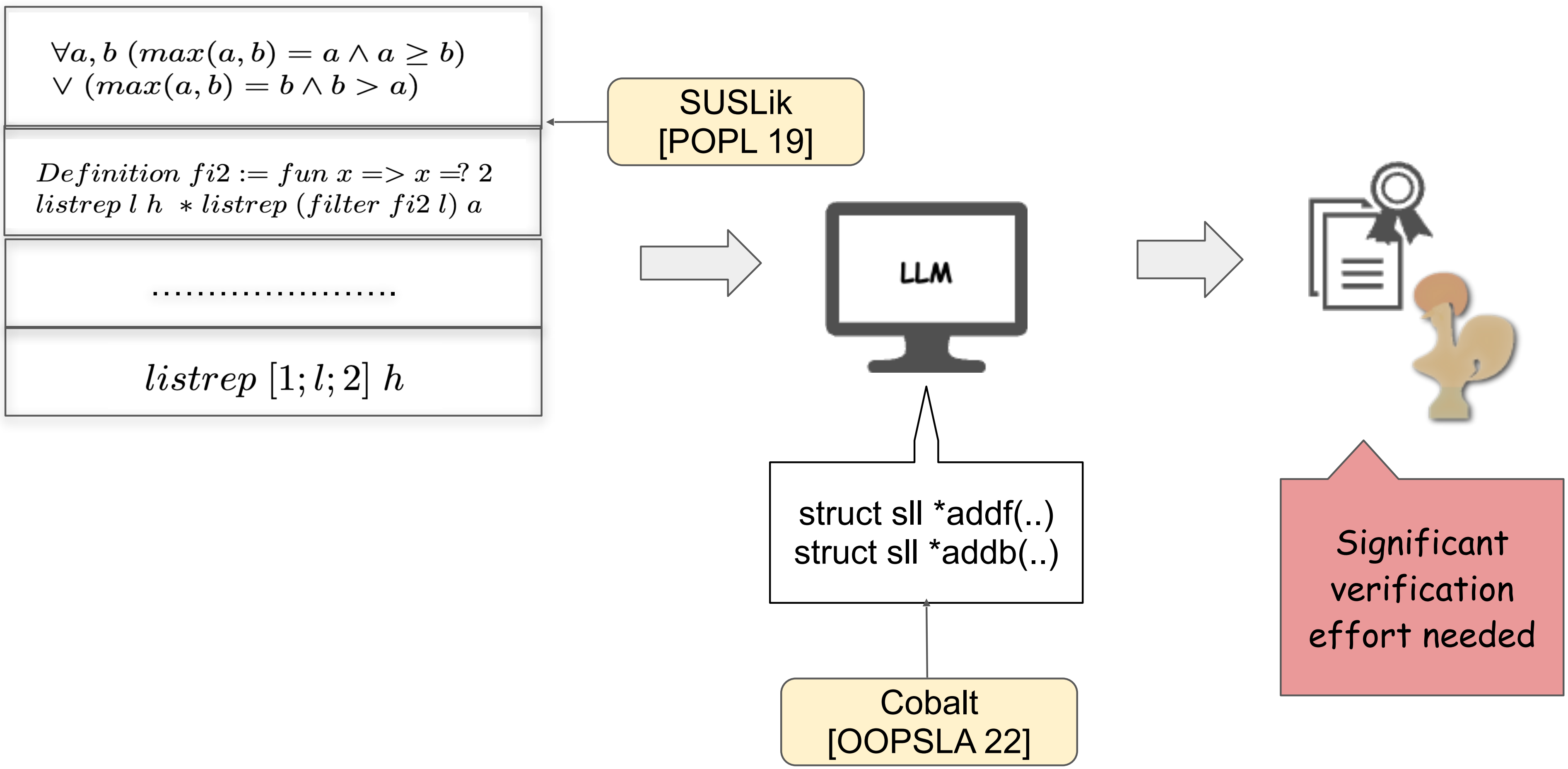

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SUSLik
[POPL 19]

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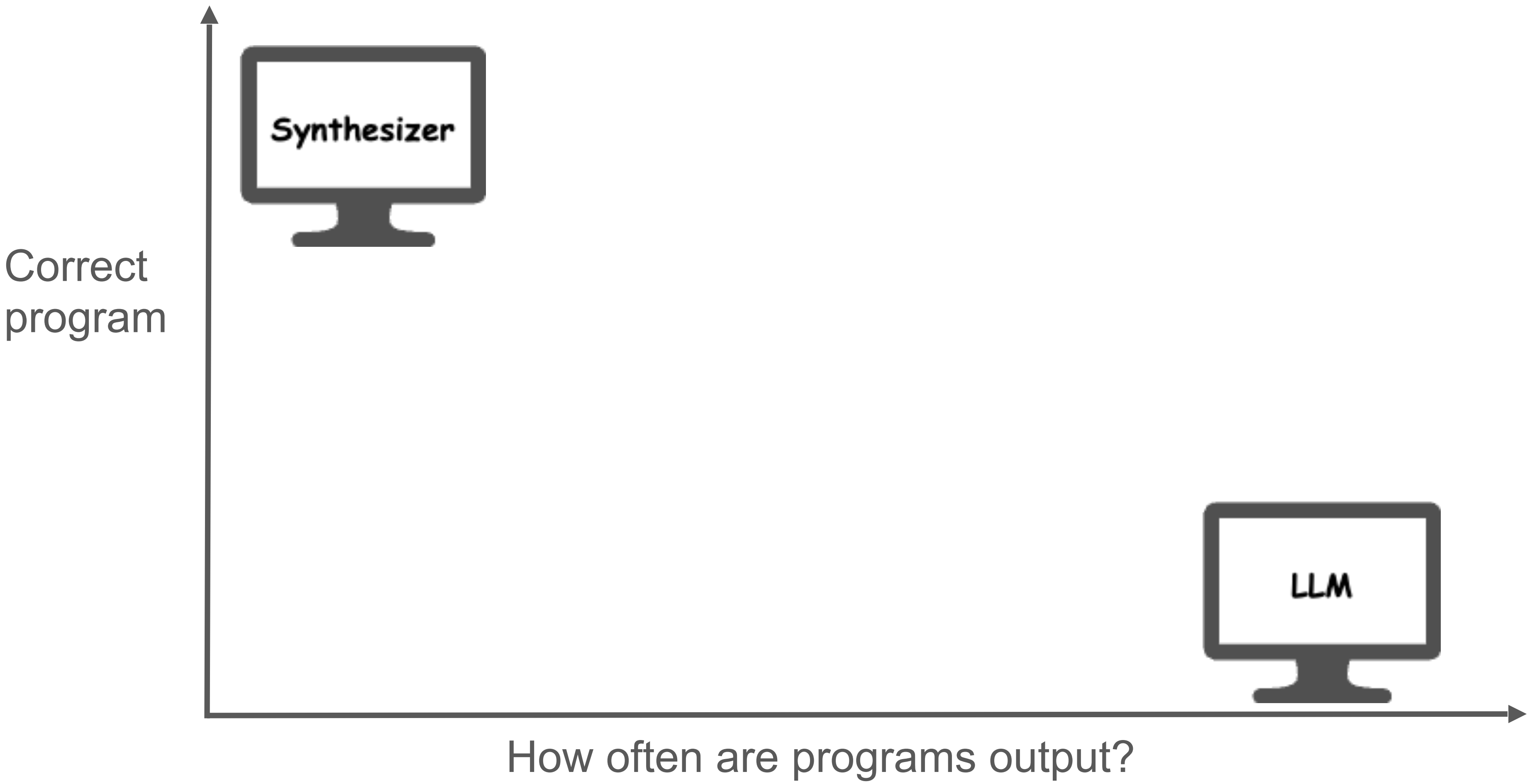
Cobalt
[OOPSLA 22]

Significant verification effort needed

Large search space.
Will always produce some output

Goal of SYNVER



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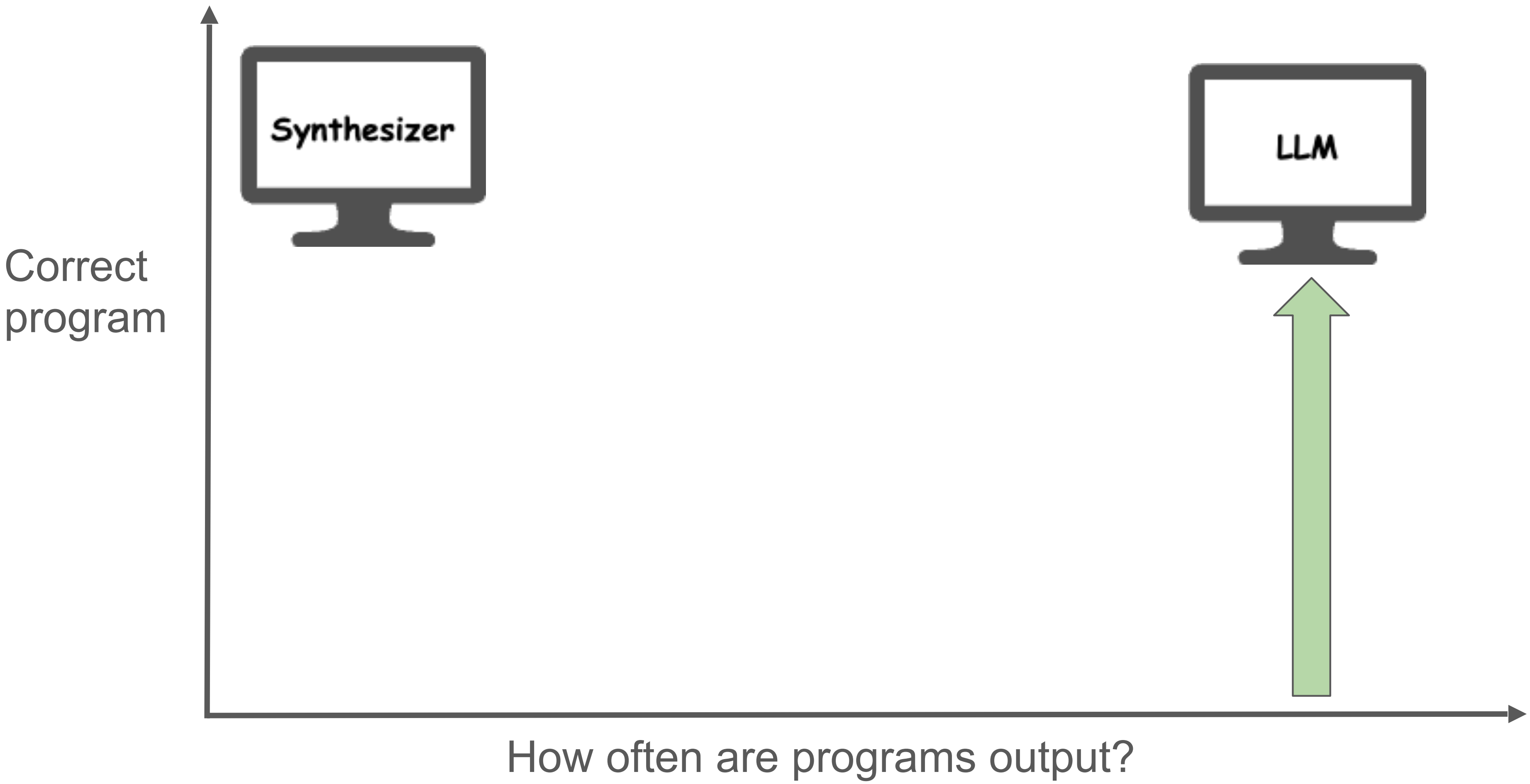

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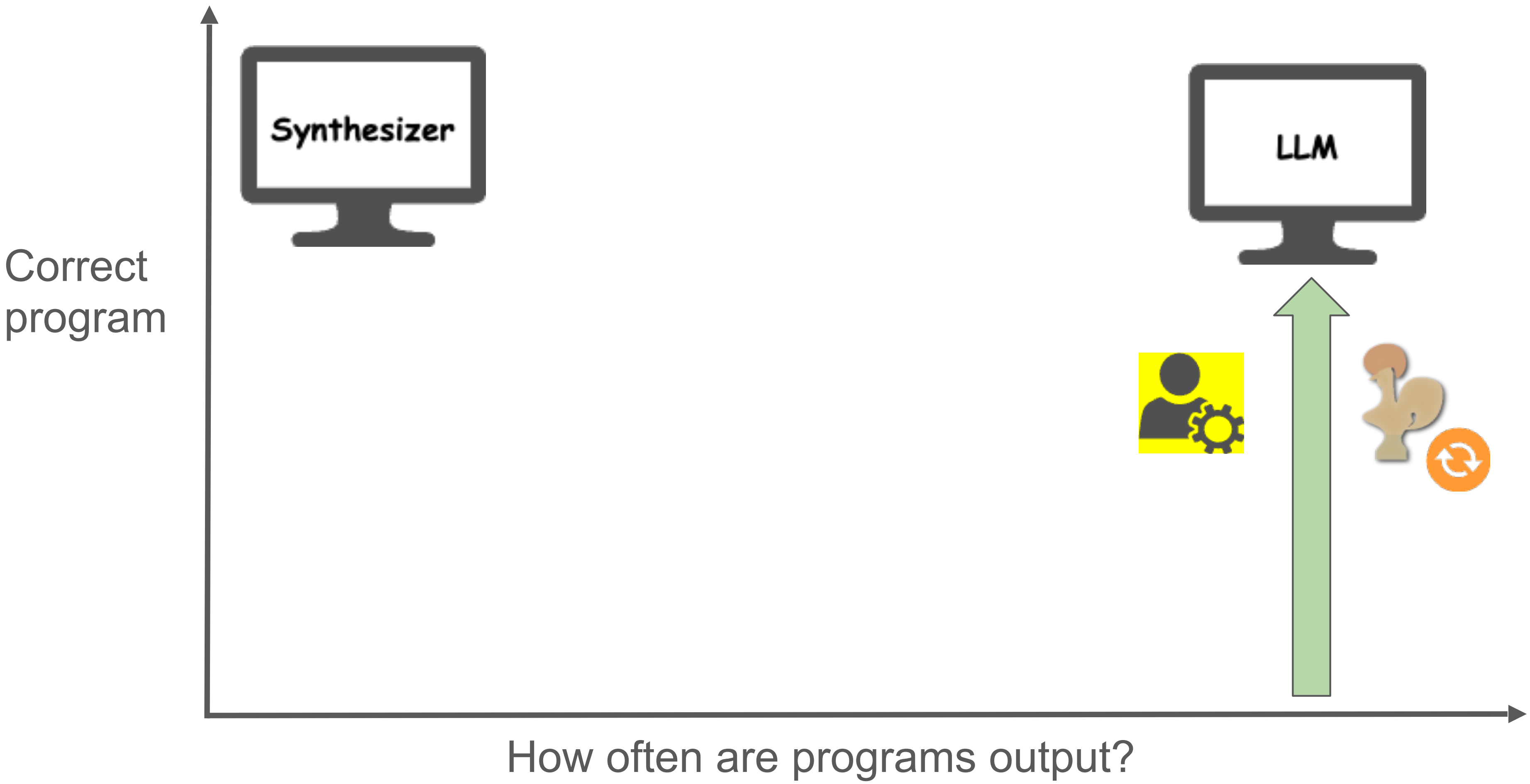


Verification Challenges

{P}

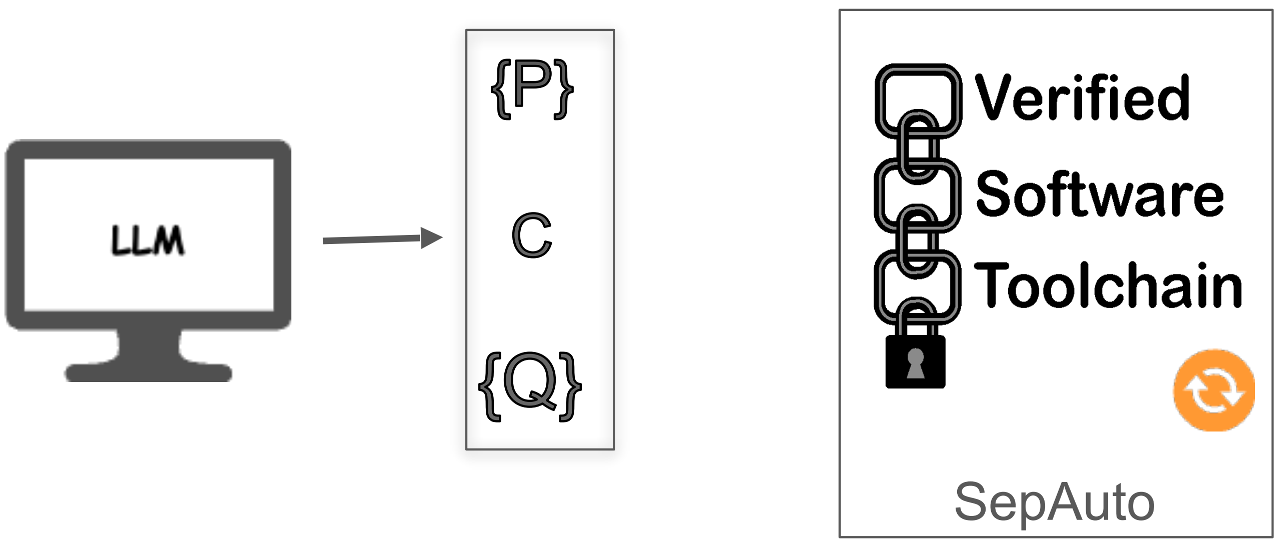
C

{Q}

Verified Software Toolchain

SepAuto

Verification Challenges



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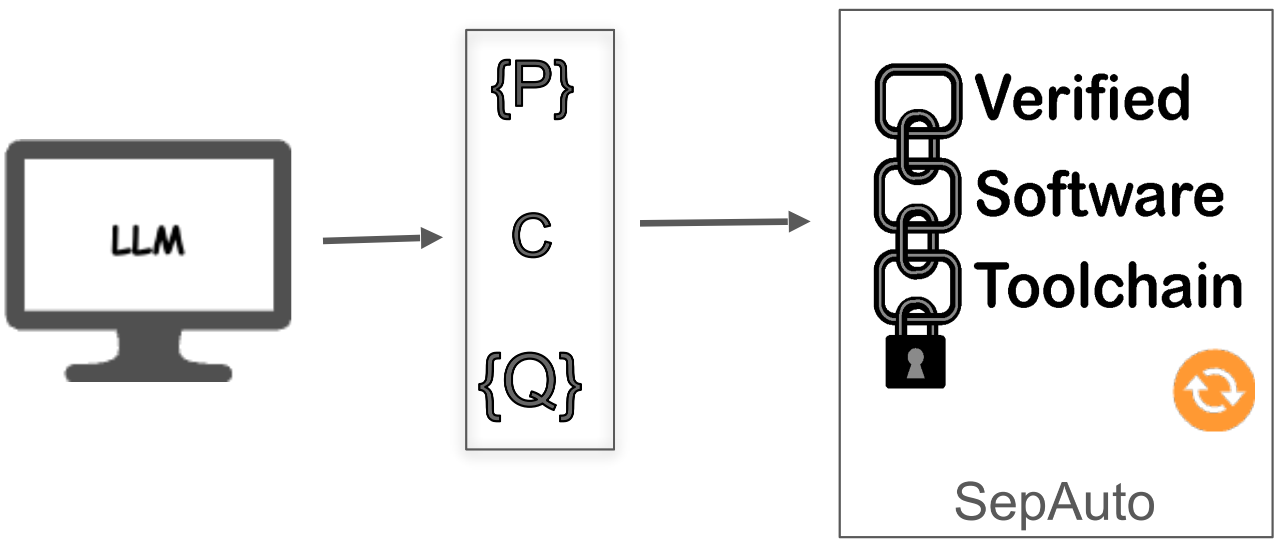

