Optimizing Synthesis with Metasketches

Artifact • Consistent • Complete • Well Documented • Easy to Reuse • Evaluated • POPL • AEC

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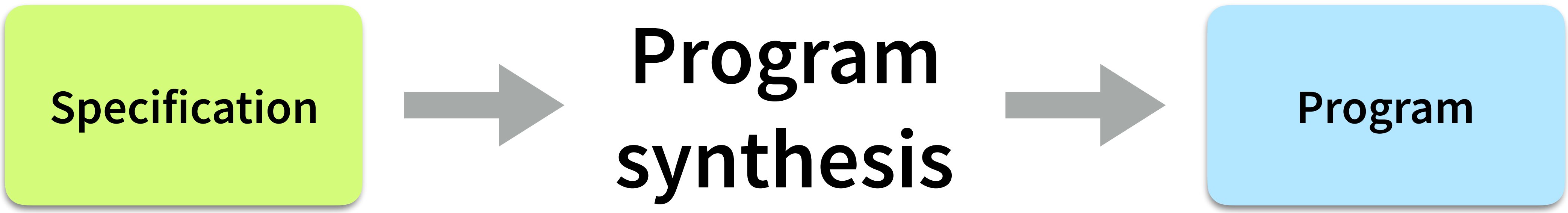
Emina Torlak
Dan Grossman
Luis Ceze
University of Washington

SYNAPSE

Program synthesis

Specification

Program synthesis



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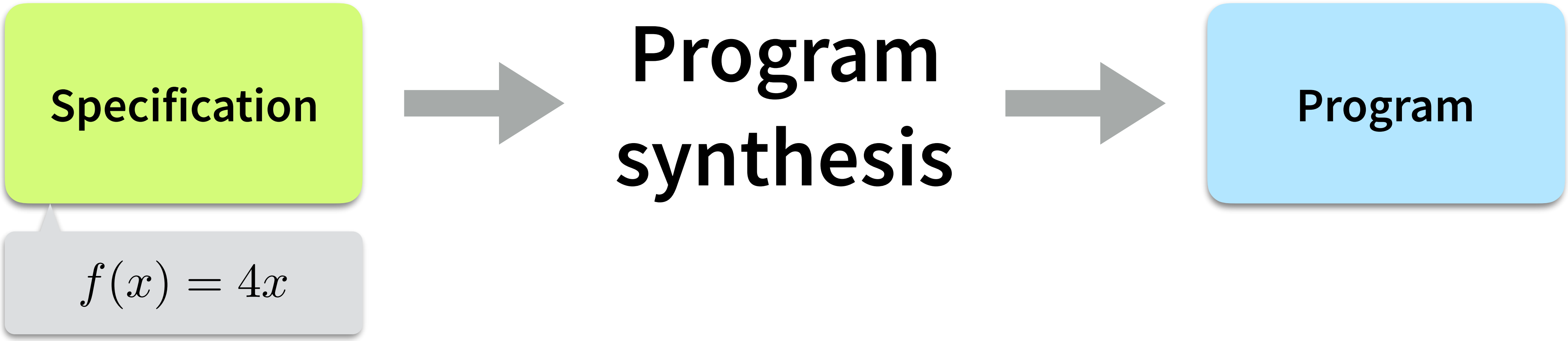

Specification

$f(x) = 4x$

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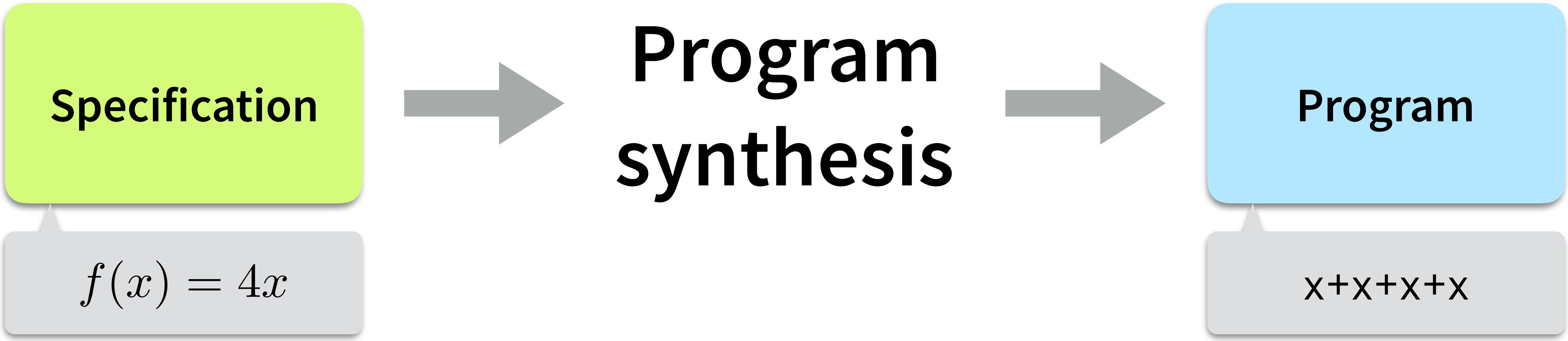

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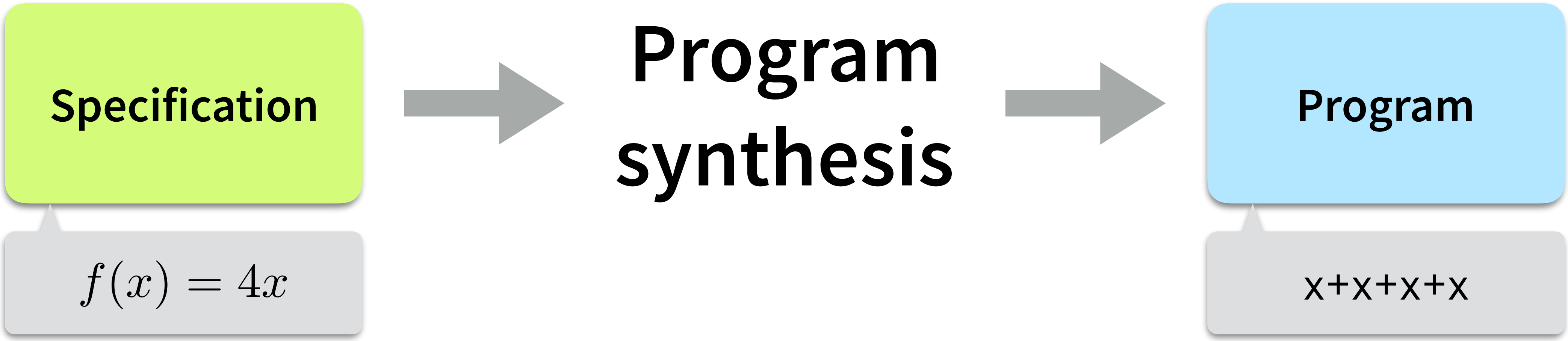
x+x+x+x

Compilation
[PLDI’14]

Data Structures
[PLDI’15]

End-user Programming
[POPL’11]



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Executable Biology
[POPL’13]

Browser Layout
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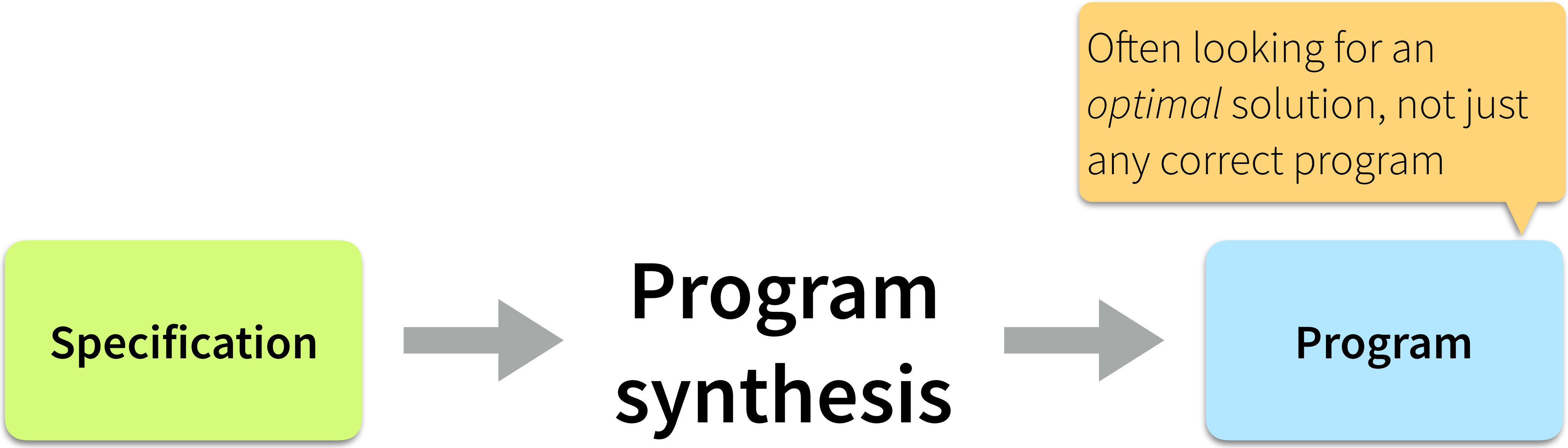