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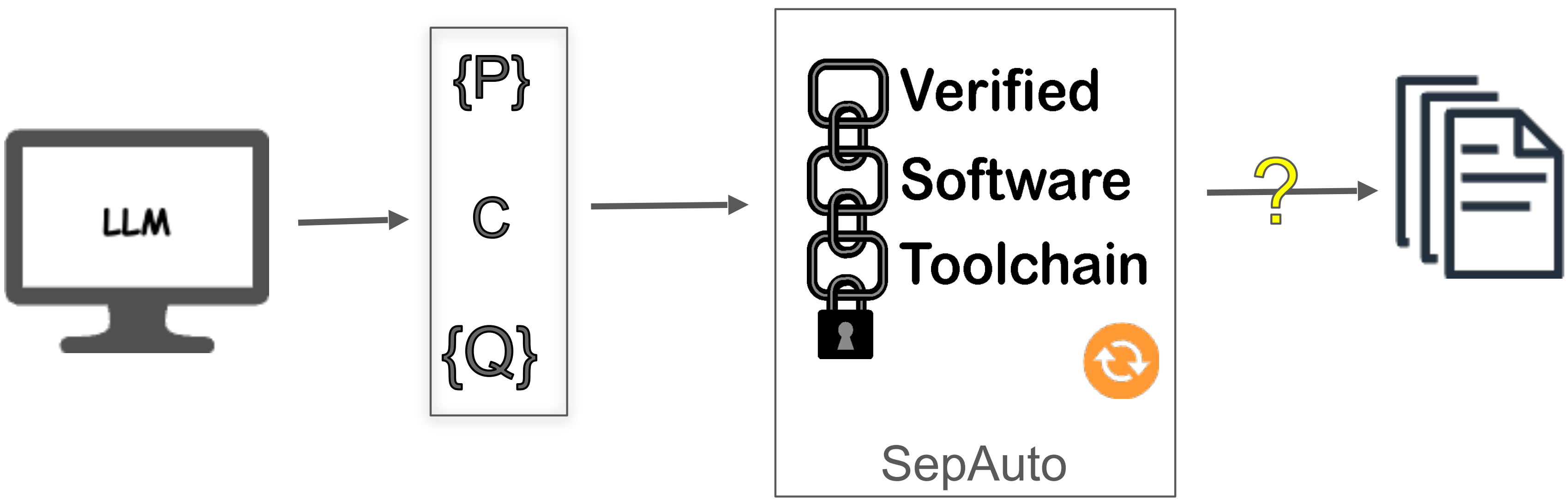

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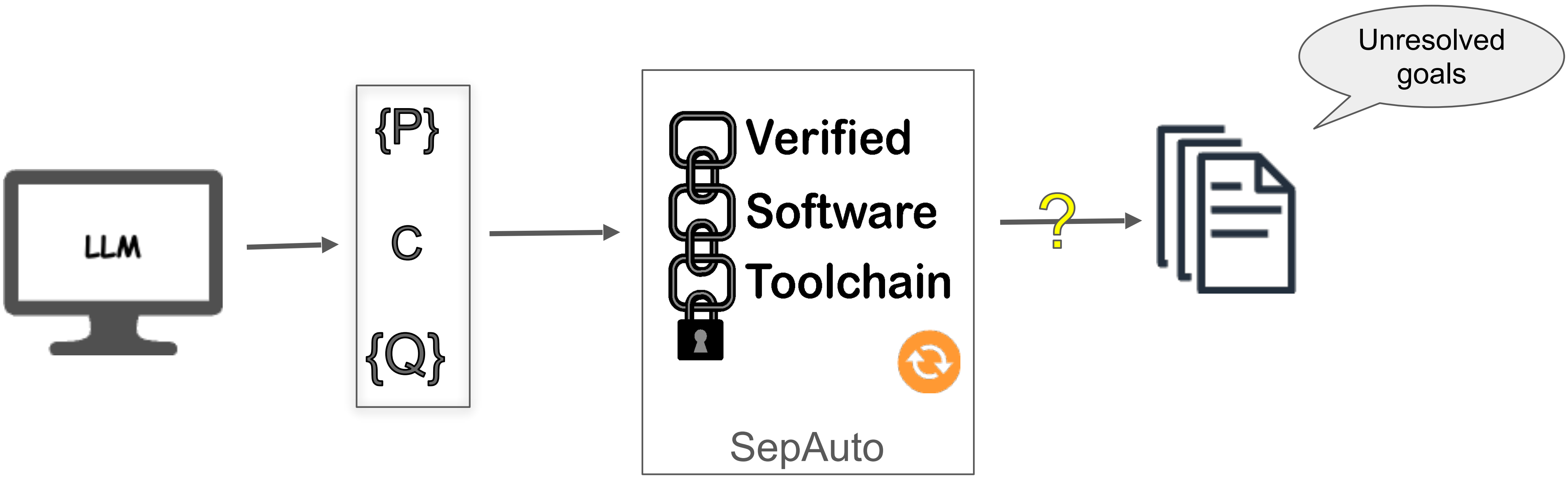

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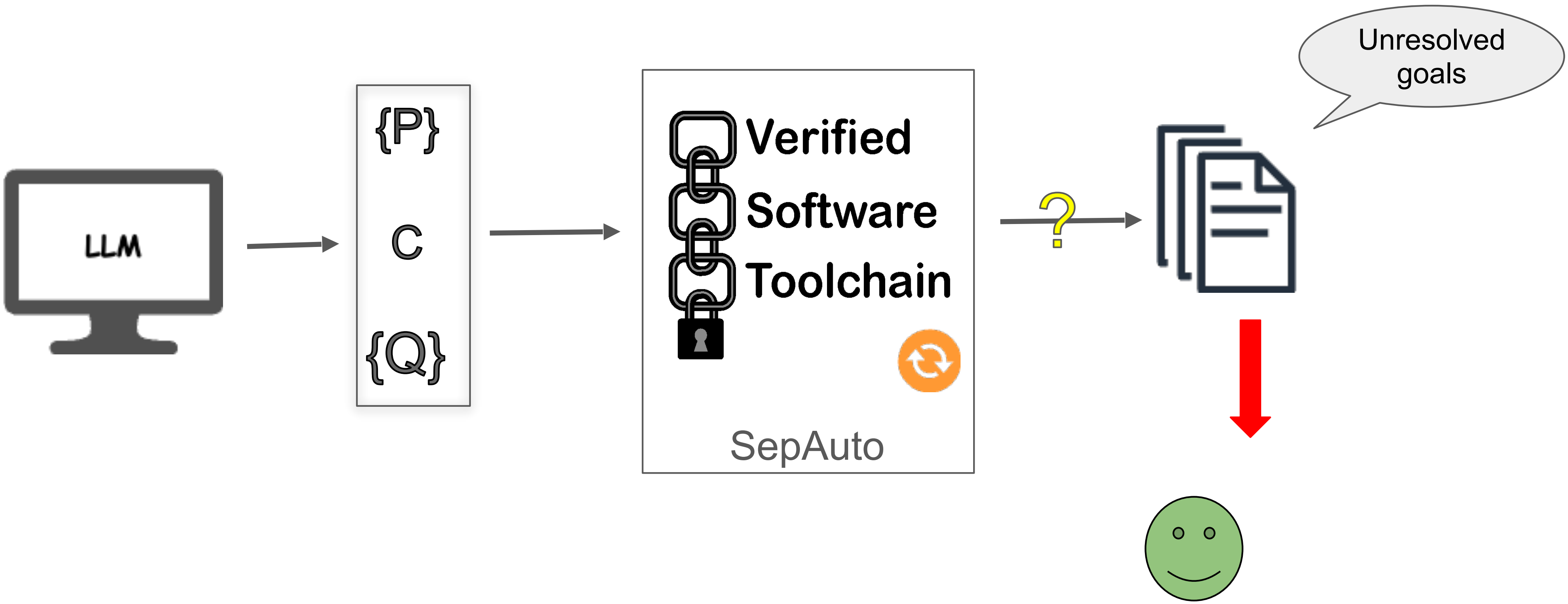

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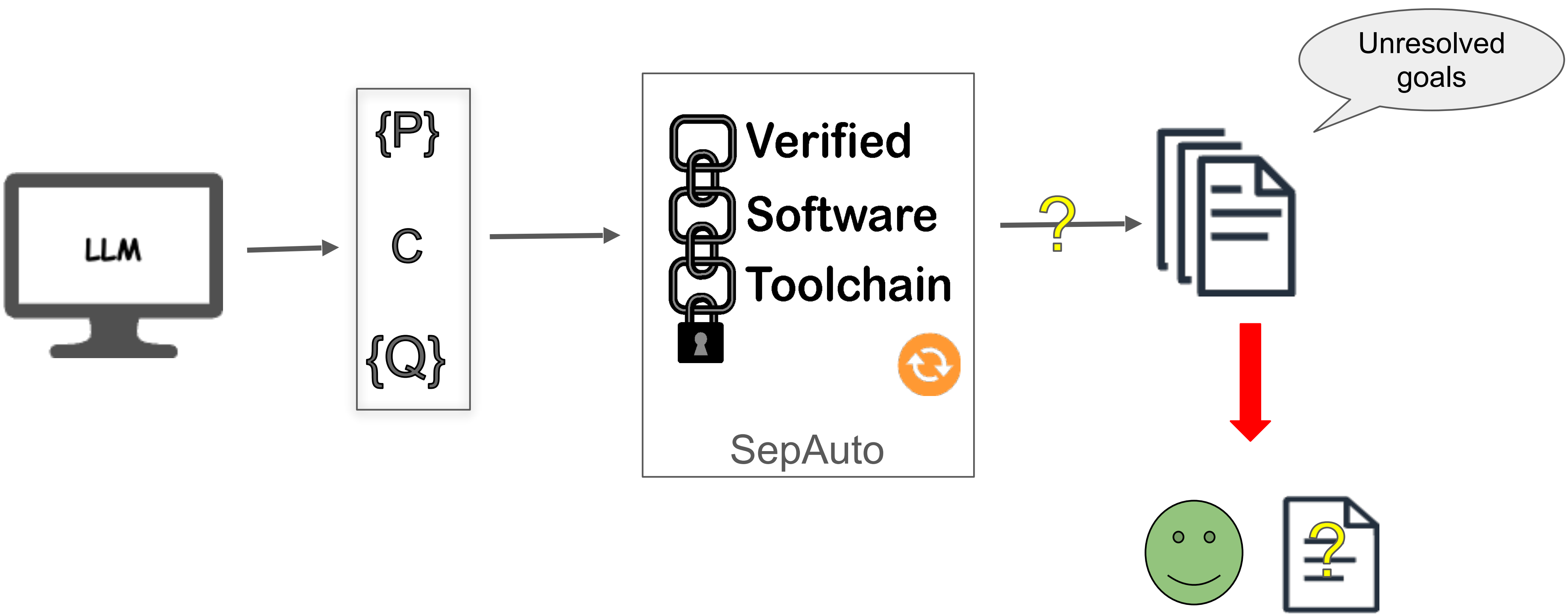

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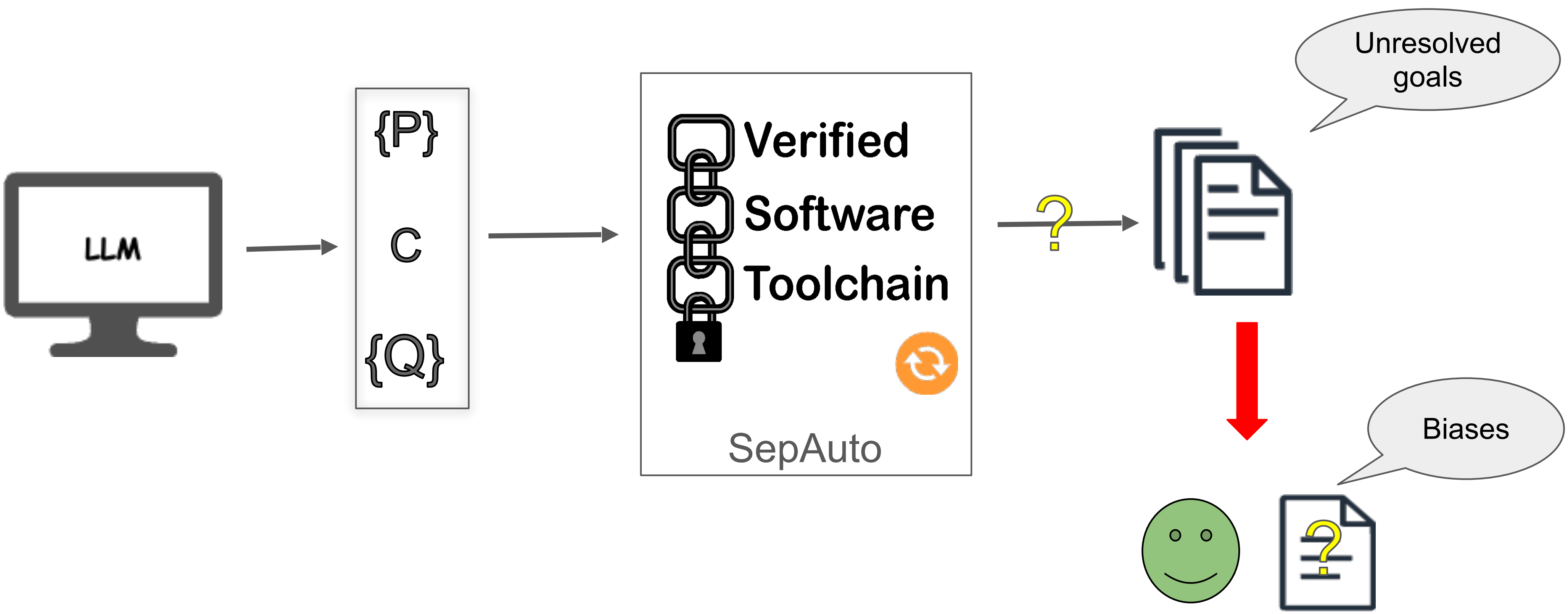

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- SepAuto - Ltac on top of VST to automate proofs
- Experimental Setup
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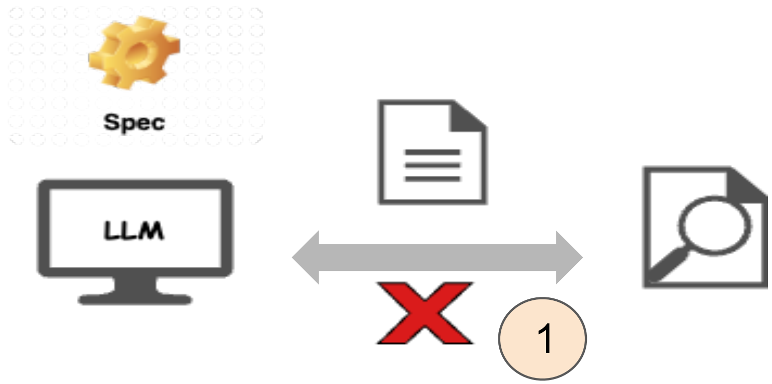

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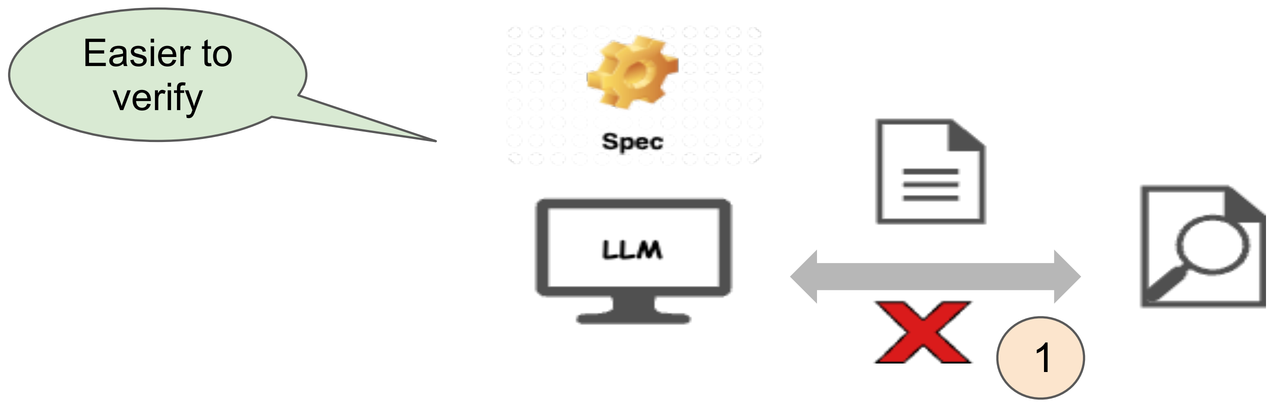

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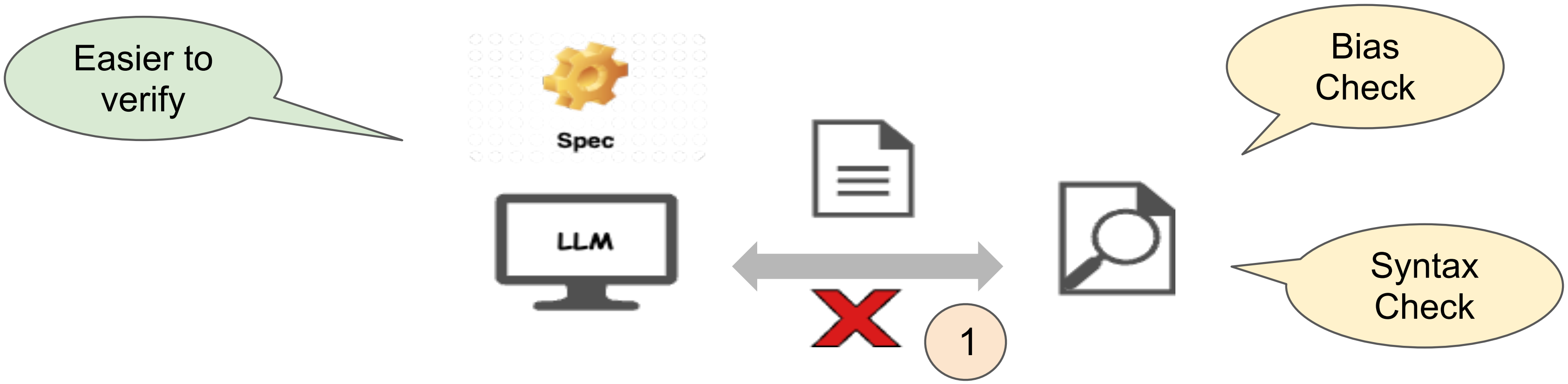