Often looking for an *optimal* solution, not just any correct program

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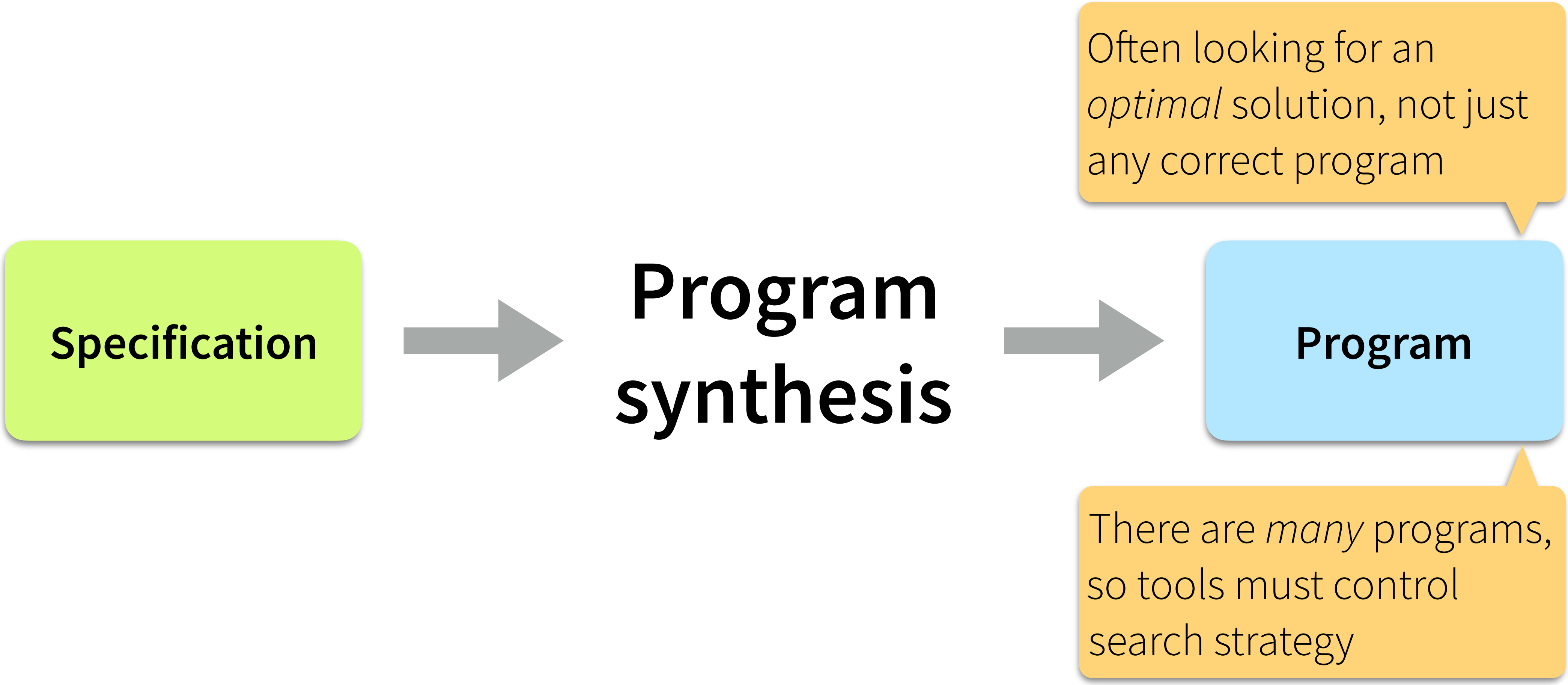

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There are *many* programs, so tools must control search strategy

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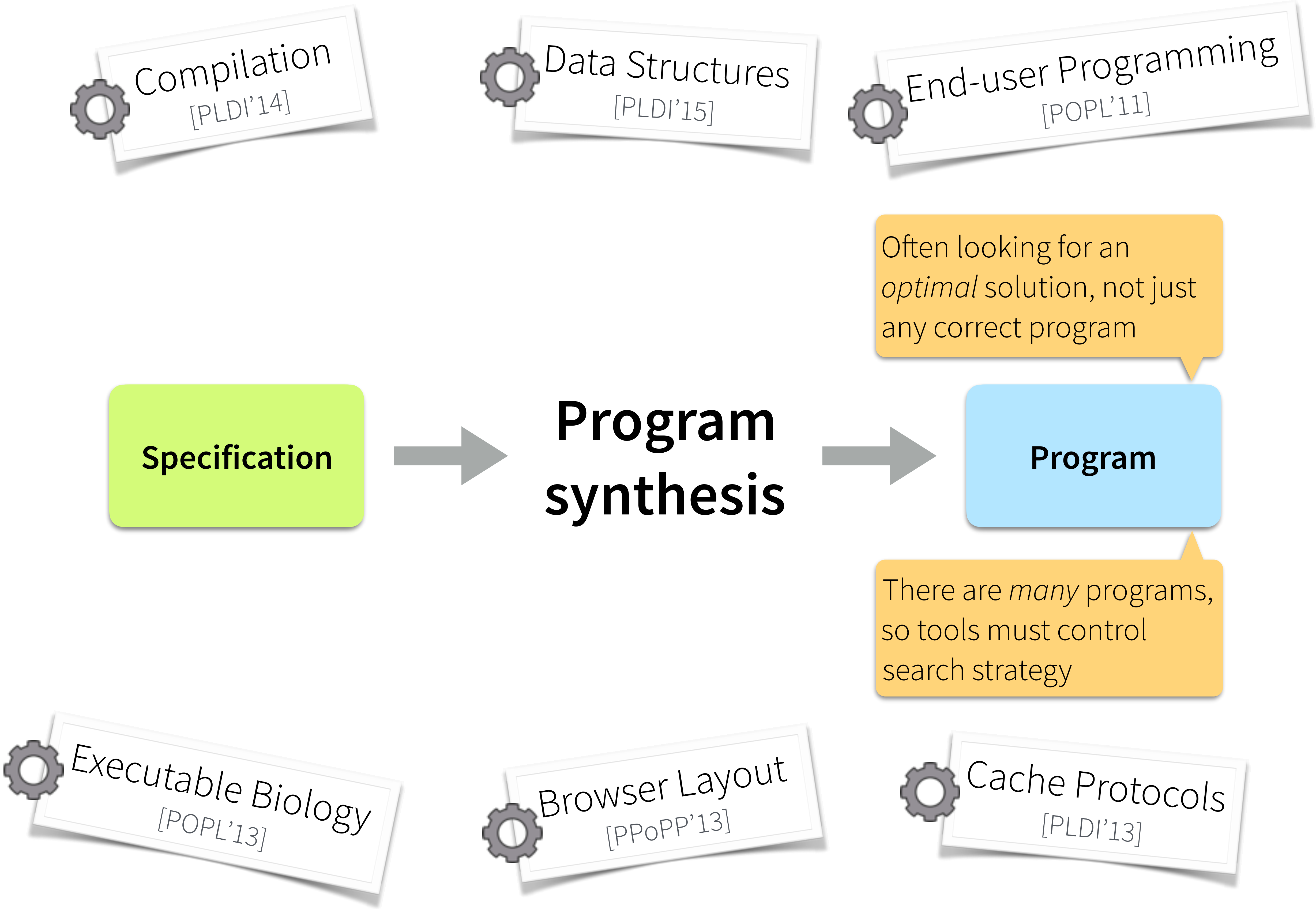

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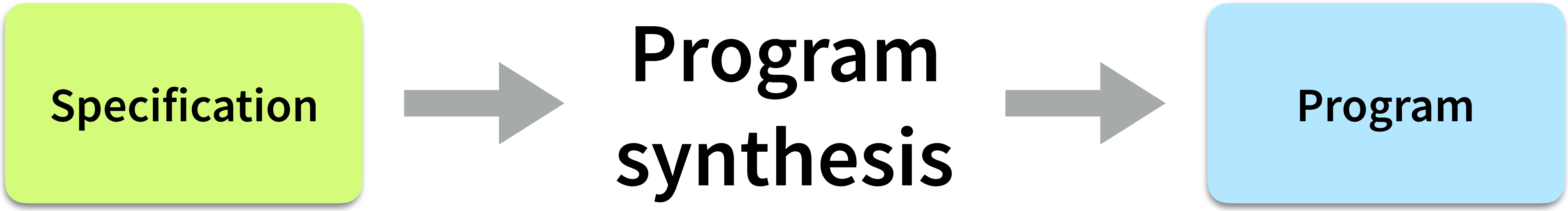

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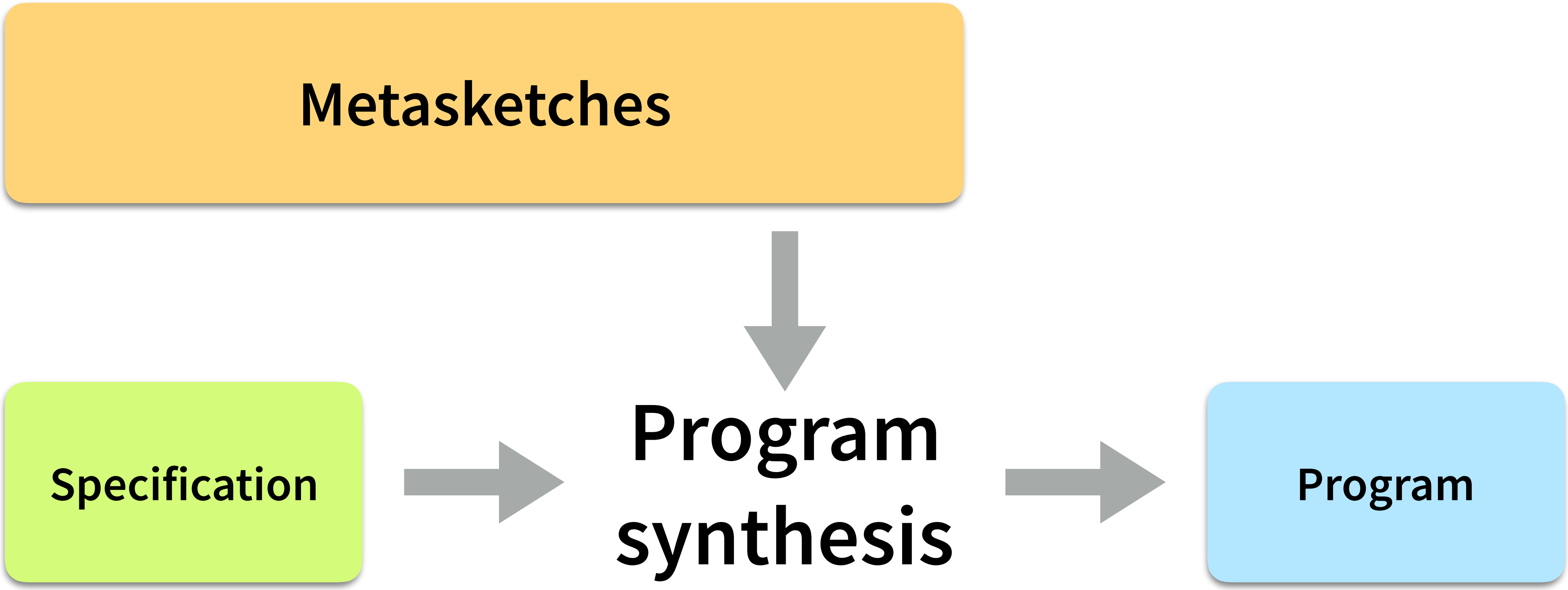

Metasketches

Specification

Program synthesis

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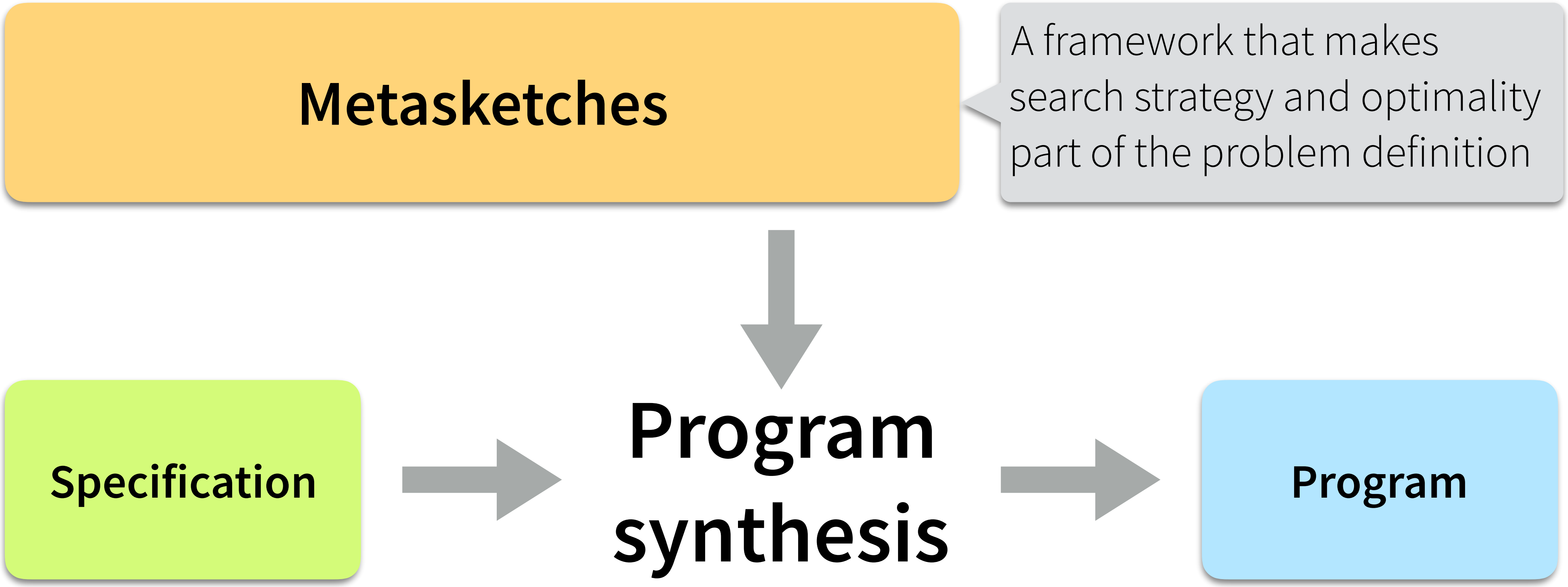


Metasketches

A framework that makes search strategy and optimality part of the problem definition

Specification

Program synthesis

Program

Metasketches

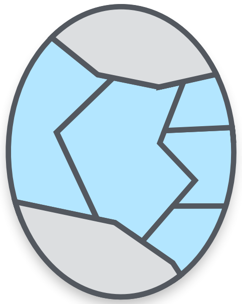
Design and structure

Metasketches

Design and structure

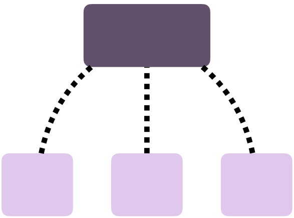
Synapse

A metasketch solver



Metasketches

Design and structure



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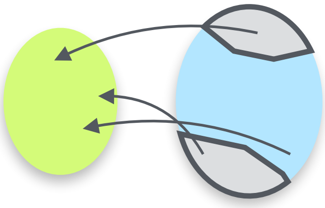
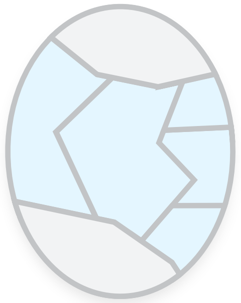
Results