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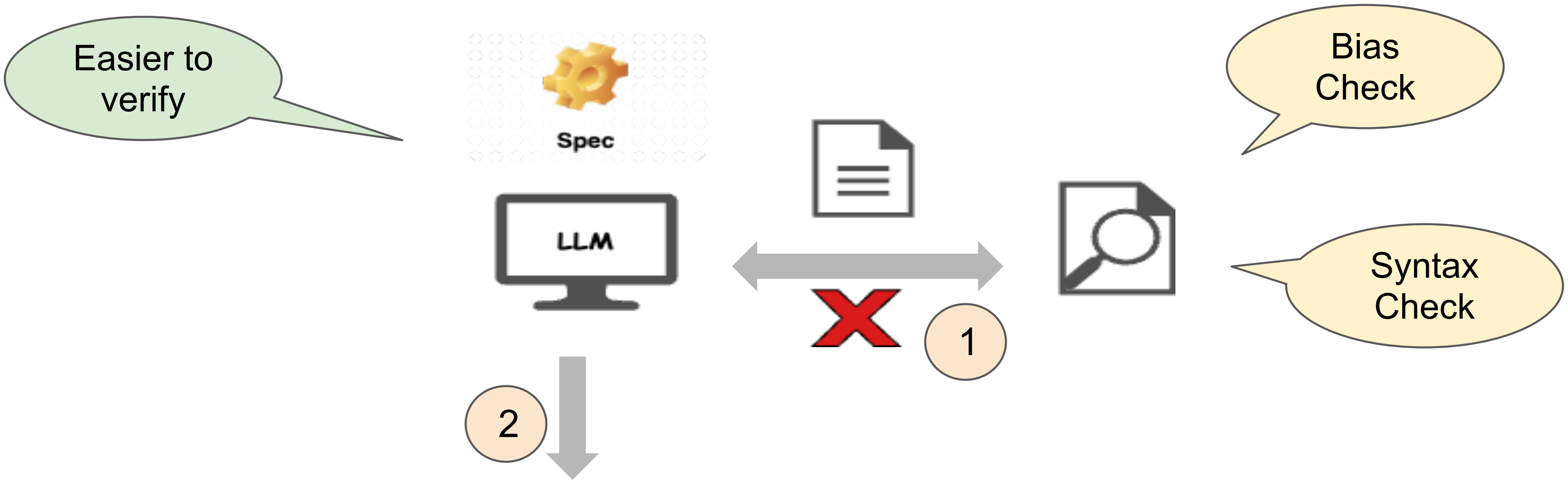

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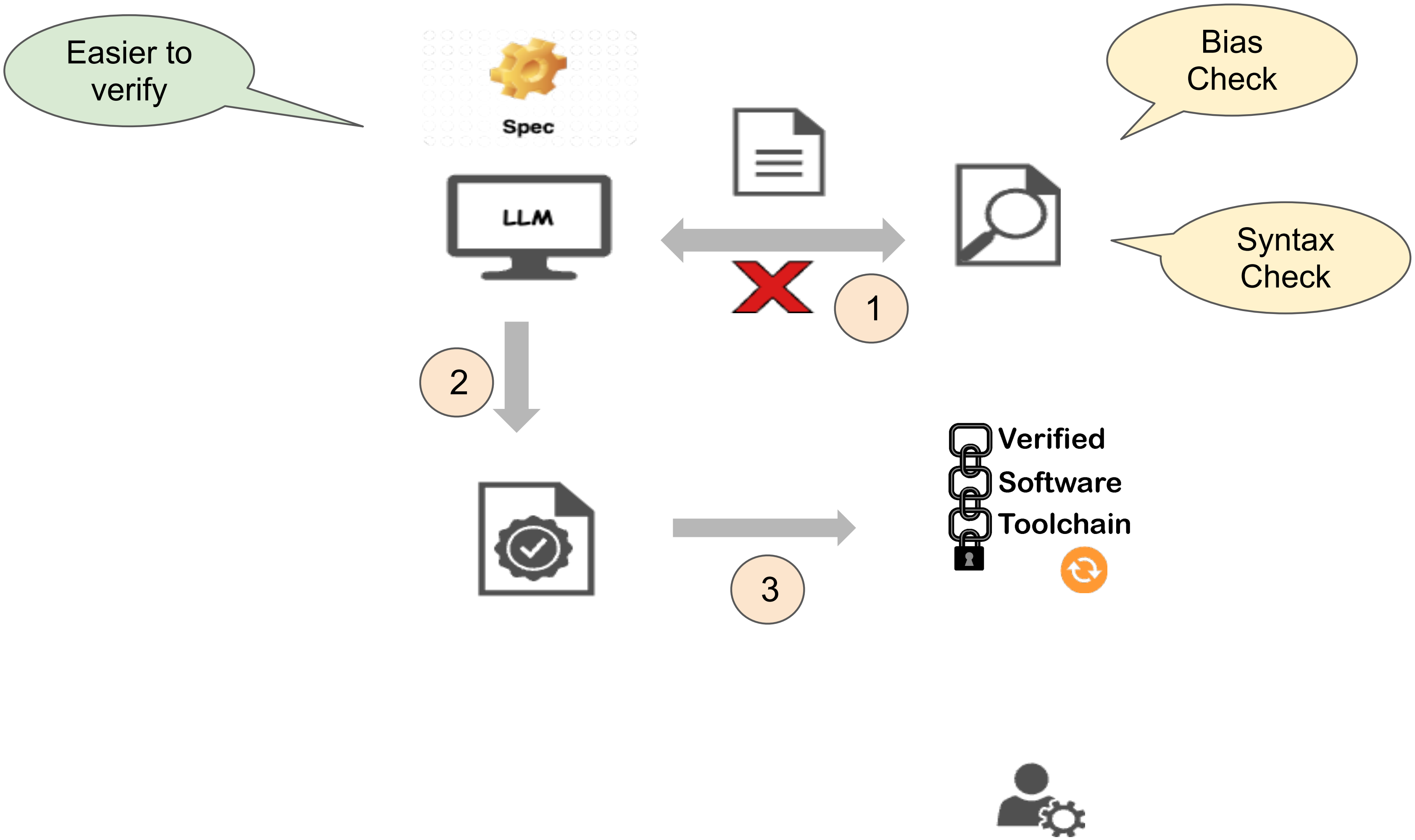

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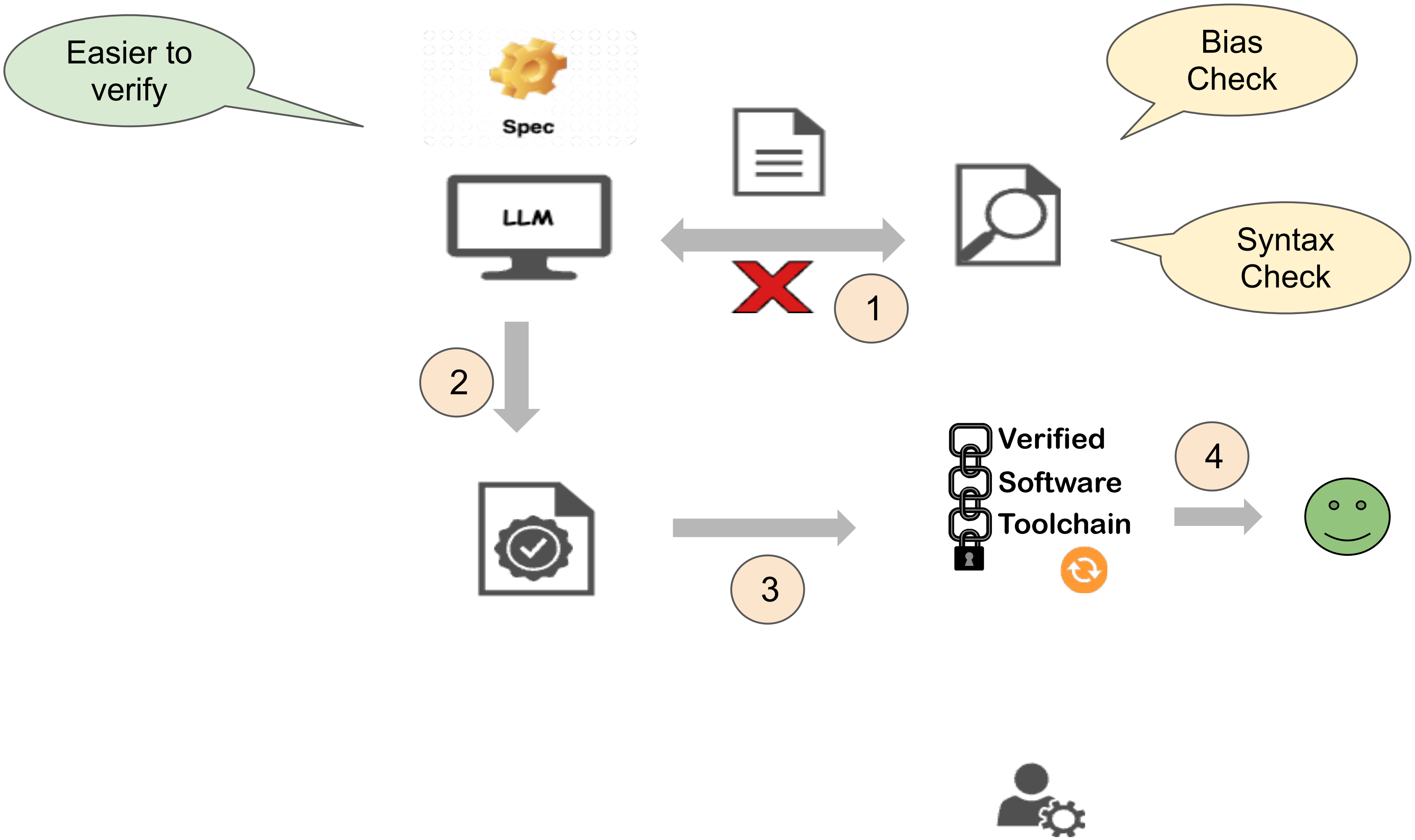

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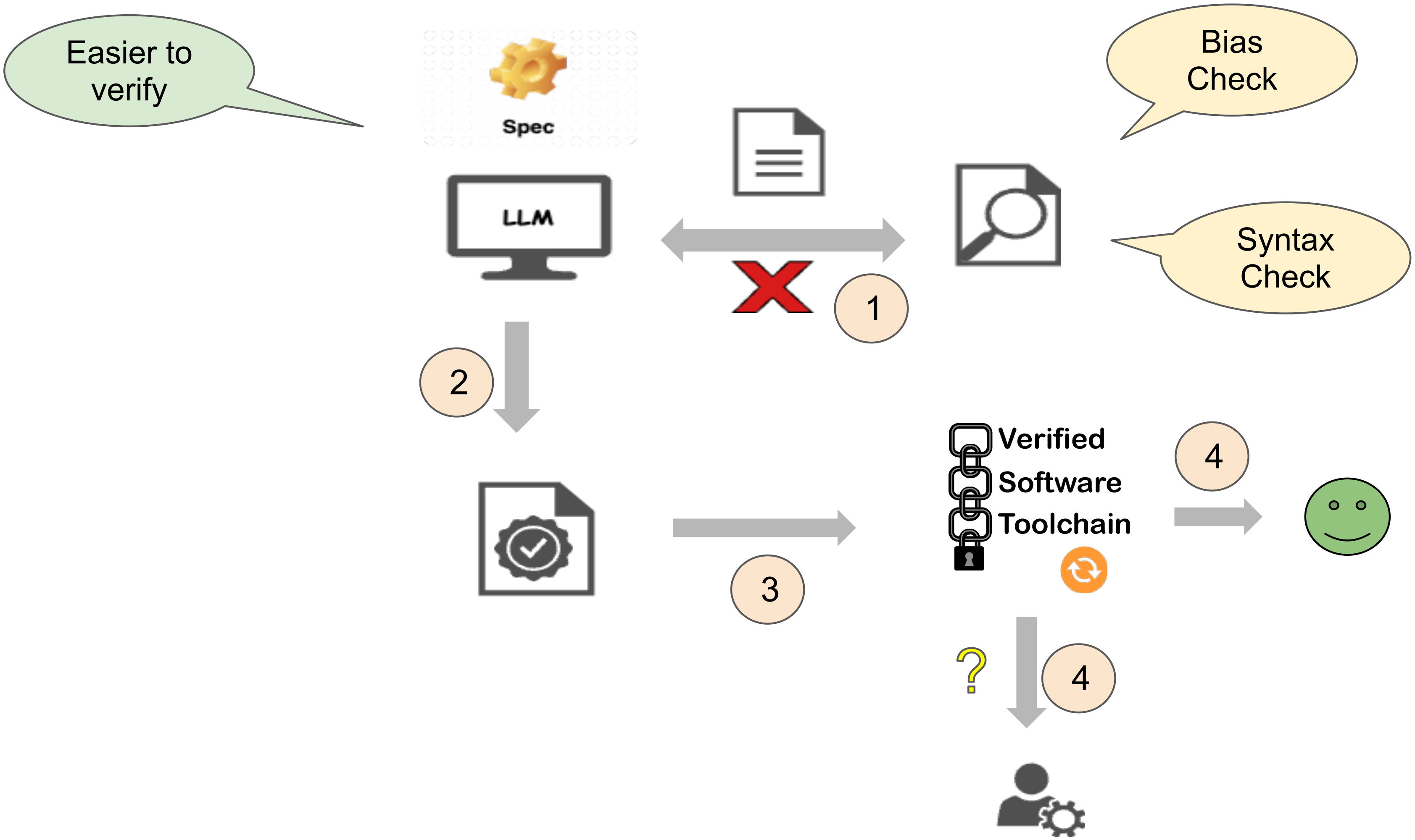

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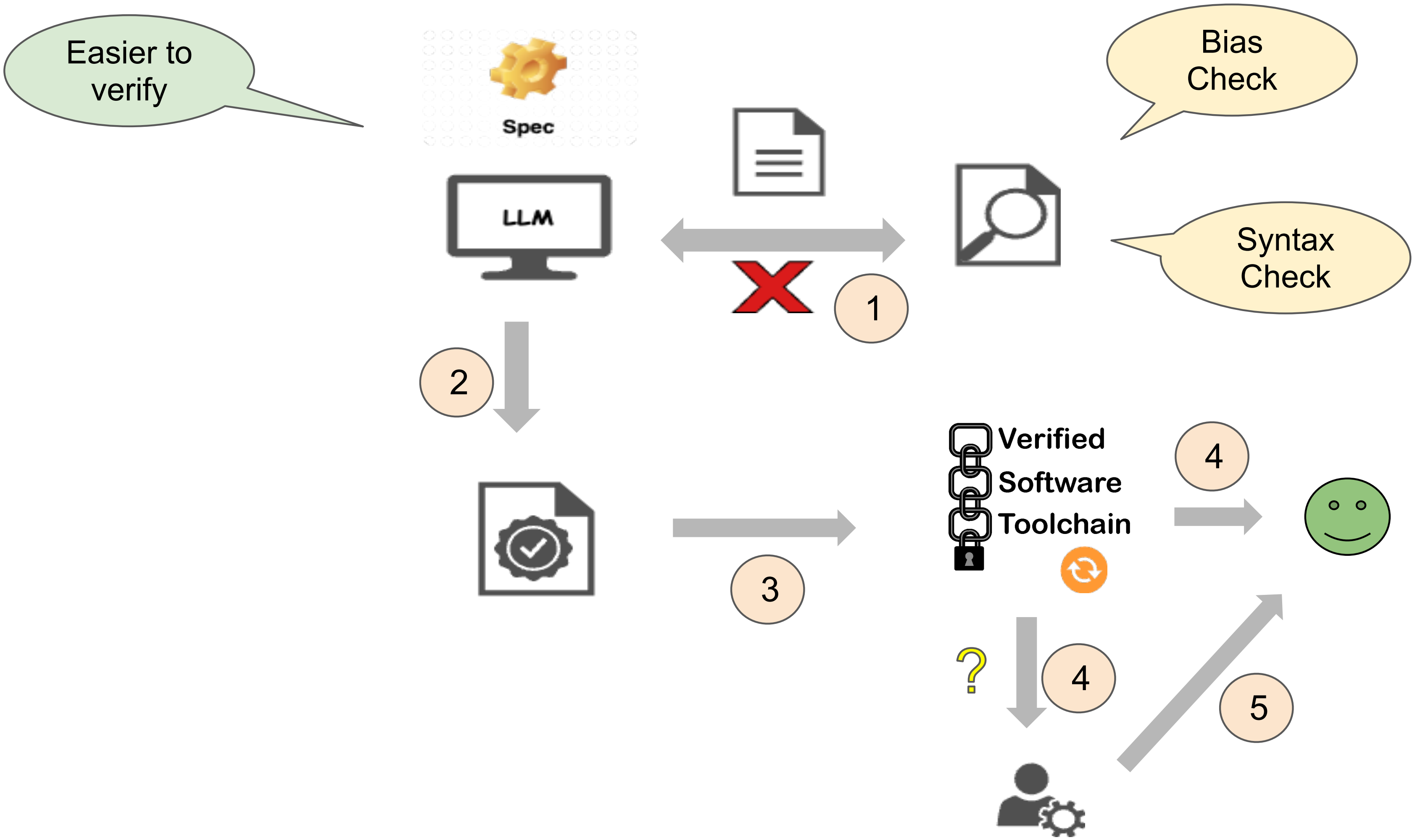

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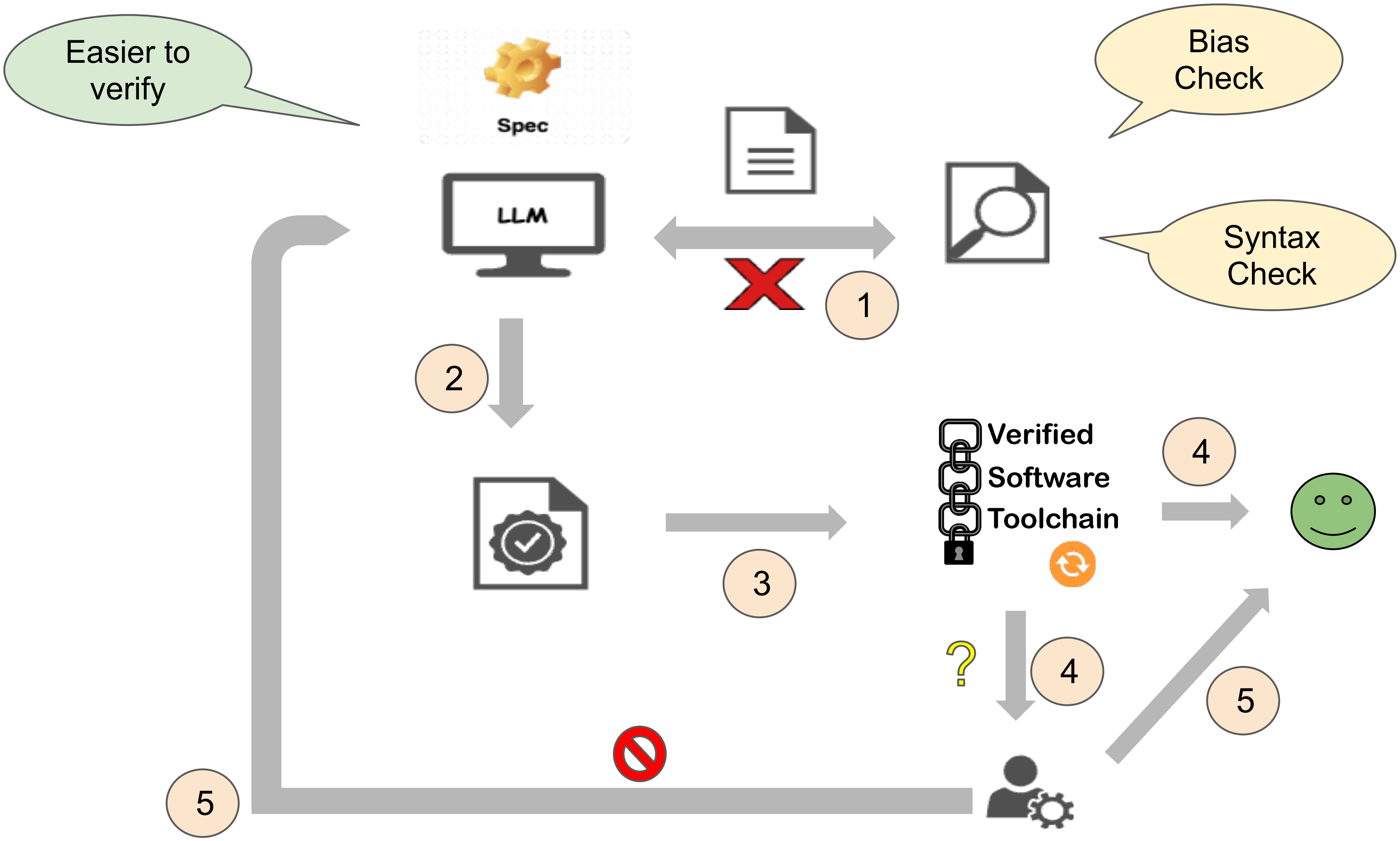