Better solutions, faster



Background

Syntax-guided synthesis



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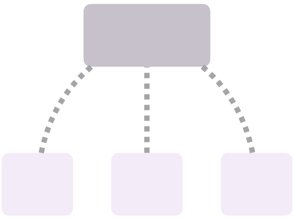

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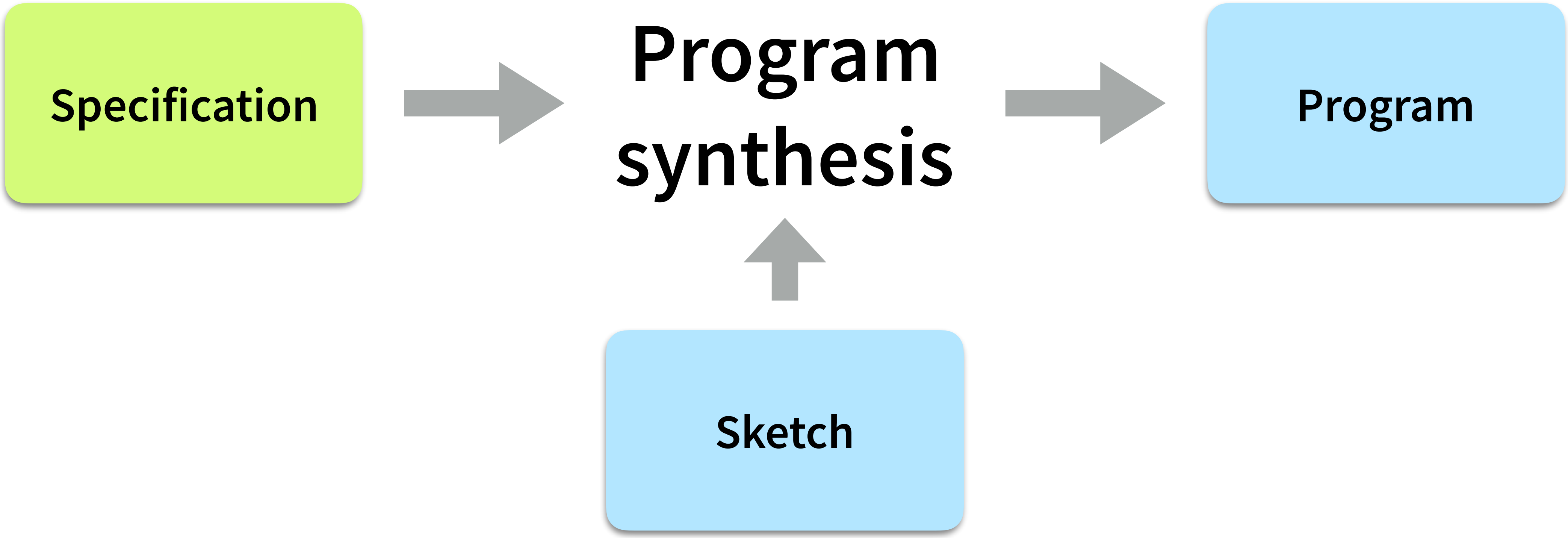