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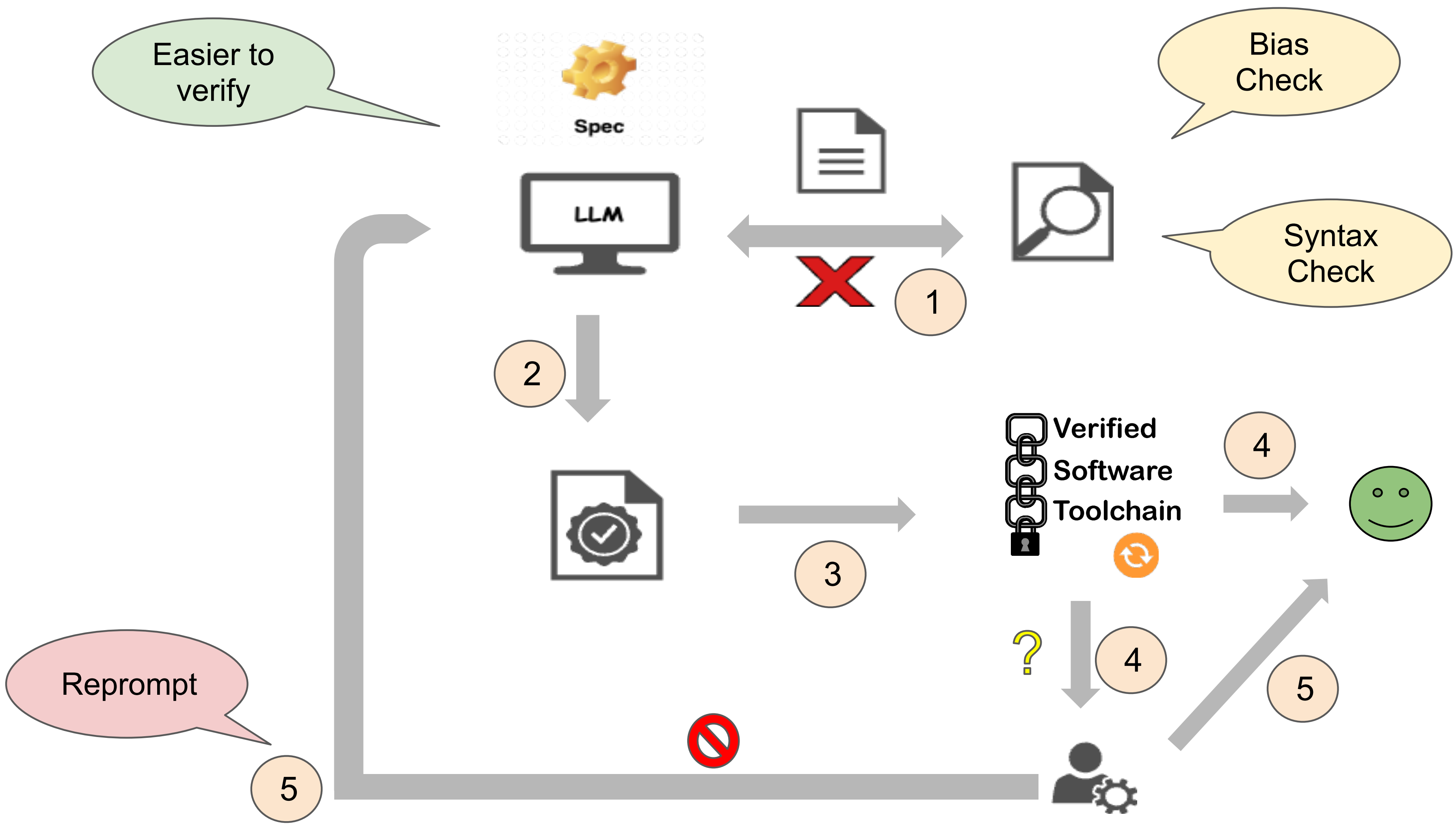

Why incorporate biases?

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↓

Generate programs that are easier to verify

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Generate programs that are easier to verify

✖ Infer novel specifications and verify them

Biases: No loops and novel helper functions

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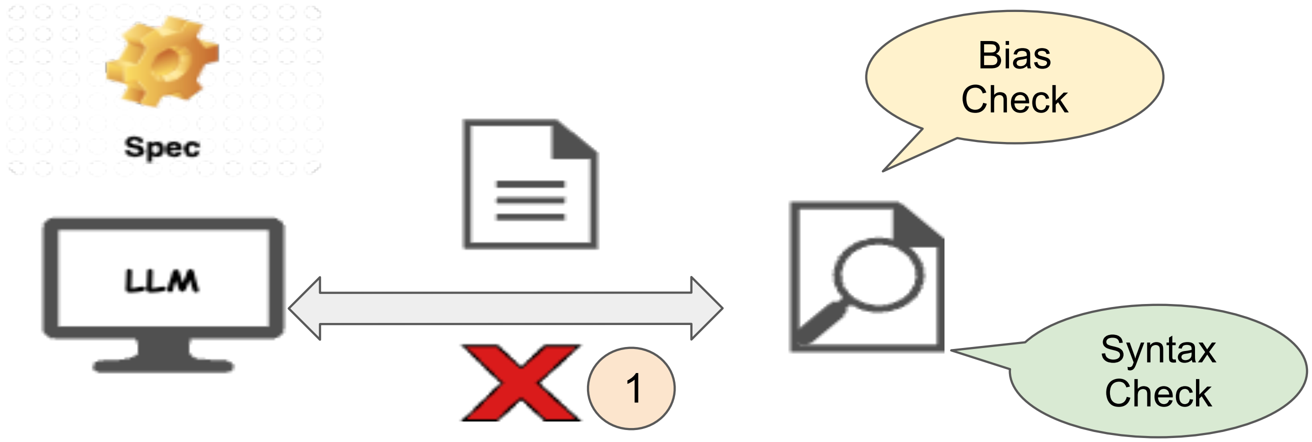

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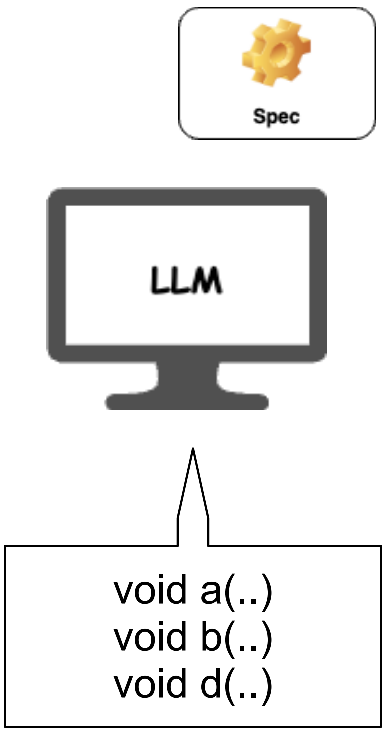

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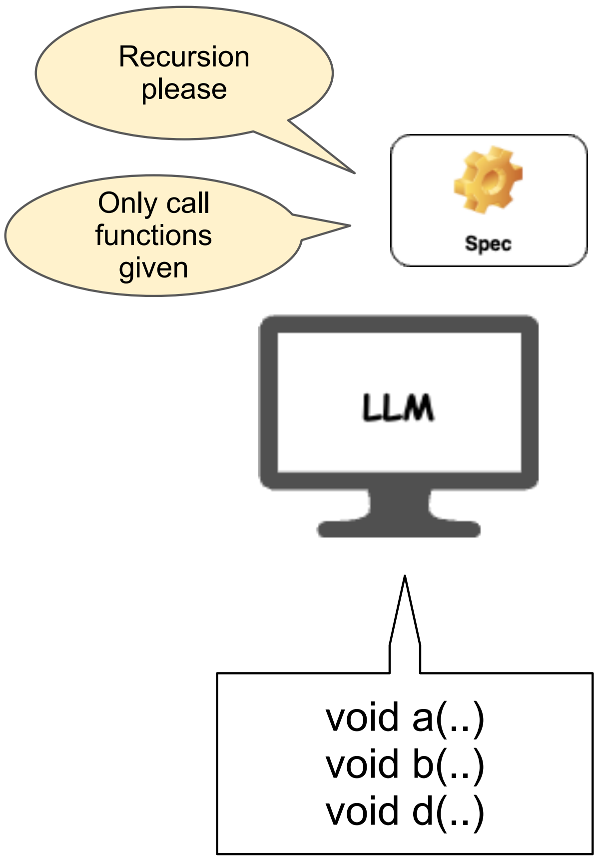

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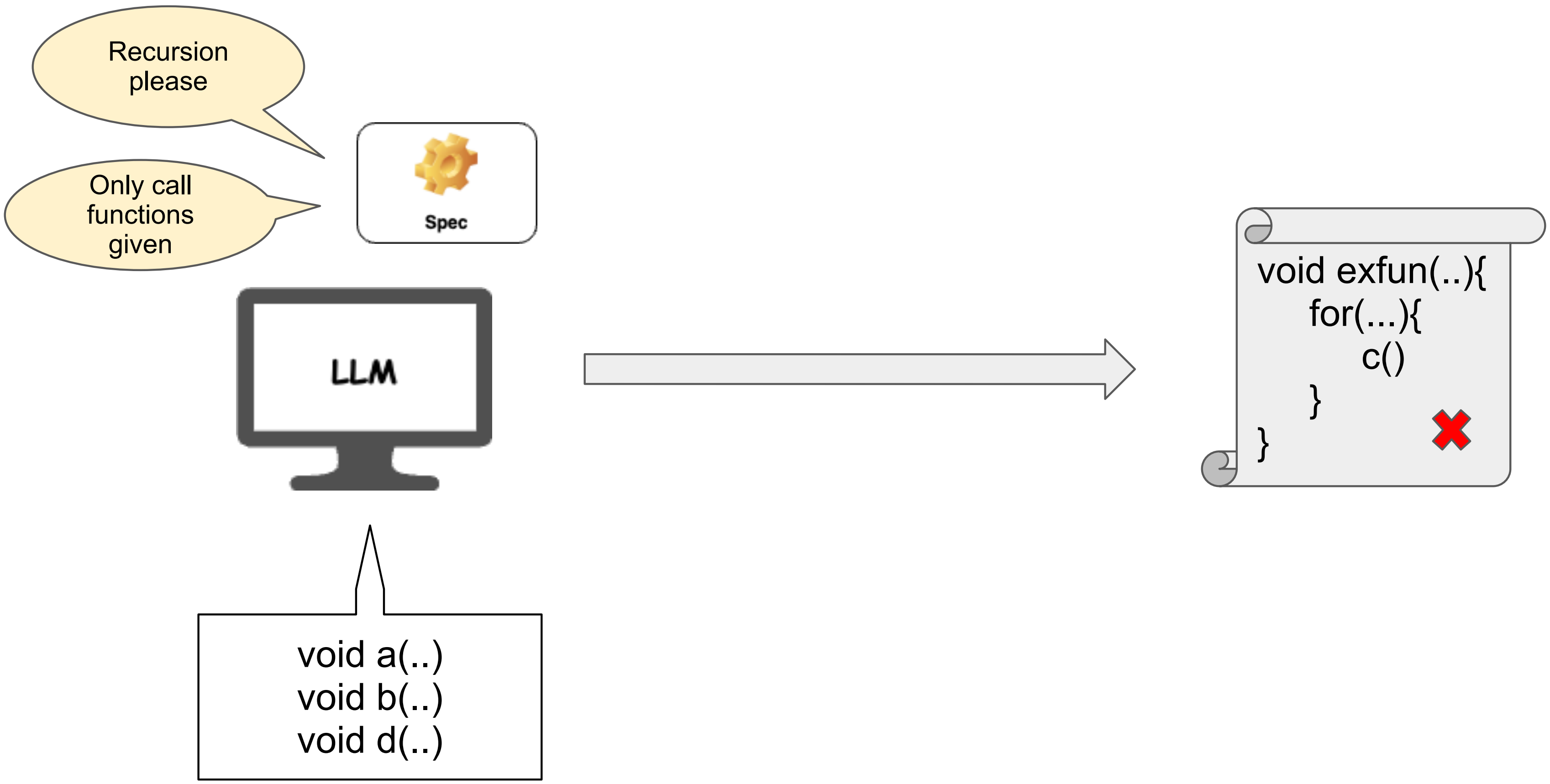

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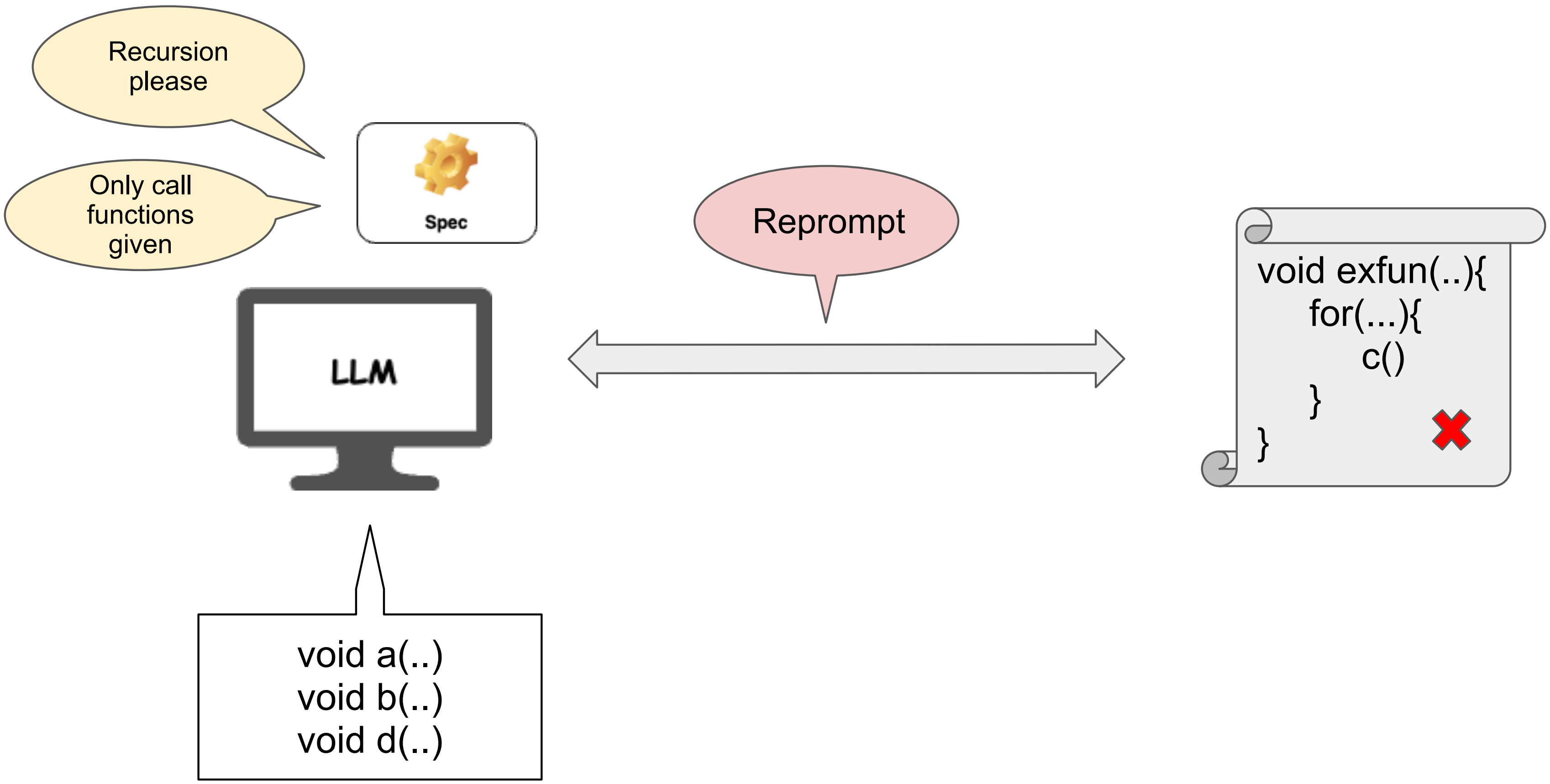

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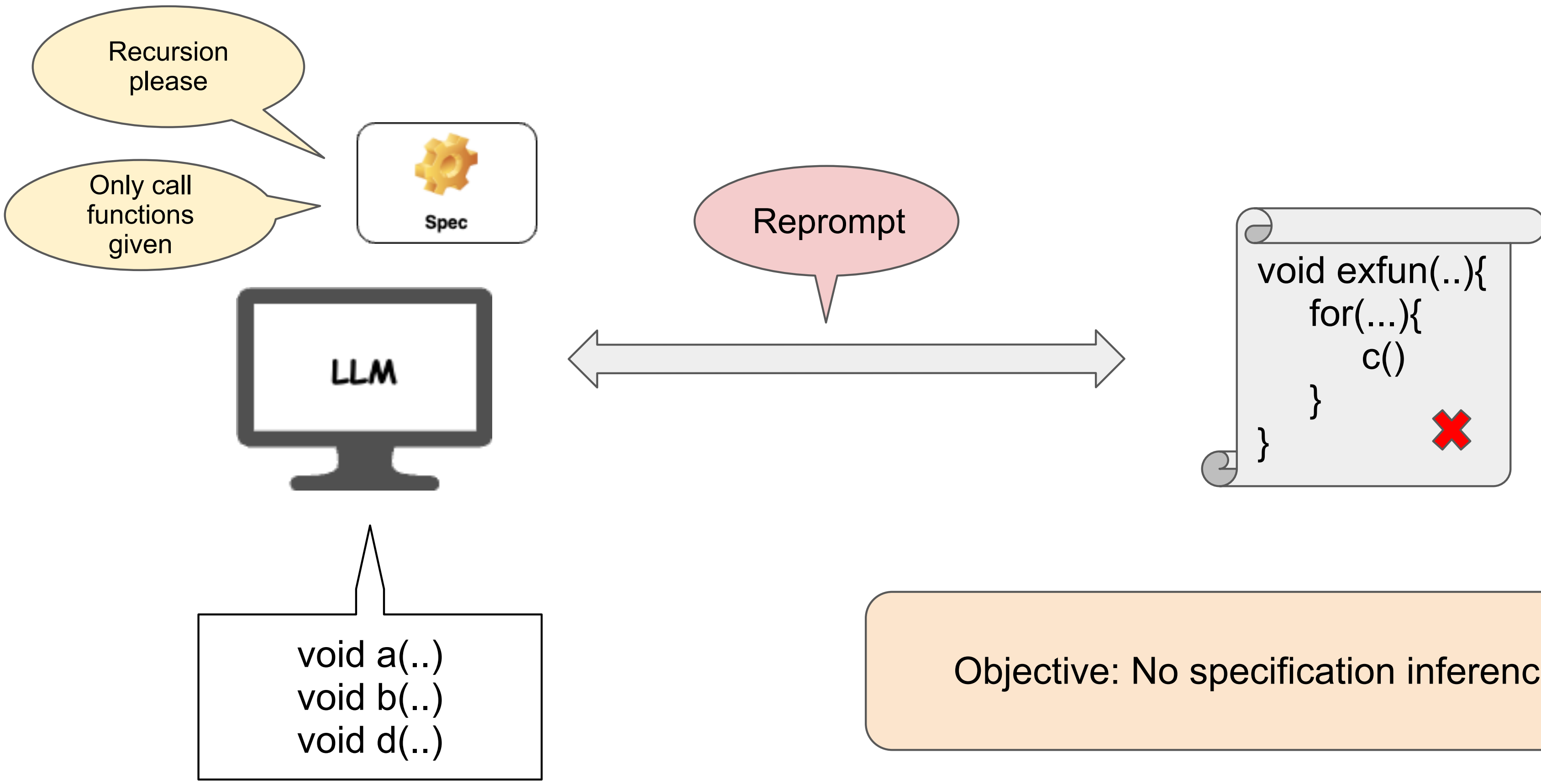


Objective: No specification inference

Writing automation friendly specifications

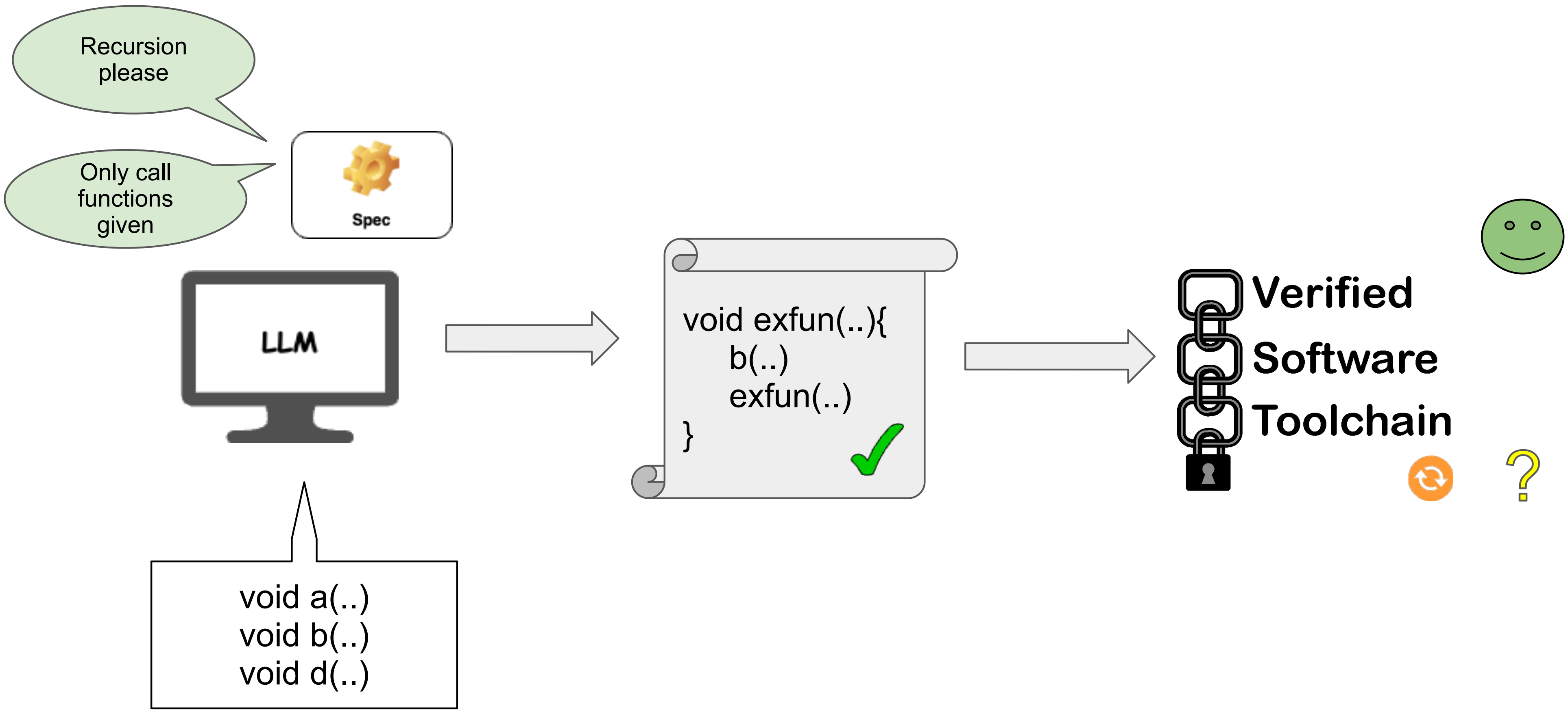
- Equivalent specifications amenable to automated reasoning
- Express with predicates like Forall, Forall2
- Check if an array is sorted in ascending order

$$\forall i, j \ 0 \le i \ < len \rightarrow i < j < len \rightarrow a[i] \le a[j]$$

$$Forall2 \ \le \ (sublist \ 0 \ (len \ - 1) \ a) \ (sublist \ 1 \ len \ a)$$

list_solve

Biases checked



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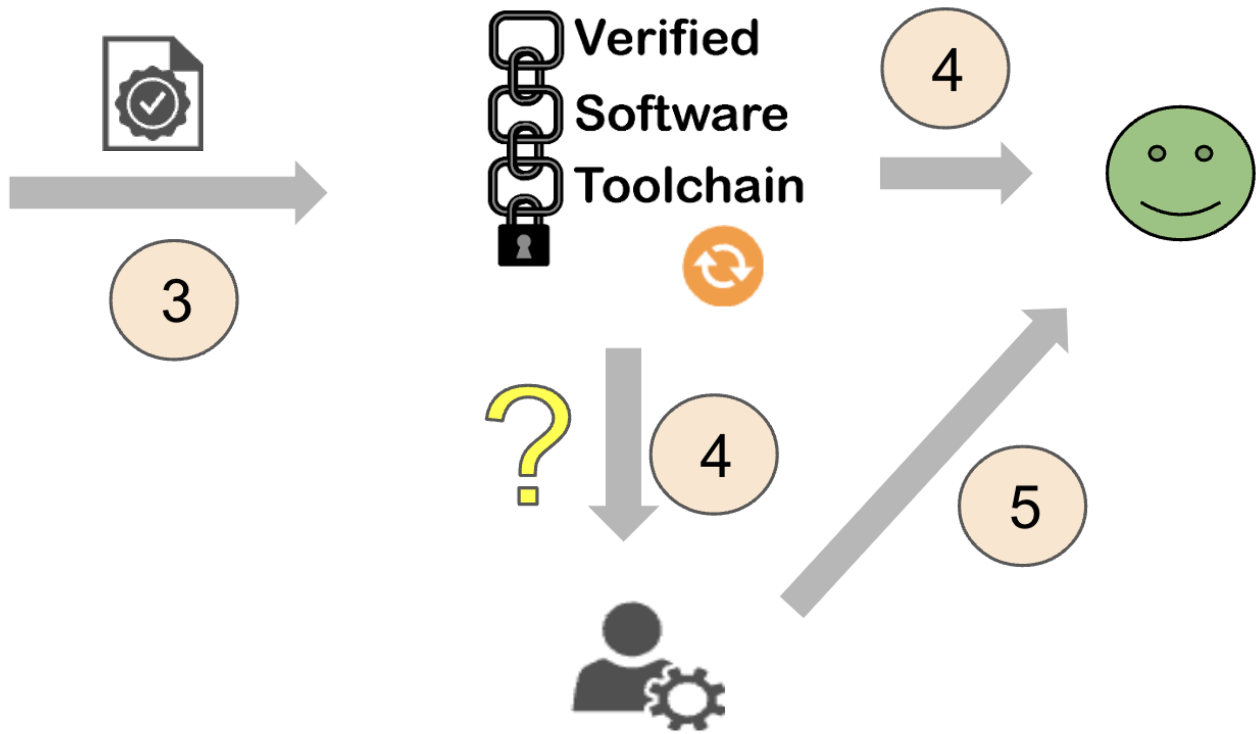

SepAuto: Forward symbolic execution

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{P} C {Q}

Verified Software Toolchain

Data structures
Proofs
Hint lemmas
Shape Analysis

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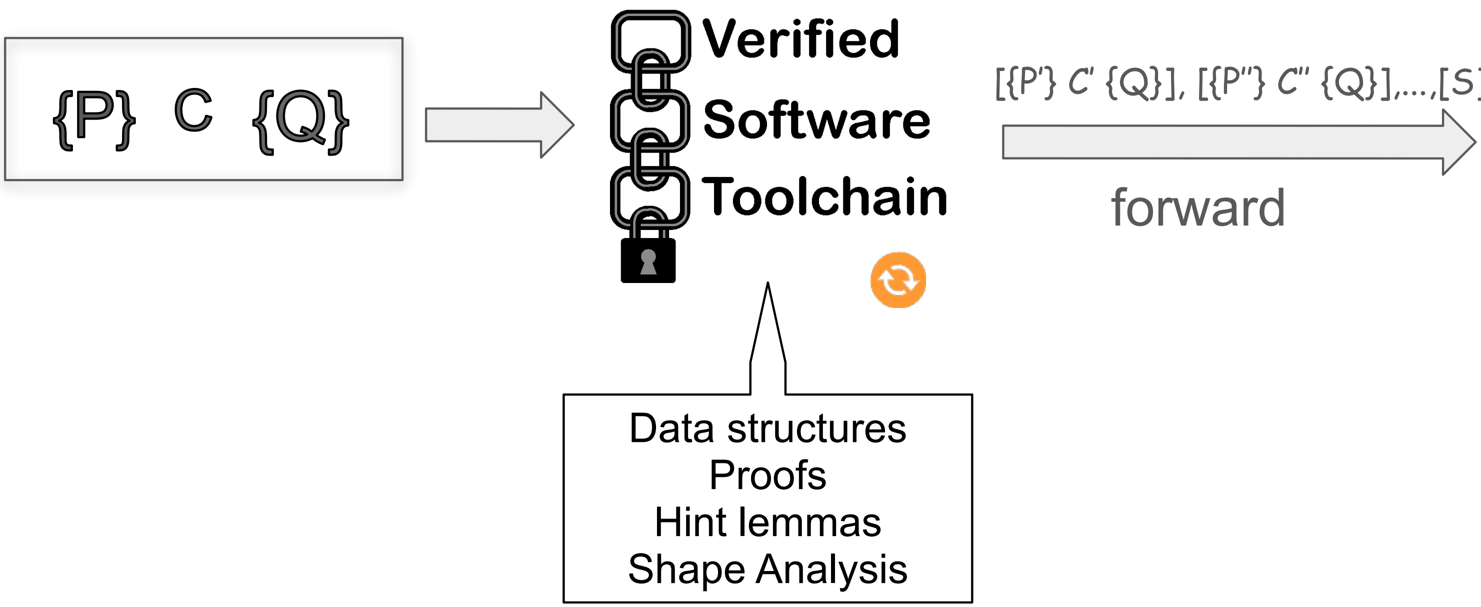

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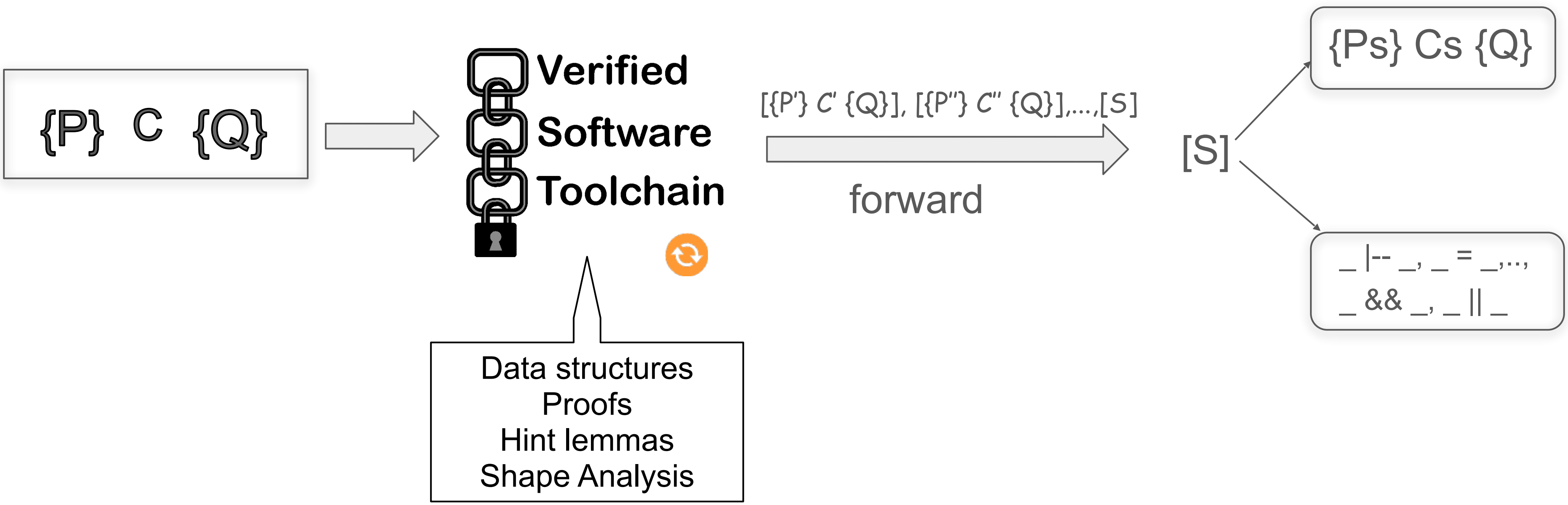

SepAuto: if statements

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{Ps} if b then c else d; e {Q}

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forward_if ✖

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Requires a joint post-condition

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transform

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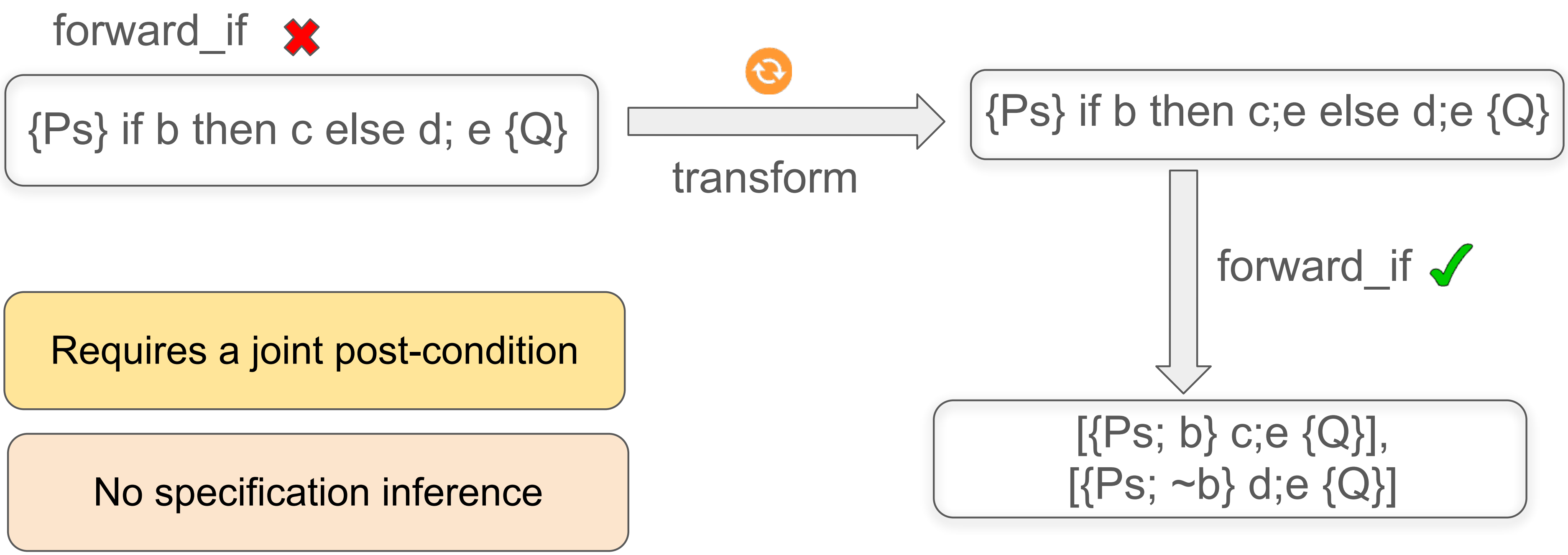

SepAuto: Function calls

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{Ps} f(....); e {Q}

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forward_call(....)