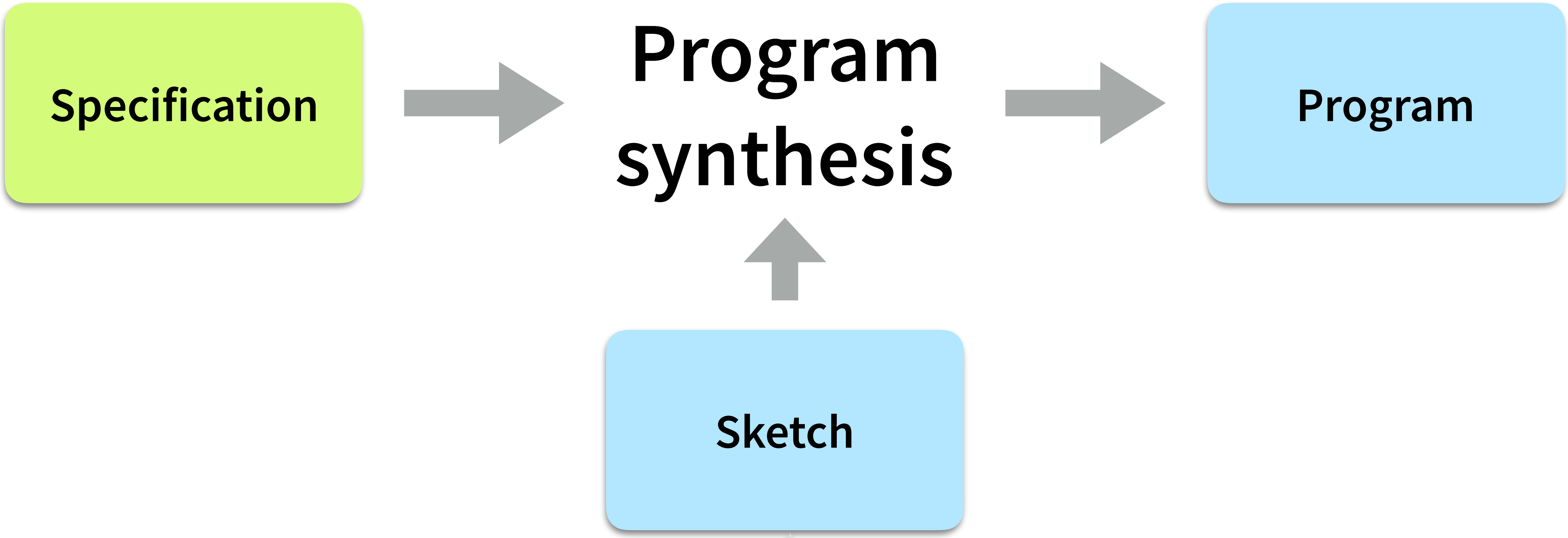
Specification

Program synthesis

Program

Sketch

Syntax-guided synthesis



Specification

Program synthesis

Program

Sketch

```
def f(x):
  return Expr

Expr := x | ?? | Expr op Expr
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  ?? := integer constant
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Syntax-guided synthesis: guess, check, learn

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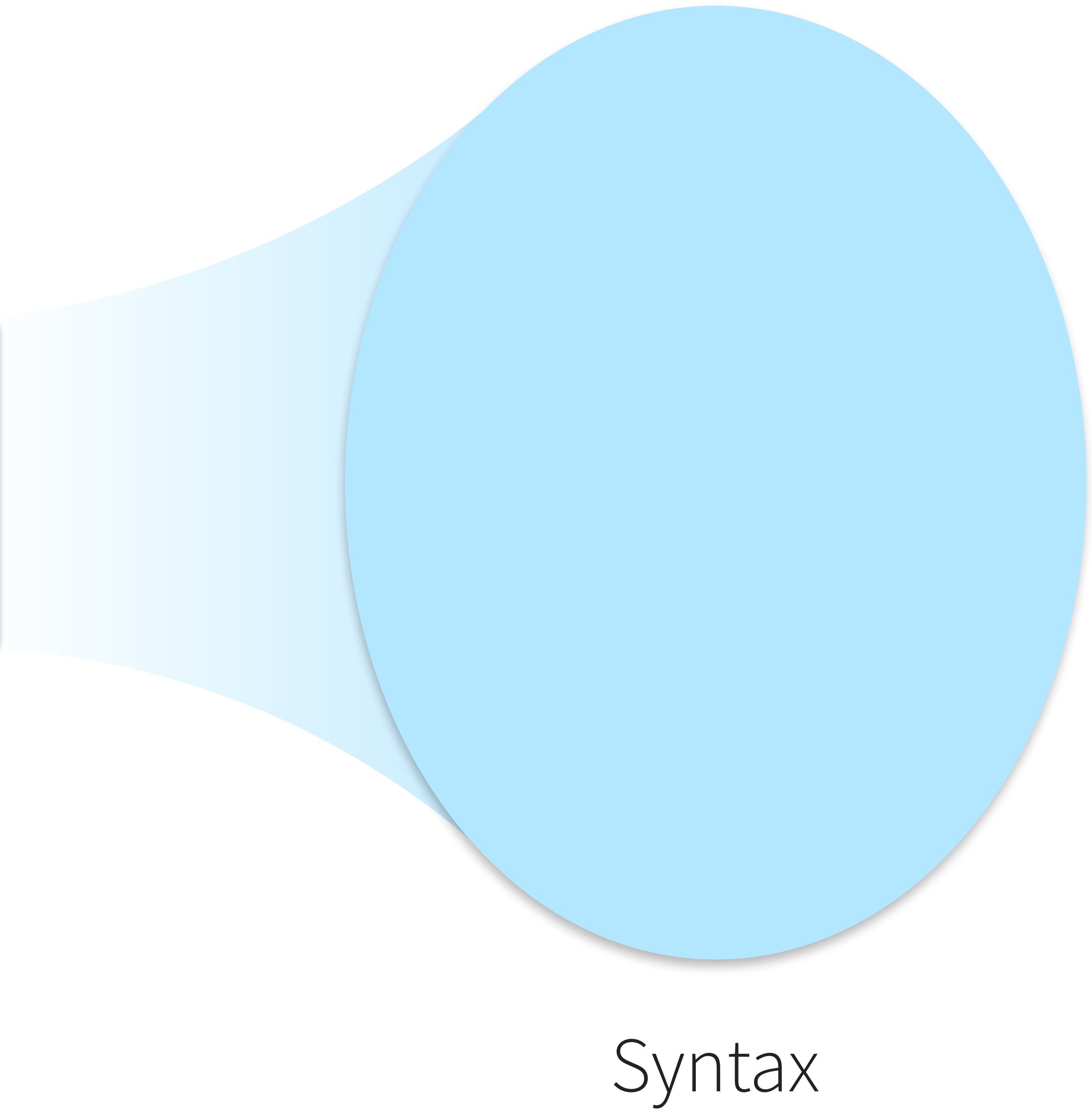
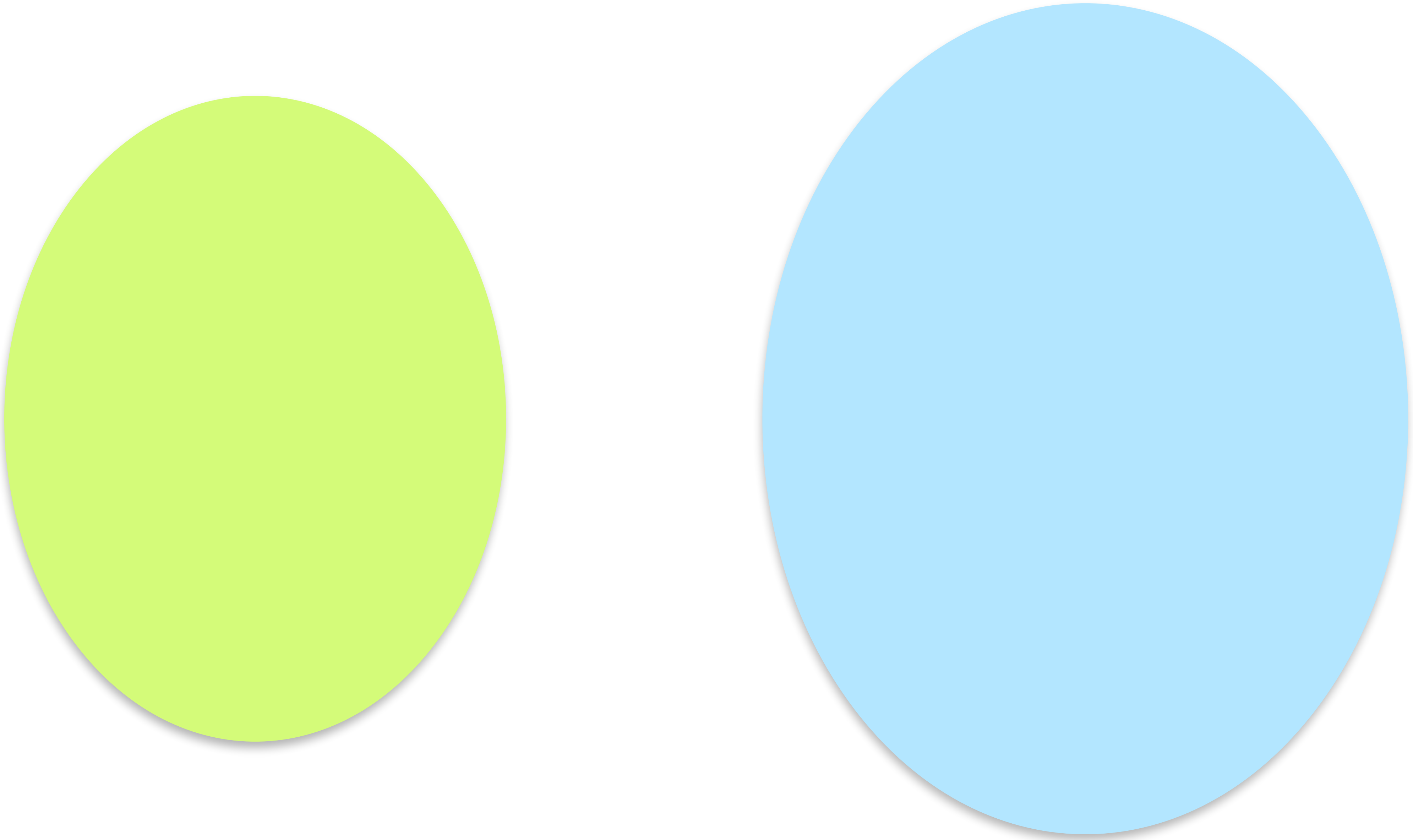


Syntax-guided synthesis: guess, check, learn

Counterexample-guided inductive synthesis [Solar-Lezama et al, 2006]



Semantics

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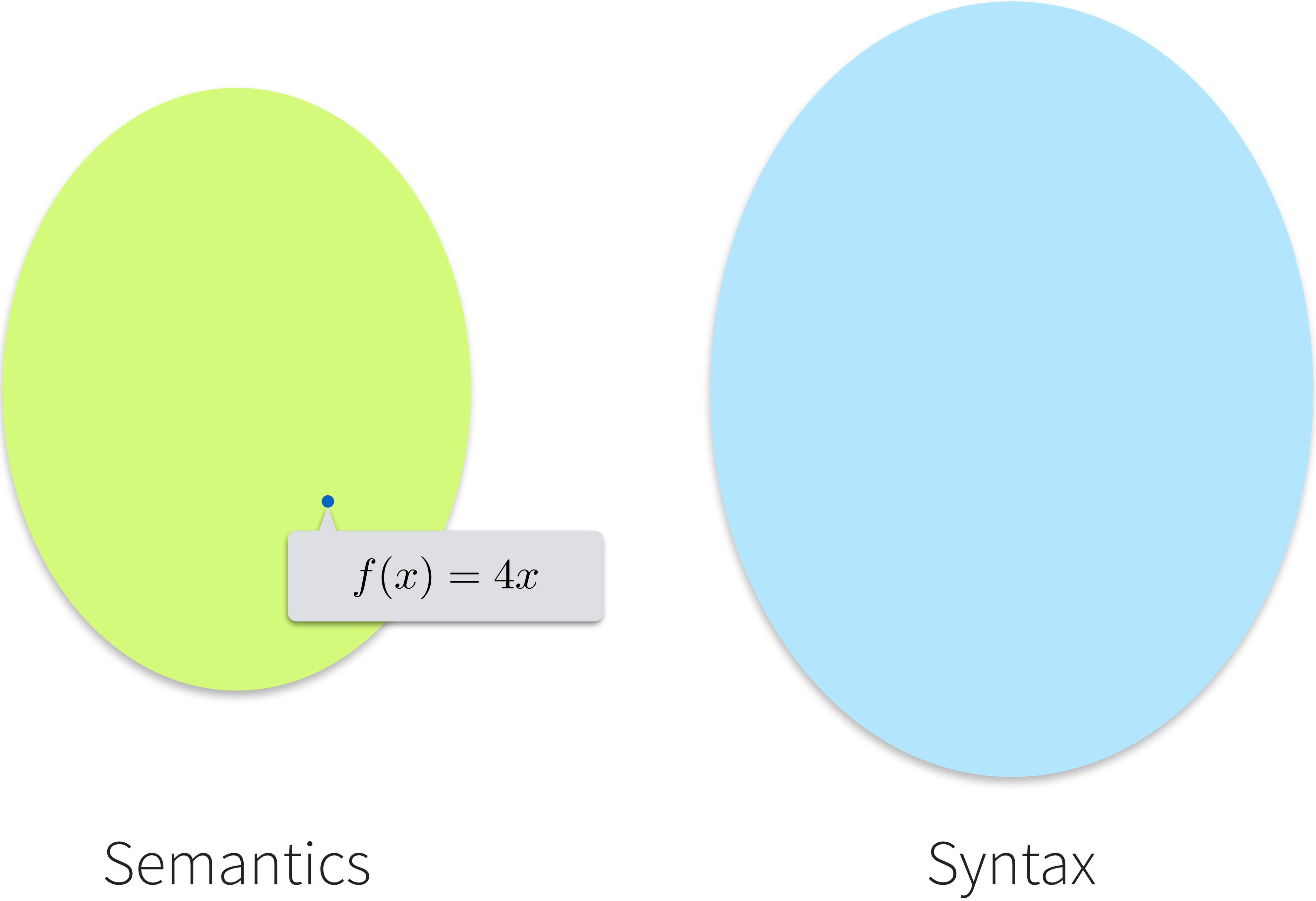