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forward_call(....) ✖

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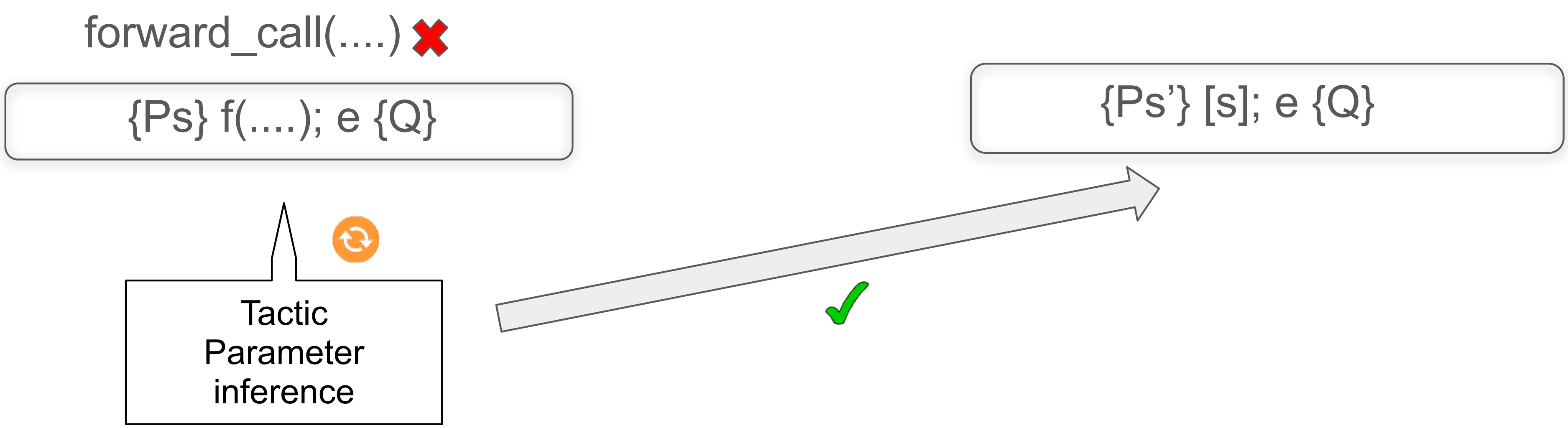

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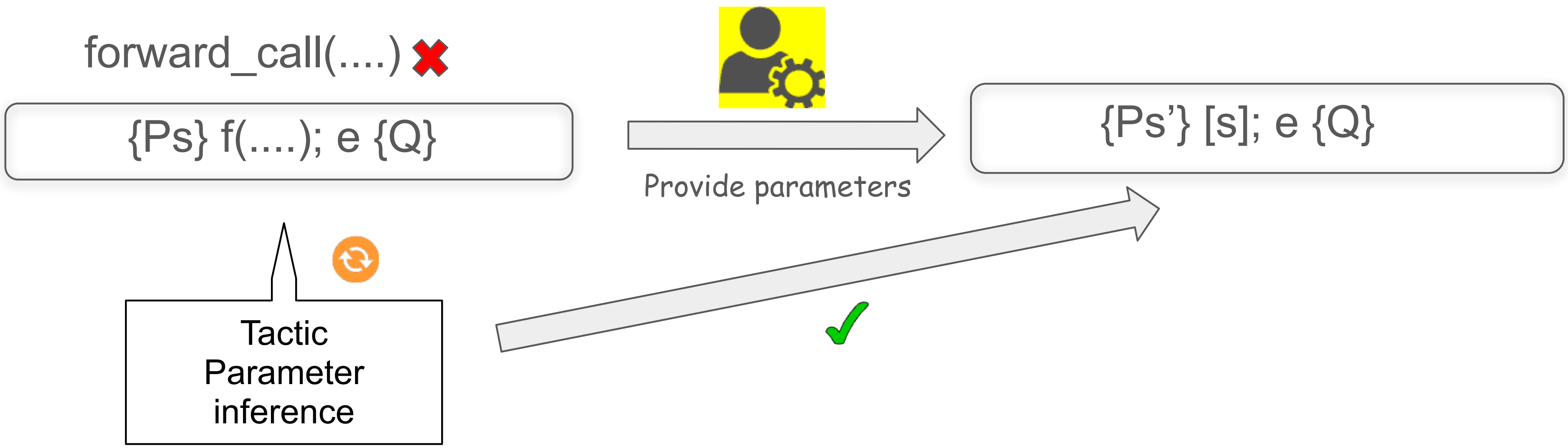
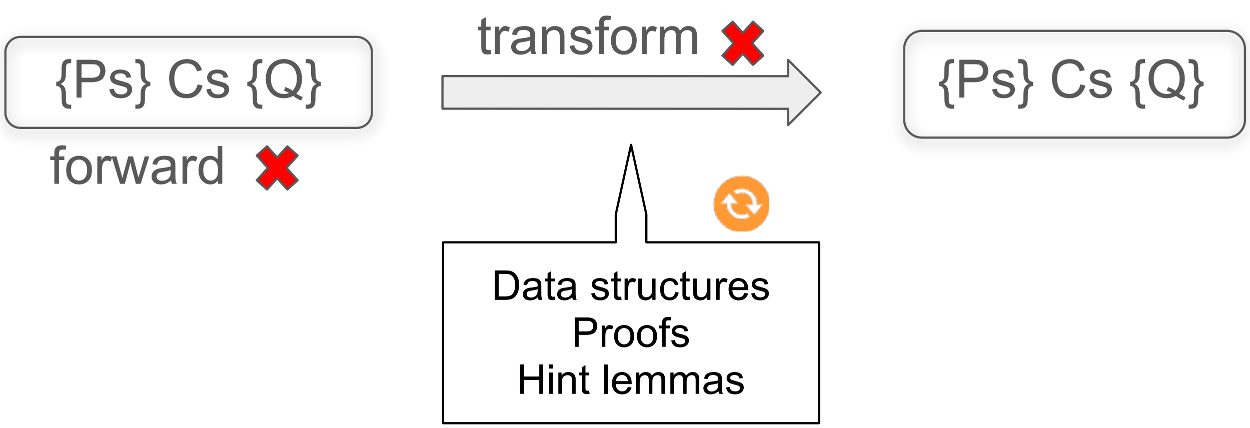


SepAuto: When forward fails



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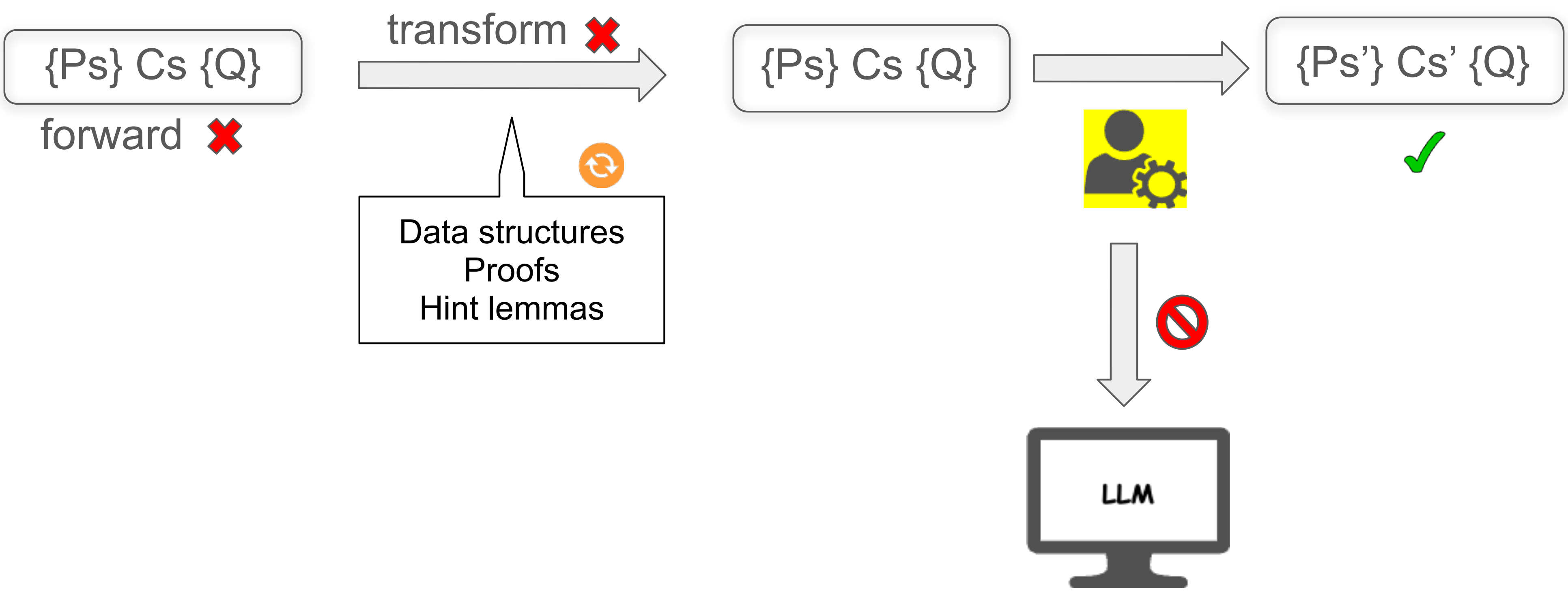
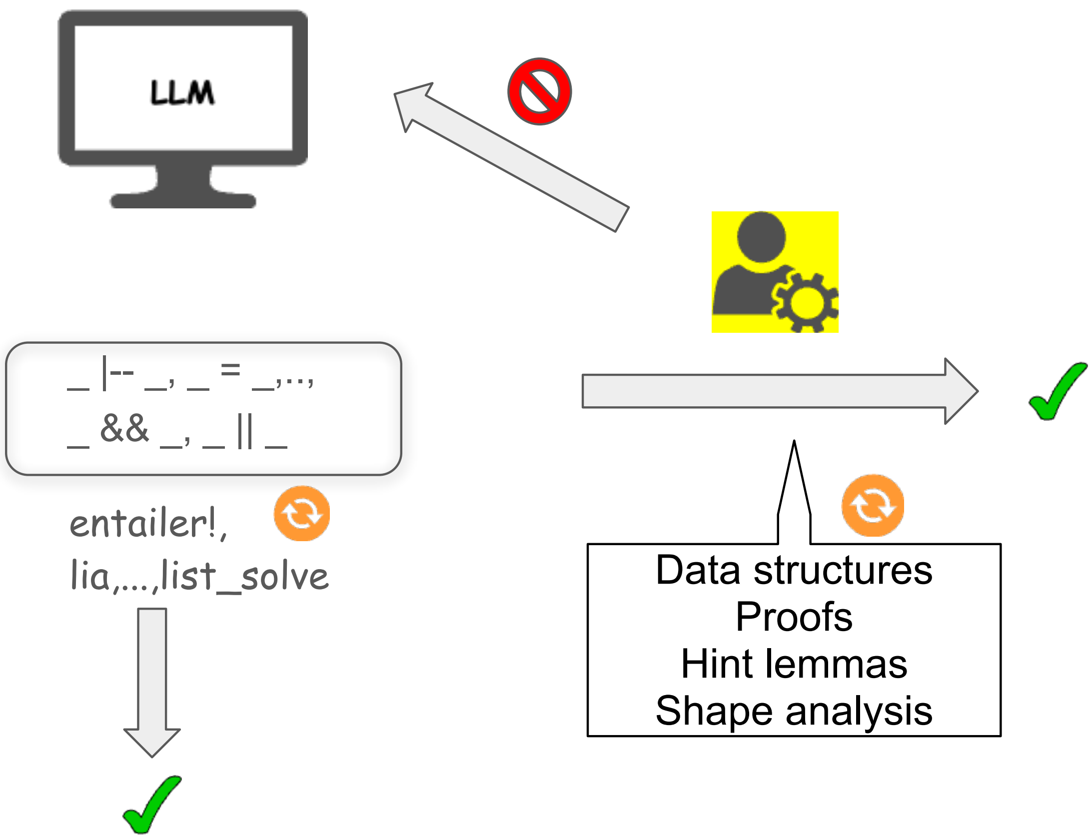


SepAuto: Non-Hoare Triples



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Experimental Setup

- Benchmark of 50 programs across basic [1], SL [2] and API [3]
- Multiple types supported for programs
- GPT-4o as the LLM
- Prompted with five components

[1] Md Rakib Hossain Misu, Cristina V. Lopes, Iris Ma, and James Noble. FSE (2024), 812–835. https://doi.org/10.1145/3643763

[2] Nadia Polikarpova and Ilya Sergey. 2019. Structuring the synthesis of heap-manipulating programs. POPL (2019), 72:1–72:30. https://doi.org/10.1145/3290385

[3] Cormen, T.H., Leiserson, C.E., Rivest, R.L., Stein, C.: Introduction to Algorithms, Third Edition. The MIT Press, 3rd edn. (2009)

Results

- GPT-4o produced correct code in the first try for 49/50 programs
- Incorrectly generated program(s) required detailed information about the algorithm

Benchmark	**Bias**	**Types**	**Recursion**	**SC**	**Attempts**
arrayLookUpTable	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✖	0	1
completegraphAdjMatrix	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✖	0	1
deleteBST	✔	$\{\mathbb{Z}\}$	✖	0	1
generateSkewedBST	✔	$\{\mathbb{Z}\}$	✖	2	3
addLastVoid	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✖	0	1
stackAPILinkedList	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✖	1	1

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Cannot parse the meaning

generateSkewedBST(a[],n) ✖

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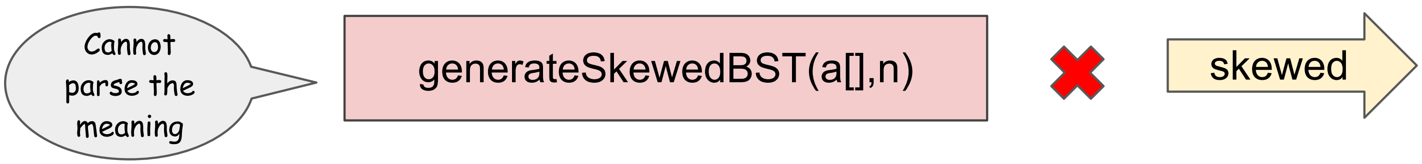

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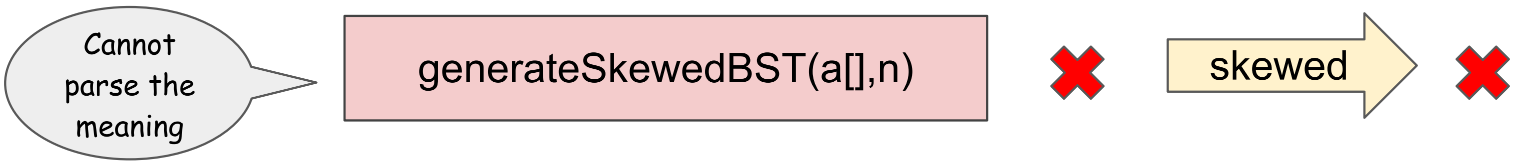

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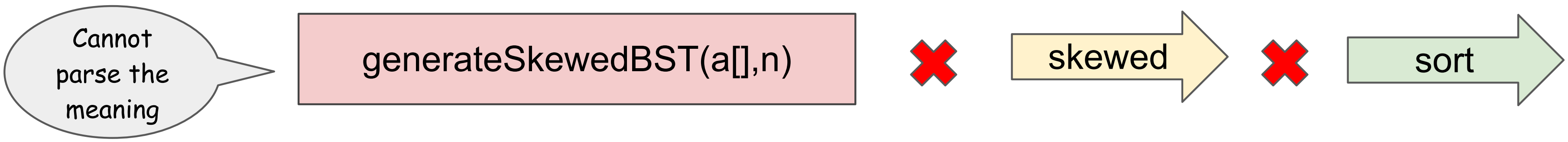

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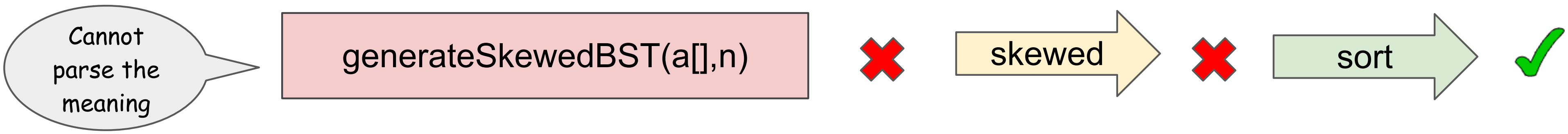
deleteBST	✔	$\{\mathbb{Z}\}$	✖	0	1
generateSkewedBST	✔	$\{\mathbb{Z}\}$	✖	2	3
addLastVoid	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✖	0	1
stackAPILinkedList	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✖	1	1

Results

- GPT-4o produced correct code in the first try for 49/50 programs
- Incorrectly generated program(s) required detailed information about the algorithm



Benchmark	Bias	Types	Recursion	SC	Attempts
arrayLookUpTable	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✖	0	1
completegraphAdjMatrix	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✖	0	1
deleteBST	✔	$\{\mathbb{Z}\}$	✖	0	1
generateSkewedBST	✔	$\{\mathbb{Z}\}$	✖	2	3
addLastVoid	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✖	0	1
stackAPILinkedList	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✖	1	1

Results

- Verifies mostly automatically
- Side conditions primarily generated for complex specifications

SL

listDelEnd	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✔	1	1
listLookup	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✔	0	1
listCopy	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✔	0	1
listInsertEnd	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✔	0	1
listFilter	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✔	0	1
listAndArraySame	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✔	0	1
listAdd1	✔	$\{\mathbb{Z}\}$	✔	0	1
bstInit	✔	$\{\mathbb{Z}\}$	✖	0	1
bstFree	✔	$\{\mathbb{Z}\}$	✔	0	1
bstLookup	✔	$\{\mathbb{Z}\}$	✔	0	1
bstInsert	✔	$\{\mathbb{Z}\}$	✔	0	1
bstMinNode	✔	$\{\mathbb{Z}\}$	✔	2	1

Basic

checkZ	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✔	1	1
consecNumbers	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✔	0	1
nIsGreater	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✔	0	1
firstodd	✔	$\{\mathbb{Z}\}$	✔	3	1
arrayMemberValue	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✔	0	1
isOddAtIndexOdd	✔	$\{\mathbb{Z}\}$	✔	3	1
lastelempos	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✔	2	1
arrayModifyWithOneValue	✔	$\{\mathbb{Z}, \mathbb{R}, \mathbb{S}\}$	✔	0	1
compareTwoArrays	✔	$\{\mathbb{Z}, \mathbb{S}\}$	✔	0	1
addArrayElementsBy1	✔	$\{\mathbb{Z}\}$	✔	0	1

RQ1: Are the biases necessary?

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Without additional biases, what programs do LLMs tend to generate?

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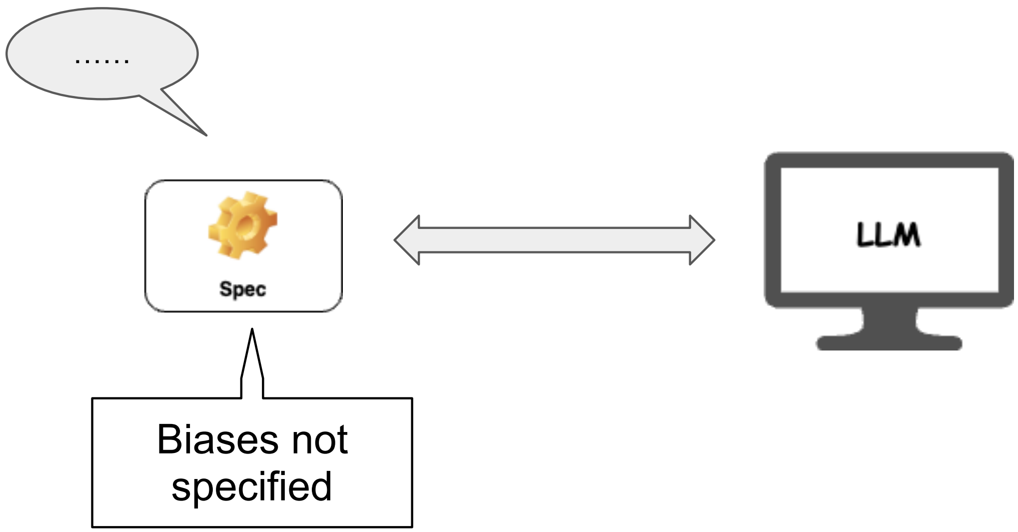

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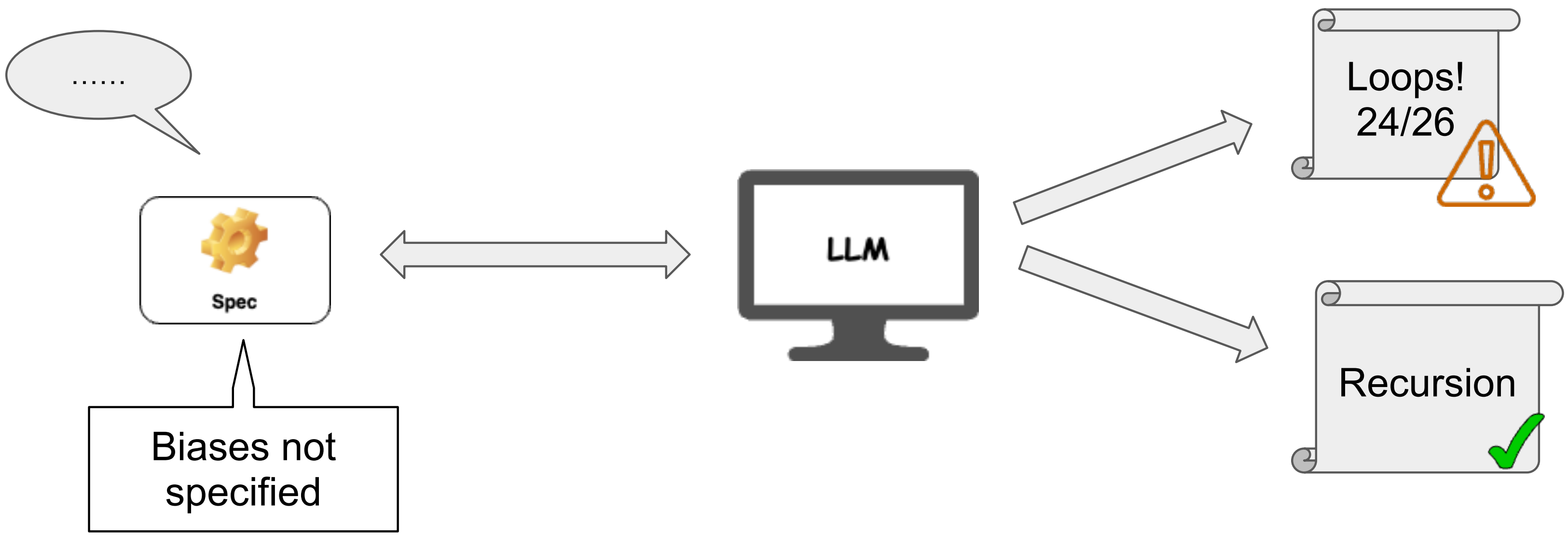