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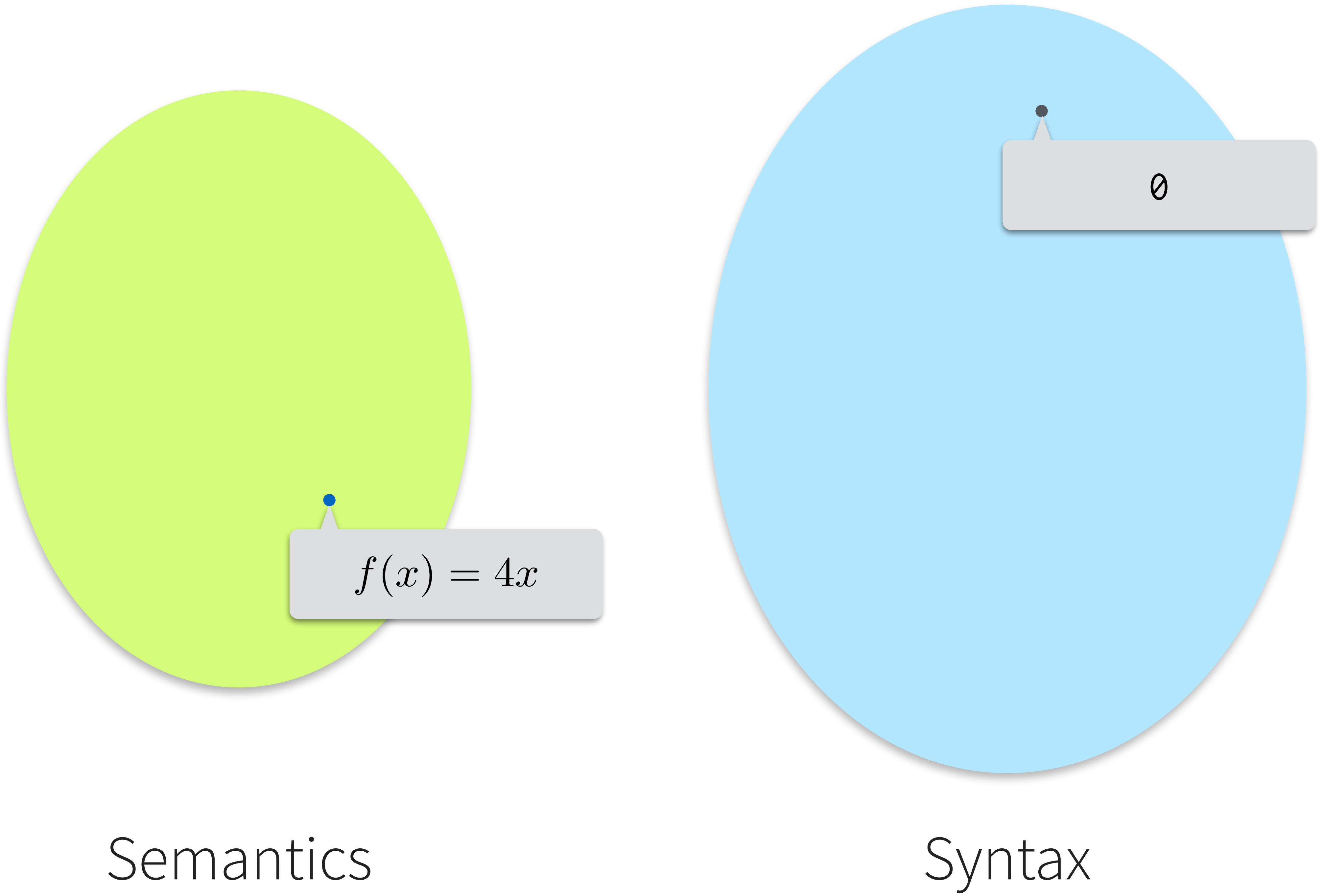

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`0`

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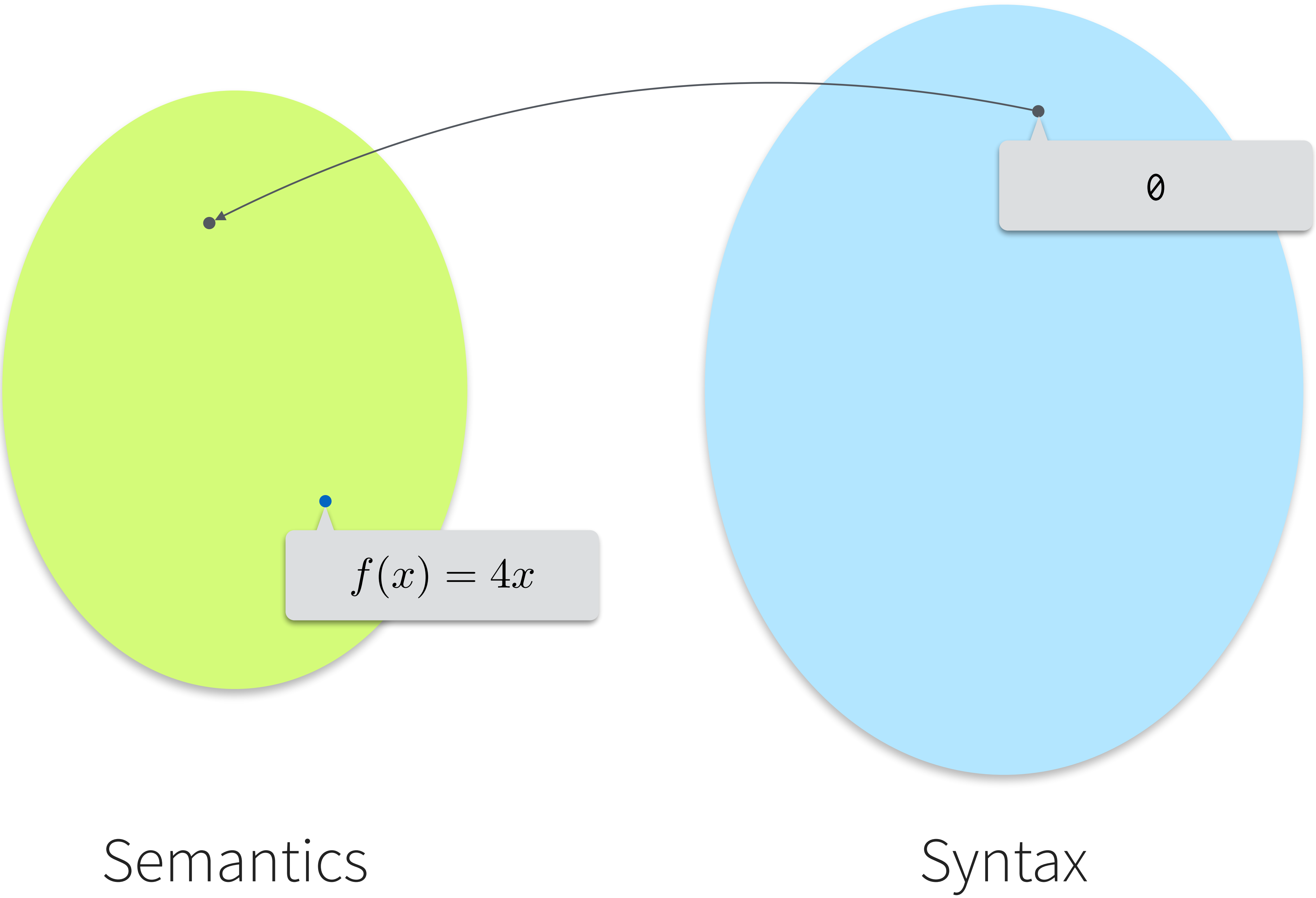

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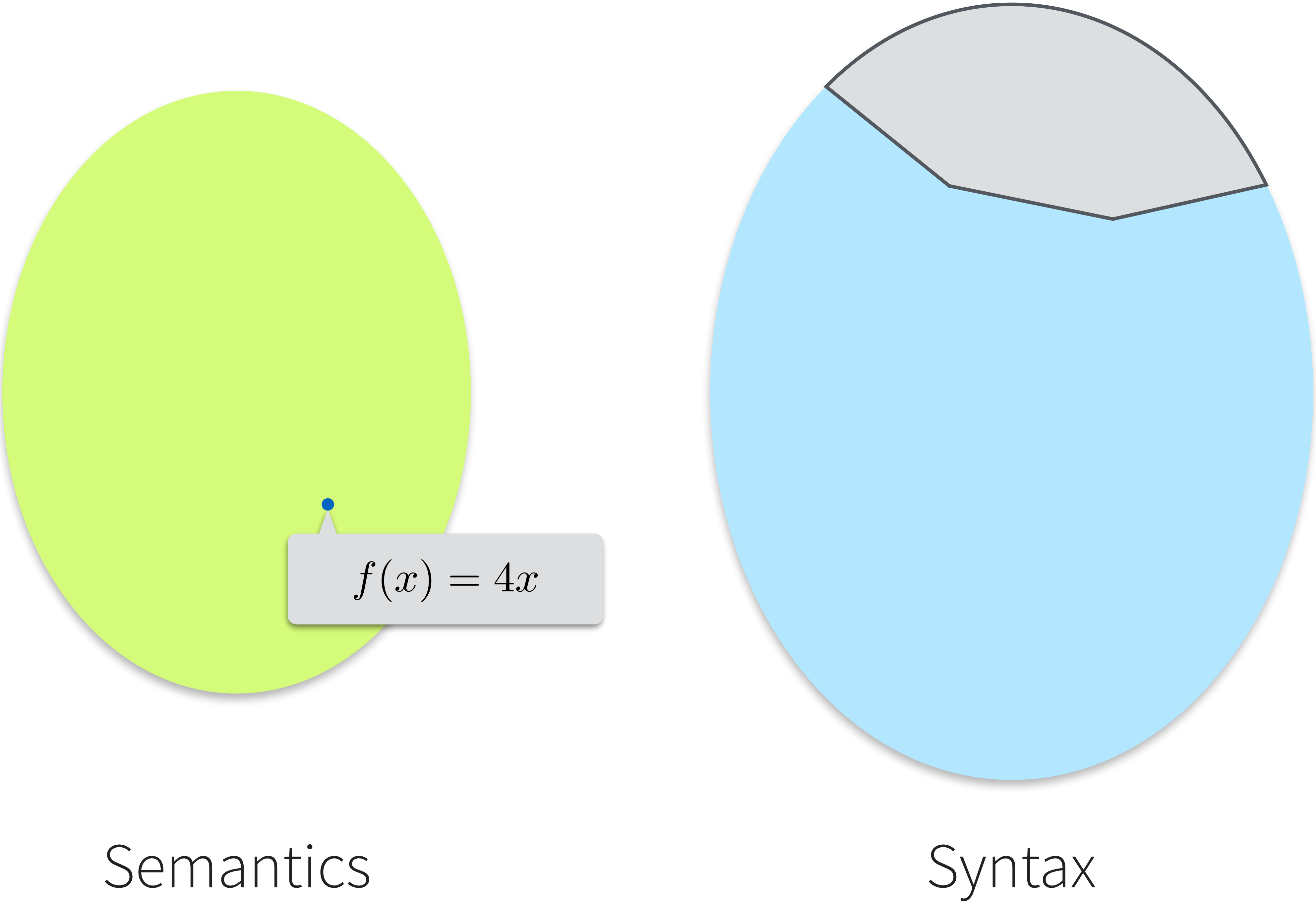