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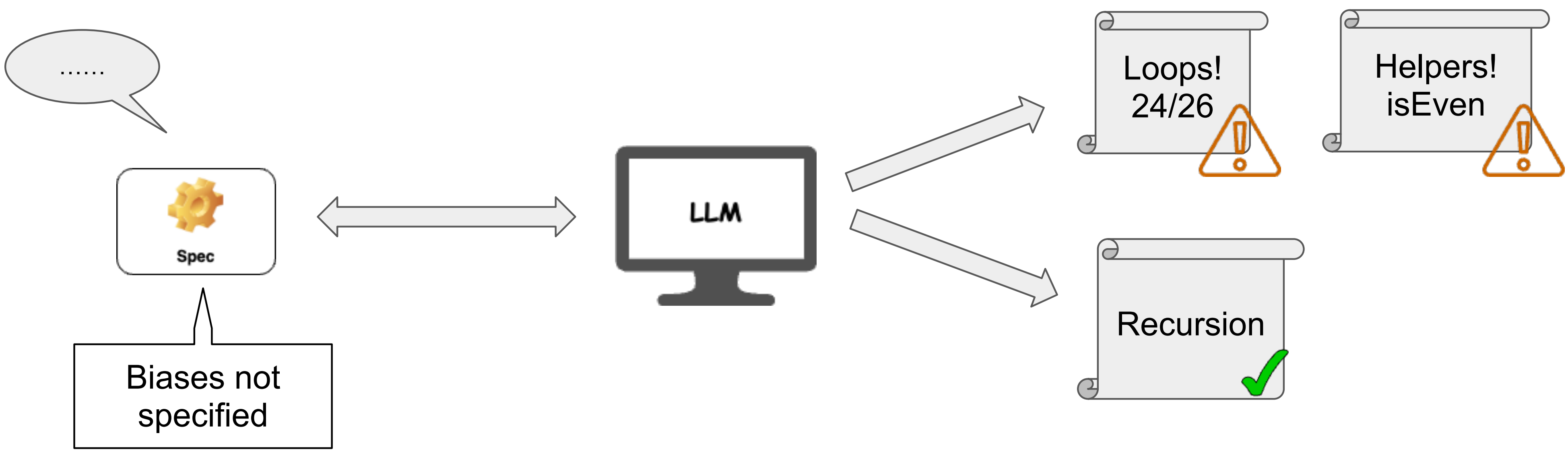

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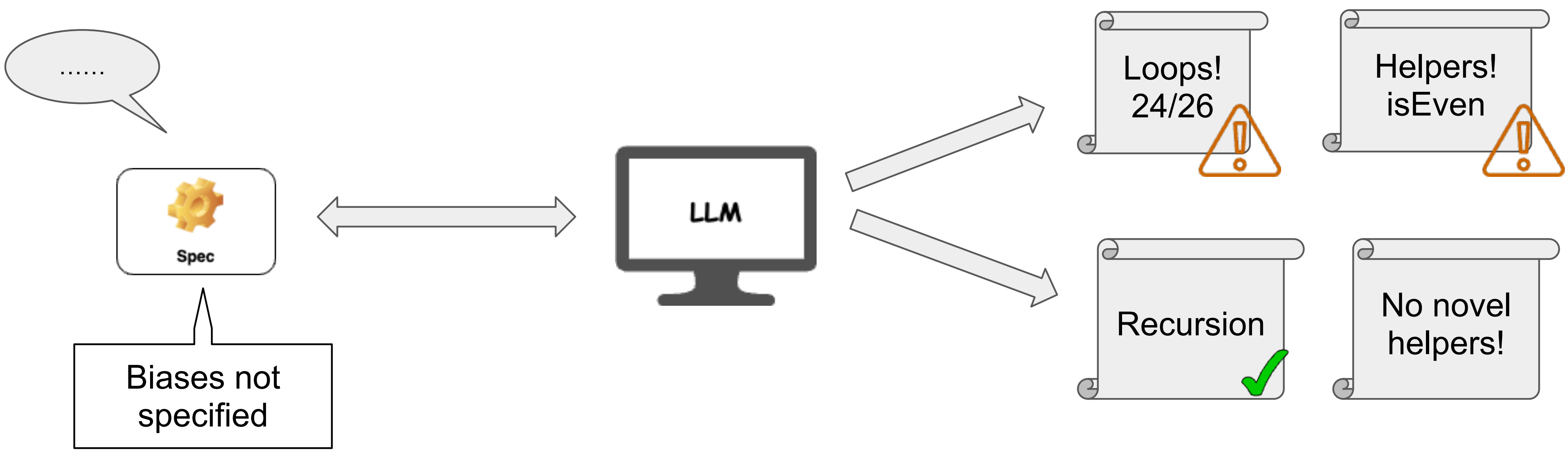

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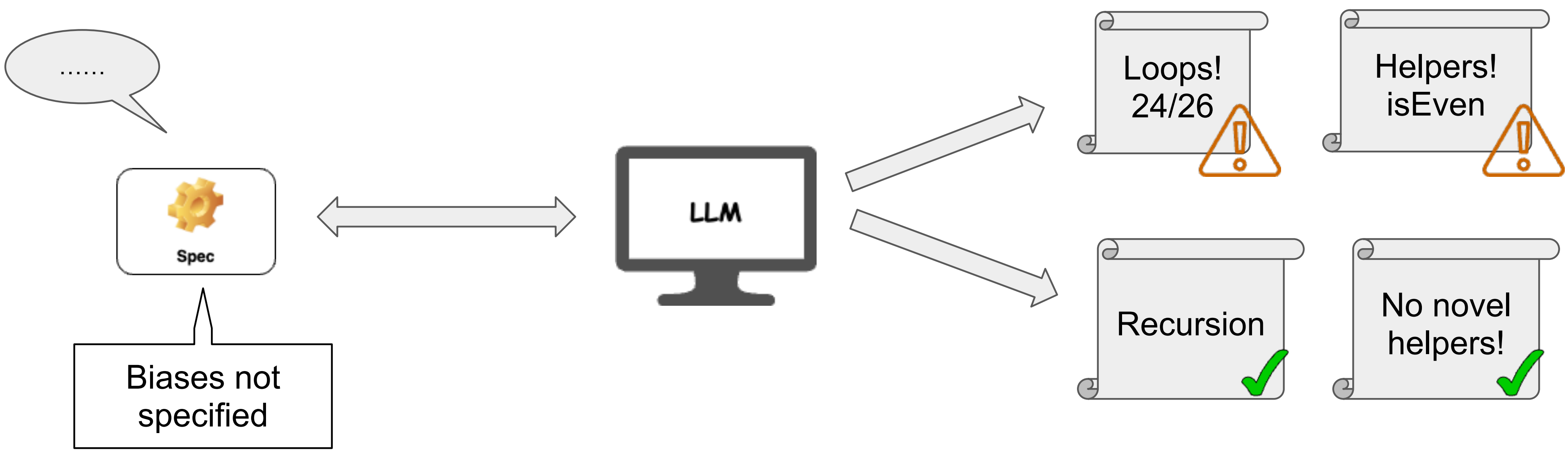

RQ2: Where does SepAuto Fail?

Unable to infer relation between two variables

```
H8 :   ind >= 0
H6 :   ind < Zlength contents
H9 :   Znth ind contents <> ele
Hform :  Znth vret contents = ele /\
         Forall (fun x : Z => x <> ele)
           (sublist (vret + 1) (ind - 1 + 1) contents)
```

```
(1/1)
Forall (fun x : Z => x <> ele)
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Forall (fun x : Z => x <> ele)
  (sublist (vret + 1) (ind + 1) contents)
```

destruct vret >=? ind

sublist_split

RQ2: Where does SepAuto Fail?

Unable to pose and prove non-trivial premises

```
H :  p <> nullval
H4 :  y = nullval <-> hs = []
```

```
(1/1)
listrep hs y
|-- listrep (sublist 1 (Zlength (h0 :: hs)) (h0 :: hs)) y
```

RQ2: Where does SepAuto Fail?

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RQ2: Where does SepAuto Fail?

Automation is unsupported for the wand operator

```
H :  p <> nullval
H6 :  field_compatible t_struct_tree [] p
H7 :  value_fits t_struct_tree
       (Vint (Int.repr k),
        (Vint (Int.repr v), (nullval, pb)))
PNpb :  is_pointer_or_null pb
```

```
(1/1)
data_at Tsh t_struct_tree
  (Vint (Int.repr k),
   (Vint (Int.repr v), (nullval, pb))) p
  * tree_rep b pb
|-- EX a0 : val,
    !! (a0 <> nullval /\ p = a0) &&
    (tree_rep (inorderSuccessor (T E k v b)) a0
       * (tree_rep (inorderSuccessor (T E k v b)) a0 -*
          tree_rep (T E k v b) p))
```

RQ2.5: SepAuto versus other verifiers?

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Where do other verifiers fail in comparison to SepAuto?

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Frama C	VeriFast	RefinedC
Basic ☺	Expressive ☺	Expressive ☺
Dynamic allocation ⚠	Annotation inference ⚠	SL implication ☺
Separation Logic ⚠	Precise messaging ⚠	Precise messaging ☺
		Hint Lemmas ⚠

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Basic	Expressive	Expressive
Dynamic allocation	Annotation inference	SL implication
Separation Logic	Precise messaging	Precise messaging
		Hint Lemmas

```
void addHelper(struct node* n, int x)
  //@ requires n!= 0 &*& lseg(n, 0, ?vs);
  //@ ensures lseg(n, 0, append(vs, cons(x, nil)));
{
  //@ open lseg(n, 0, vs);
  if(n->next == 0) {
    // @ open lseg(0, 0, _);
    struct node* nn = create_node(0, x);
    n->next = nn;
  } else {
    addHelper(n->next, x);
  }
}
```

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}
```

Postcondition ✗

RQ2.5: SepAuto versus other verifiers?

```
[[rc::parameters("l : {list Z}", "p : loc", "n : Z" )]]
[[rc::args("p @ &own<l @ list_t>", "n @ int<i32>")]]
[[rc::exists("b : bool")]]
[[rc::returns("b @ builtin_boolean")]]
[[rc::ensures("own p : l @ list_t", "{b ↔ n ∈ l}")]]
//[[rc::tactics("all: try set_solver.")]]
bool member_rec (list_t *p, int k) {
  if (*p == NULL) {
    return false;
  }
  int head = (*p)->val;
  if (head == k) {
    return true;
  }
  return member_rec(&(*p)->next, k);
}
```

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}
```

```
HCASE :  CASE_DISTINCTION_INFO
          (optional == ... : n :: x1 ≠ [])
          [loc_38; loc_38]
HCASE0 :  CASE_DISTINCTION_INFO
           (if false, false) [loc_38]
H1 :  n ≤ max_int i32
H0, H2 :  min_int i32 ≤ n
H3 :  n ≤ max_int i32
HCASE1 :  CASE_DISTINCTION_INFO
           (if bool_decide (n = n), true)
           [loc_21]
________________________________________
(1/3)
True ↔ n ∈ n :: x1
________________________________________
(2/3)
x' ↔ n ∈ x0 :: x1
________________________________________
(3/3)
False ↔ n ∈ []
```

RQ2.5: SepAuto versus other verifiers?

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    return true;
  }
  return member_rec(&(*p)->next, k);
}
```

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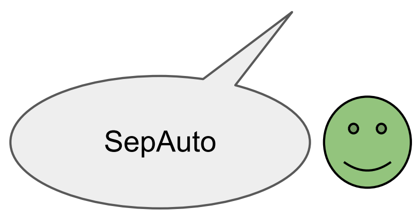
False ↔ n ∈ []
```



RQ3: Do the components of the prompt matter?

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How much does each component of the prompt contribute to generating the correct, desired programs?

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Biases

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Biases

English Description

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- Biases
- English Description
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- Biases
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- I/O Examples

RQ3: Prompt Components

$$Definition\ fi2 := fun\ x => x =?\ 2$$
$$listrep\ l\ h\ * listrep\ (filter\ fi2\ l)\ a$$

Biases

English

Name

Formal Spec.

I/O Examples

RQ3: Prompt Components

Biases ✓

English ✗

Name ✗

Formal Spec. ✓

I/O Examples ⊘

$$\begin{array}{l} Definition\ fi2 := fun\ x => x =? 2 \\ listrep\ l\ h\ \ * listrep\ (filter\ fi2\ l)\ a \end{array}$$

```
#include "treelistdef.c"
struct sll* abc(struct sll* h) {
    if (h == NULL) {
        return NULL;
    }
    if (h->key == 2) {
        h->next = abc(h->next);
        return h;
    }
    else {
        return abc(h->next);
    }
}
```

RQ3: Prompt Components

Biases ✓

English ✗

Name ✗

Formal Spec. ✓

I/O Examples

$$Definition\ fi2 := fun\ x => x =?\ 2$$
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    else {
        return abc(h->next);
    }
}
```

$$listrep\ (filter\ fi2\ l)\ a$$ ✗

RQ3: Prompt Components

Biases	✓
English	✗
Name	✗
Formal Spec.	✓
I/O Examples	⊘

Basic: 17/19

SL: 12/23

$$Definition\ fi2 := fun\ x \Rightarrow x =?\ 2$$
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$listrep\ (filter\ fi2\ l)\ a$ ✗

RQ3: Prompt Components

Biases	✓
English	✗
Name	✓
Formal Spec.	✓
I/O Examples	⊘

$$\mathit{Definition}\ \mathit{fi2} := \mathit{fun}\ x => x =?\ 2$$
$$\mathit{listrep}\ l\ h\ * \mathit{listrep}\ (\mathit{filter}\ \mathit{fi2}\ l)\ a$$

RQ3: Prompt Components

Biases ✓

English ✗

Name ✓

Formal Spec. ✓

I/O Examples ⃠

```c
#include "treelistdef.c"
struct sll* copyfilteredListWhereElementis2AndReturnItsHead(struct sll *h)
{
    if (h == NULL) {
        return NULL;
    }
    if (h->key == 2)
    {
        struct sll* new_node = (struct sll*)malloc(sizeof(struct sll));
        new_node->key = 2;
        new_node->next = copyfilteredListWhereElementis2AndReturnItsHead(h->next);
        return new_node;
    }
    else
    {
        return copyfilteredListWhereElementis2AndReturnItsHead(h->next);
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}
```

$$Definition\ fi2 := fun\ x => x =?\ 2$$
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RQ3: Prompt Components

Biases	✓
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✓

RQ3: Prompt Components

Biases ✓

English ✗

Name ✓

Formal Spec. ✓

I/O Examples ⃠

Basic: 17/19

SL: 20/23

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$$Definition\ fi2 := fun\ x => x =?\ 2$$
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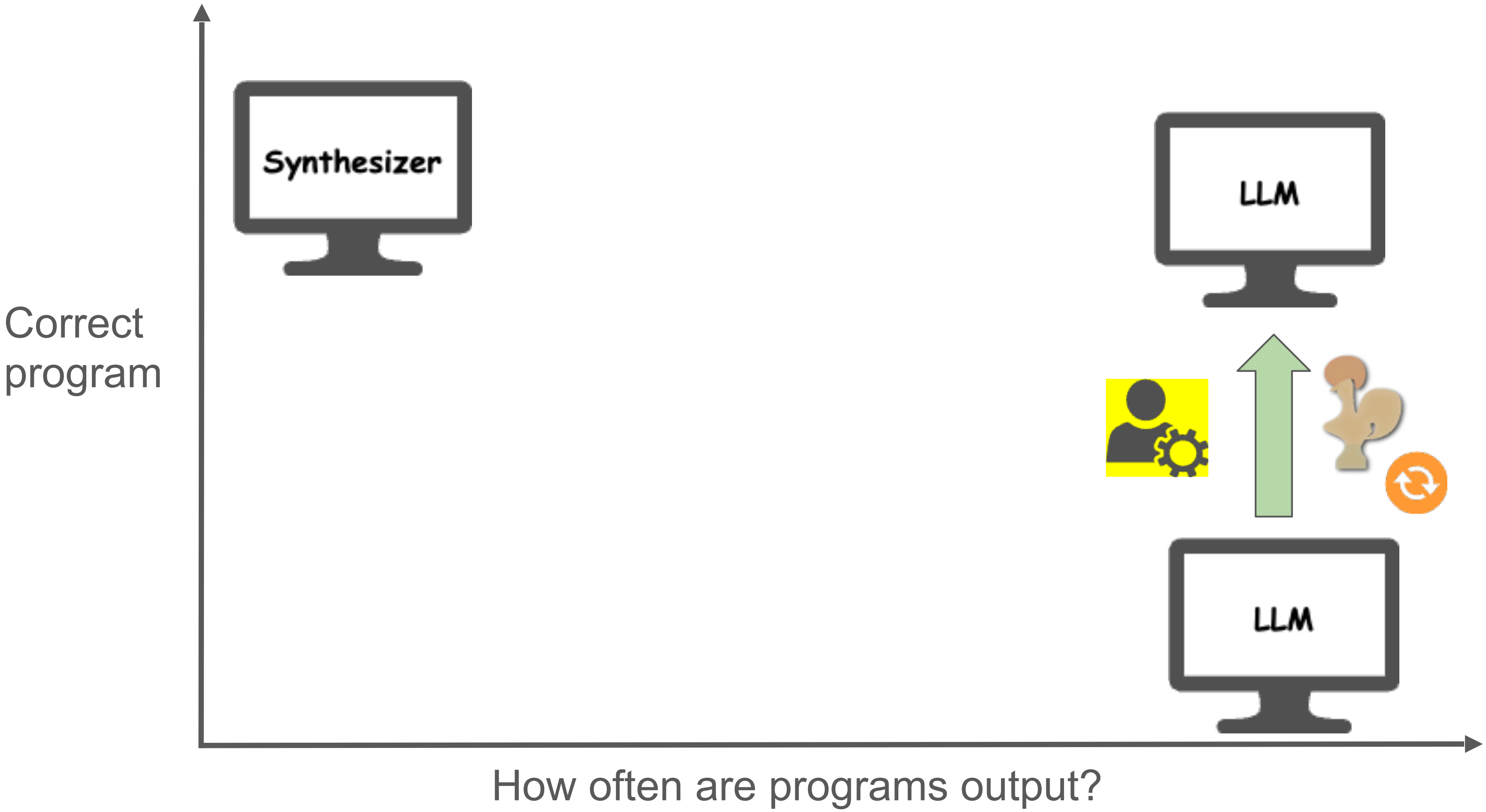
✓

Conclusions

- LLMs with foundational verifiers as general purpose synthesizers
- Large search space well suited for a popular, mainstream language like C
- LLMs respond positively to biases and natural language
- Automation is well suited to the biases
- SepAuto is not complete
- Data leakage may have required less re prompting

Current State



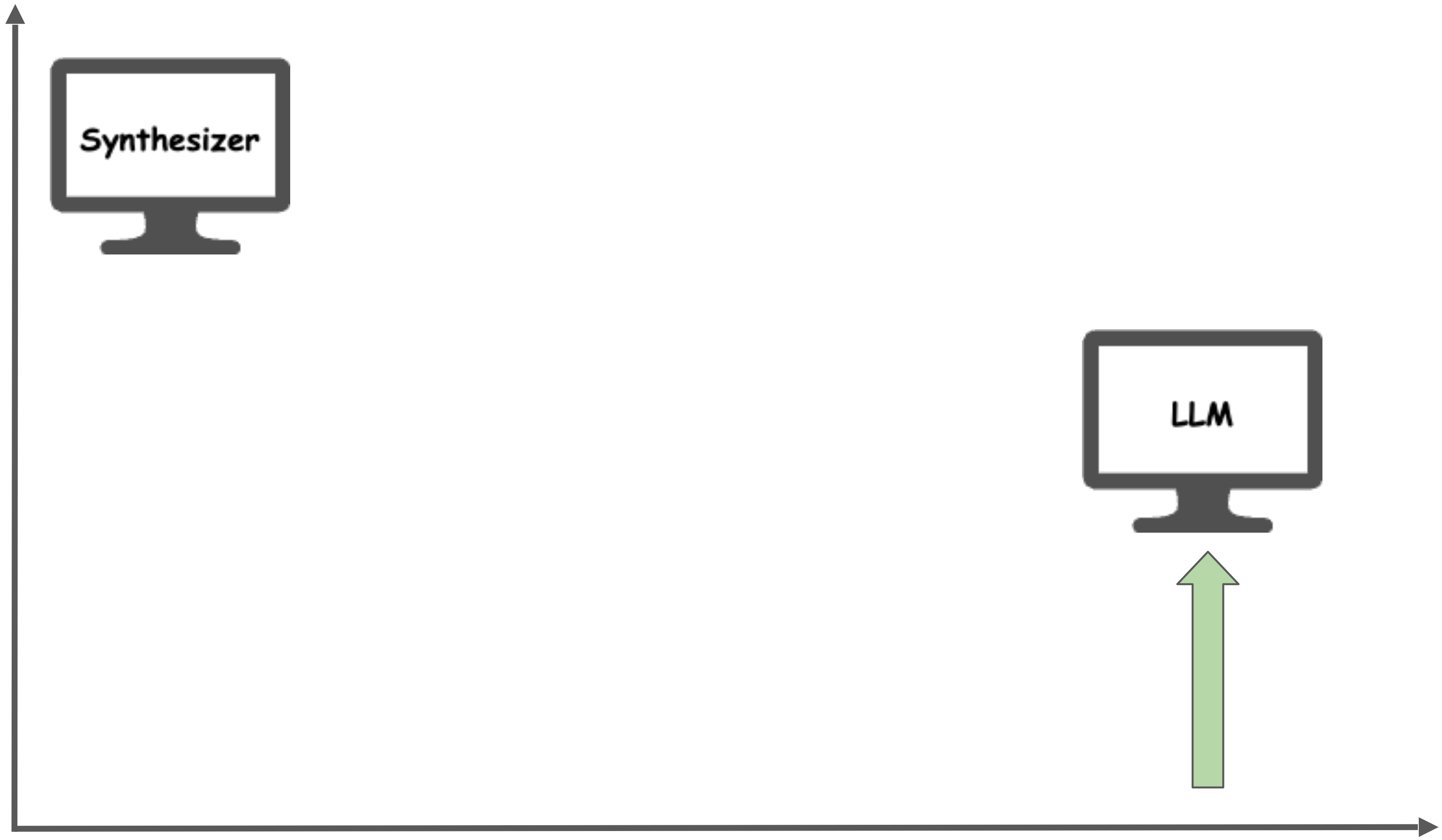
What’s next?

Correct program

SYNVER

How often are programs output?

What’s next?



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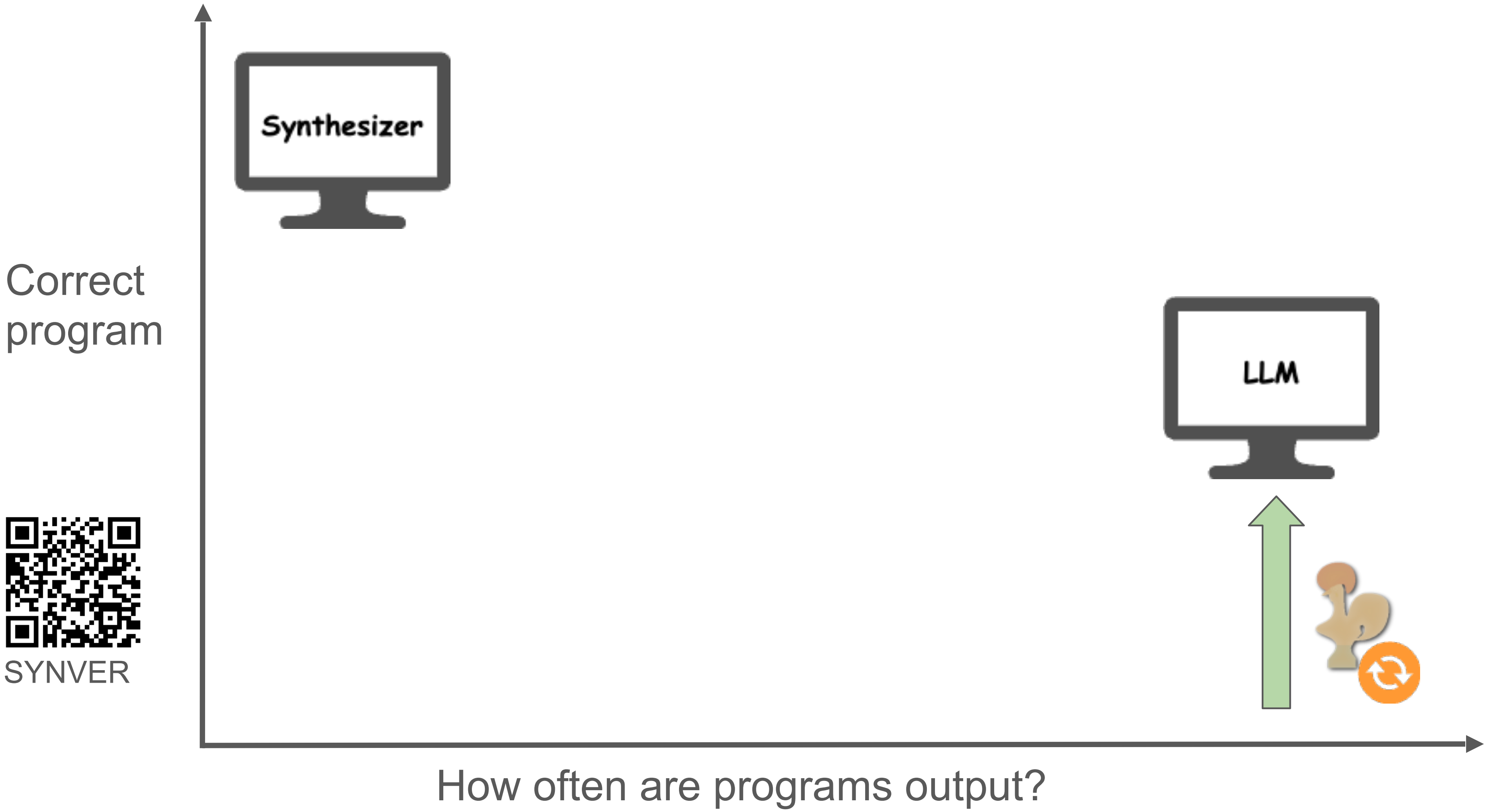
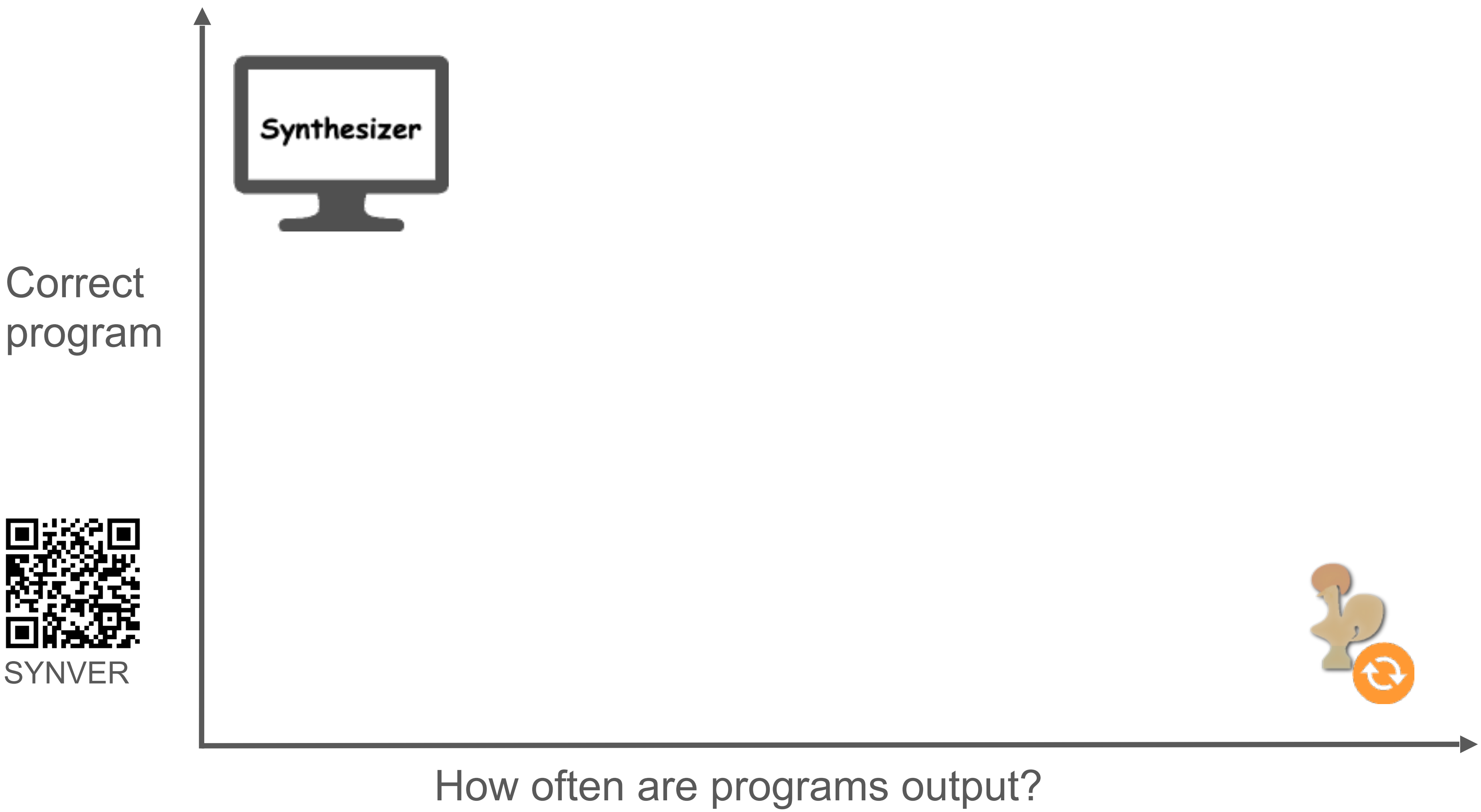
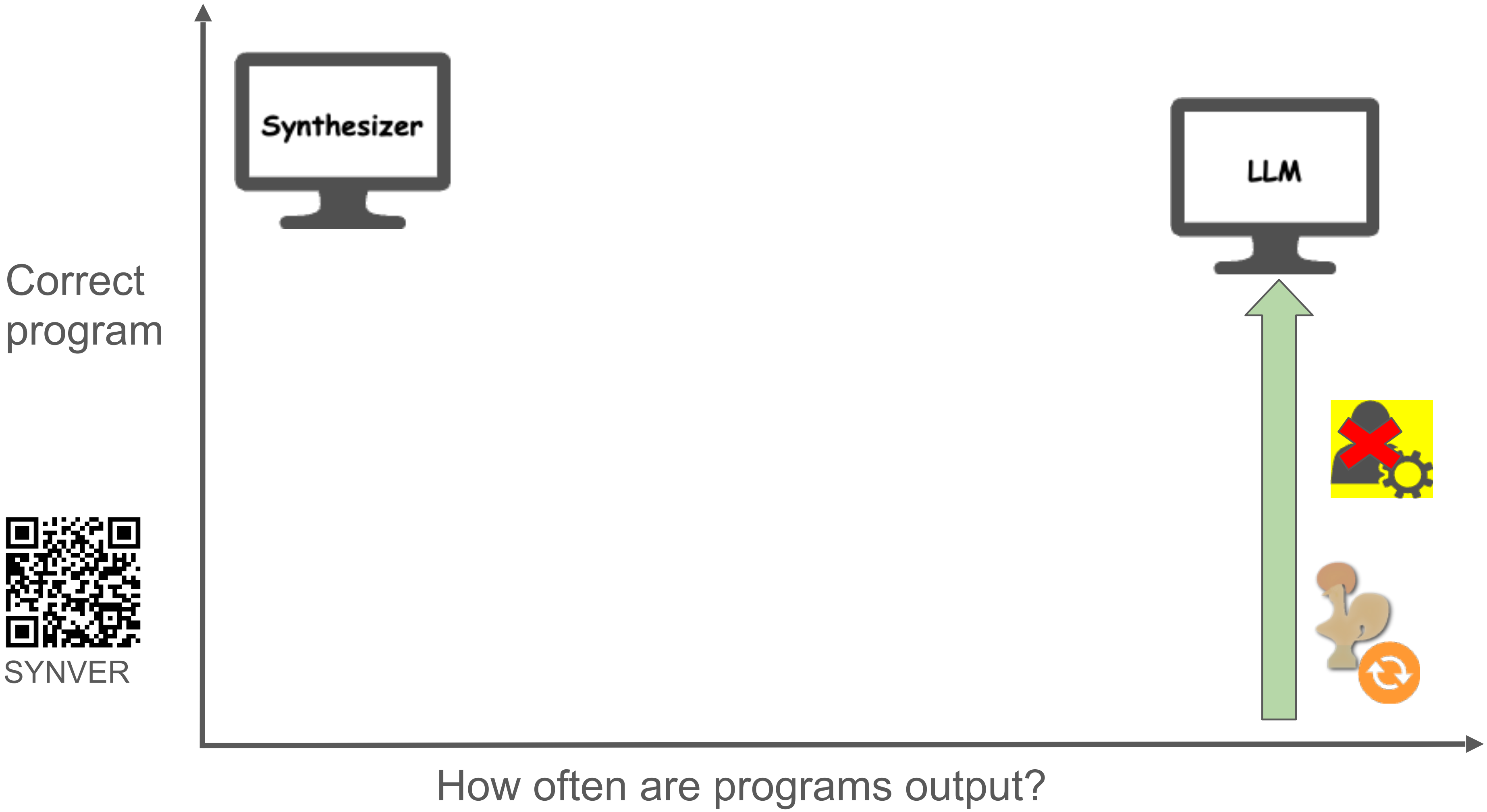


Correct program
SYNVER
Synthesizer
LLM
How often are programs output?

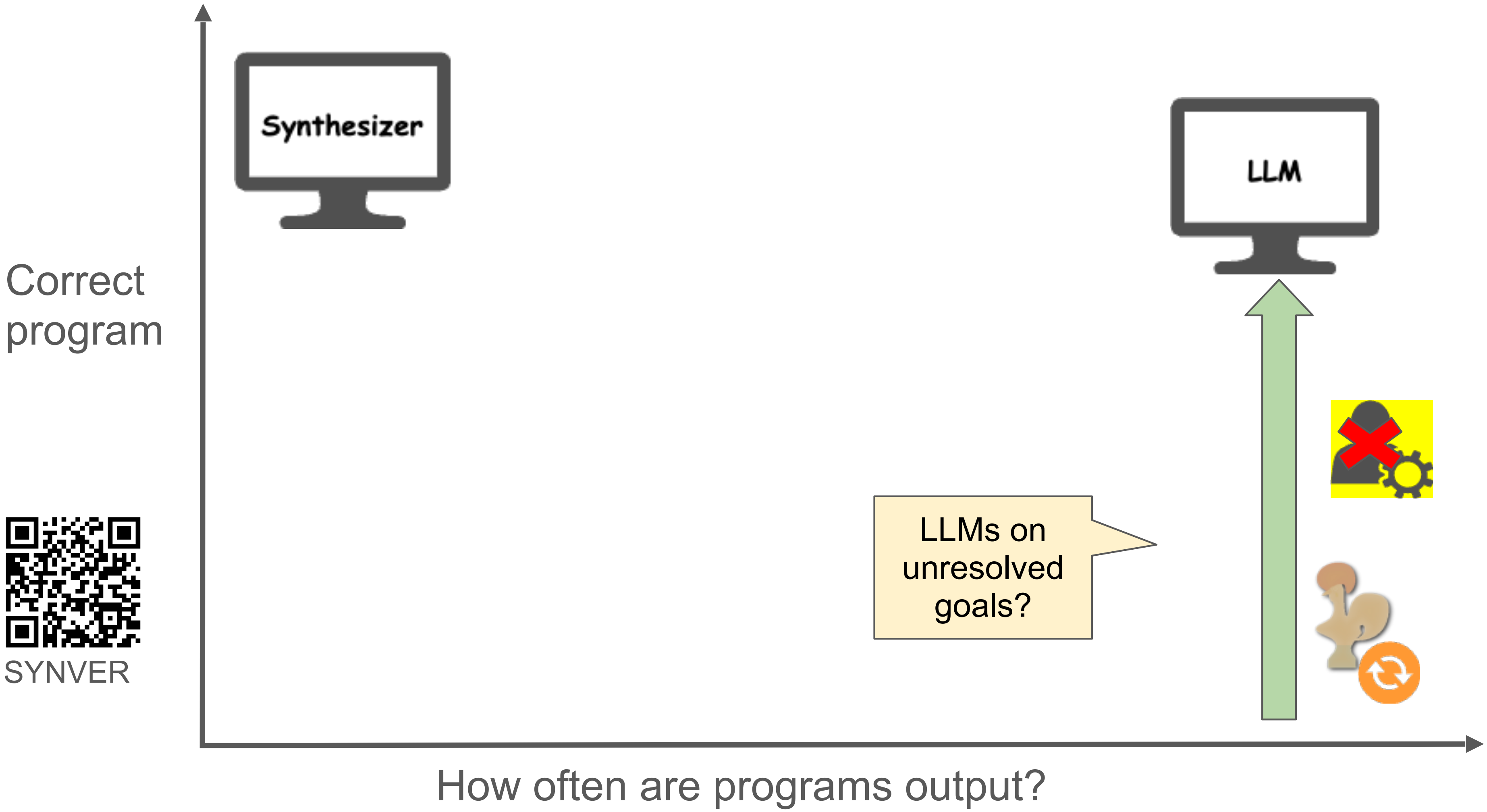
What’s next?


Synthesizer
Correct program
SYNVER
How often are programs output?

What’s next?


Synthesizer
LLM
Correct
program
SYNVER
How often are programs output?

What's next?


Synthesizer
LLM
Correct program
SYNVER
LLMs on unresolved goals?
How often are programs output?