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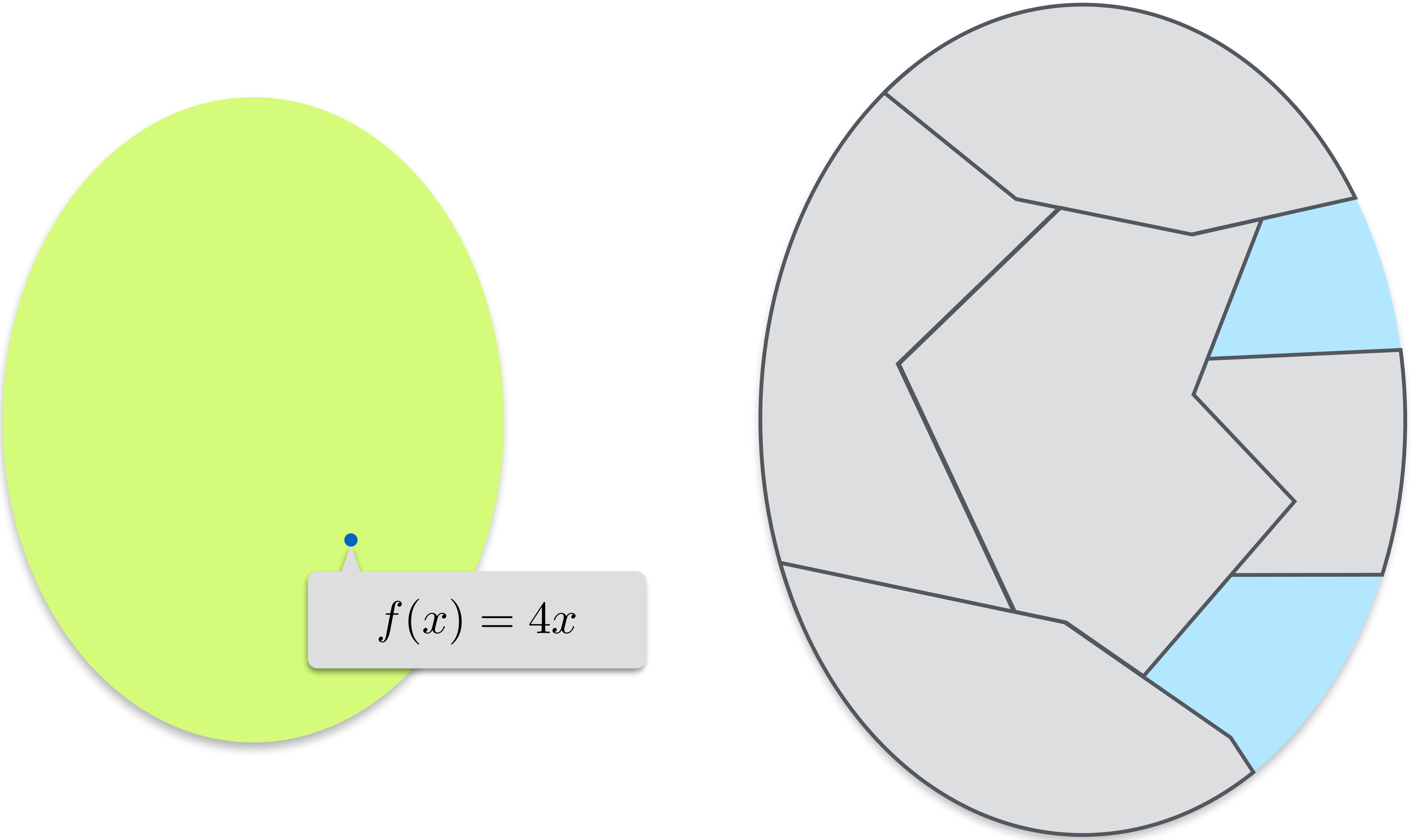

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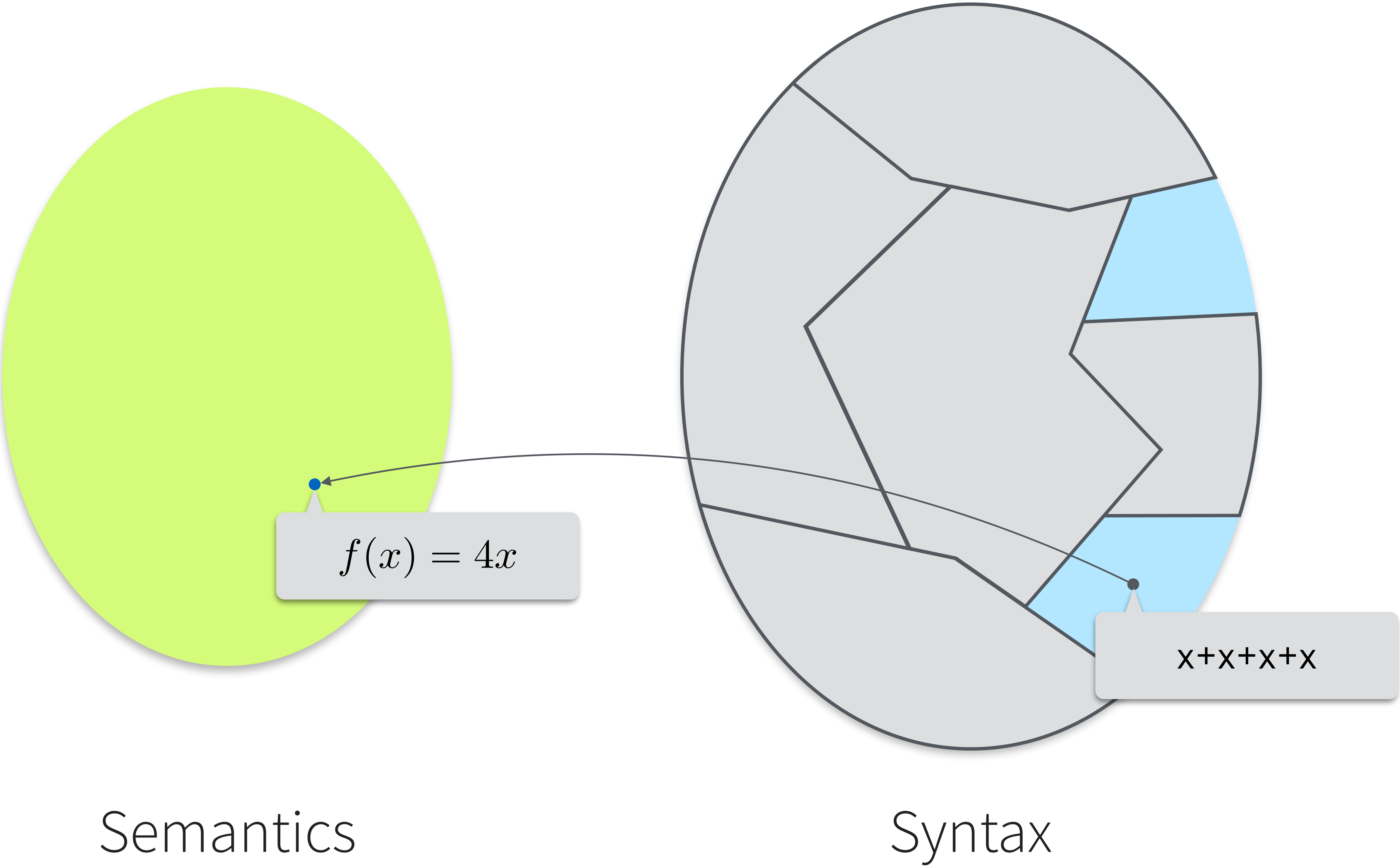

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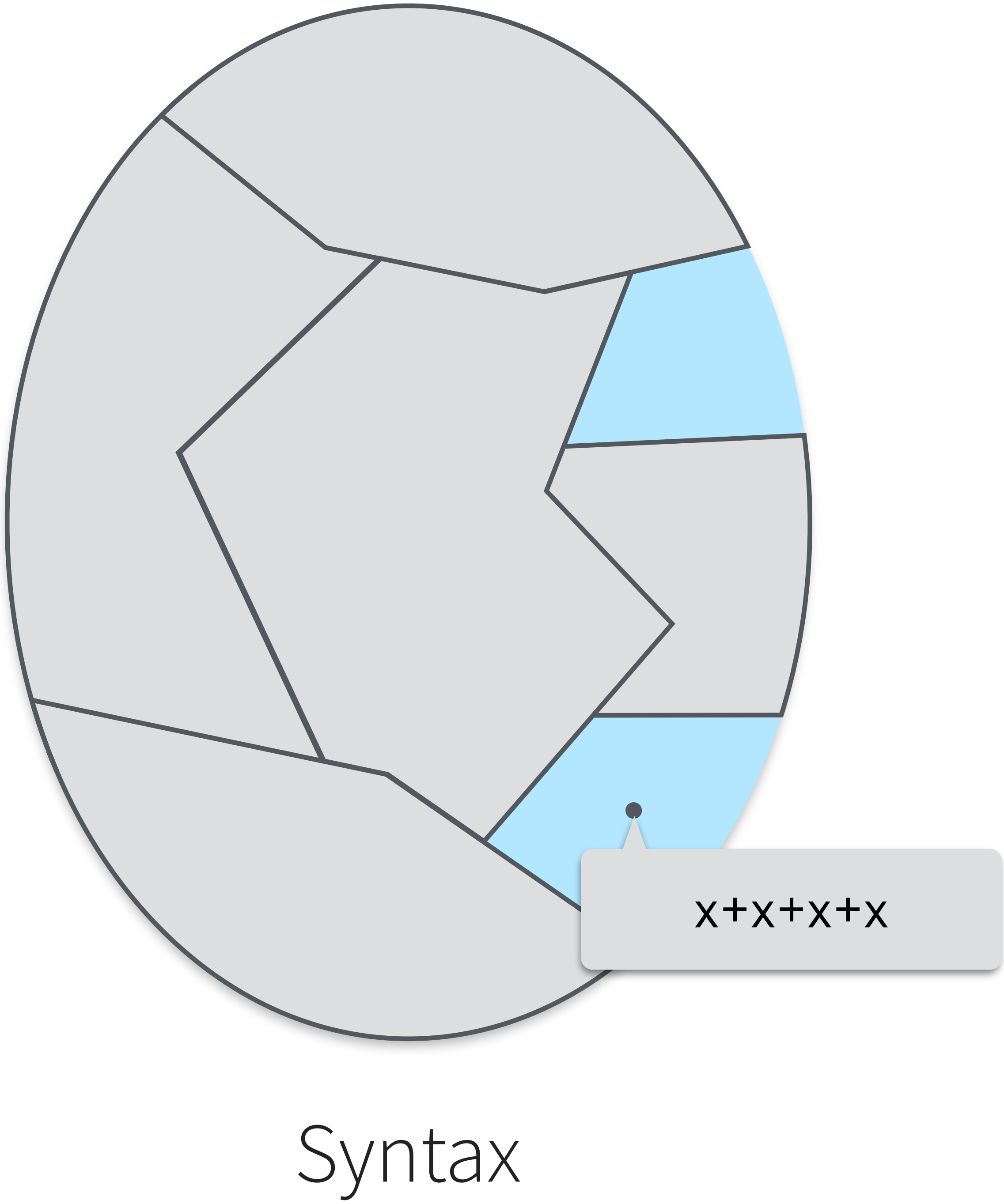

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1. **Search order** is critical
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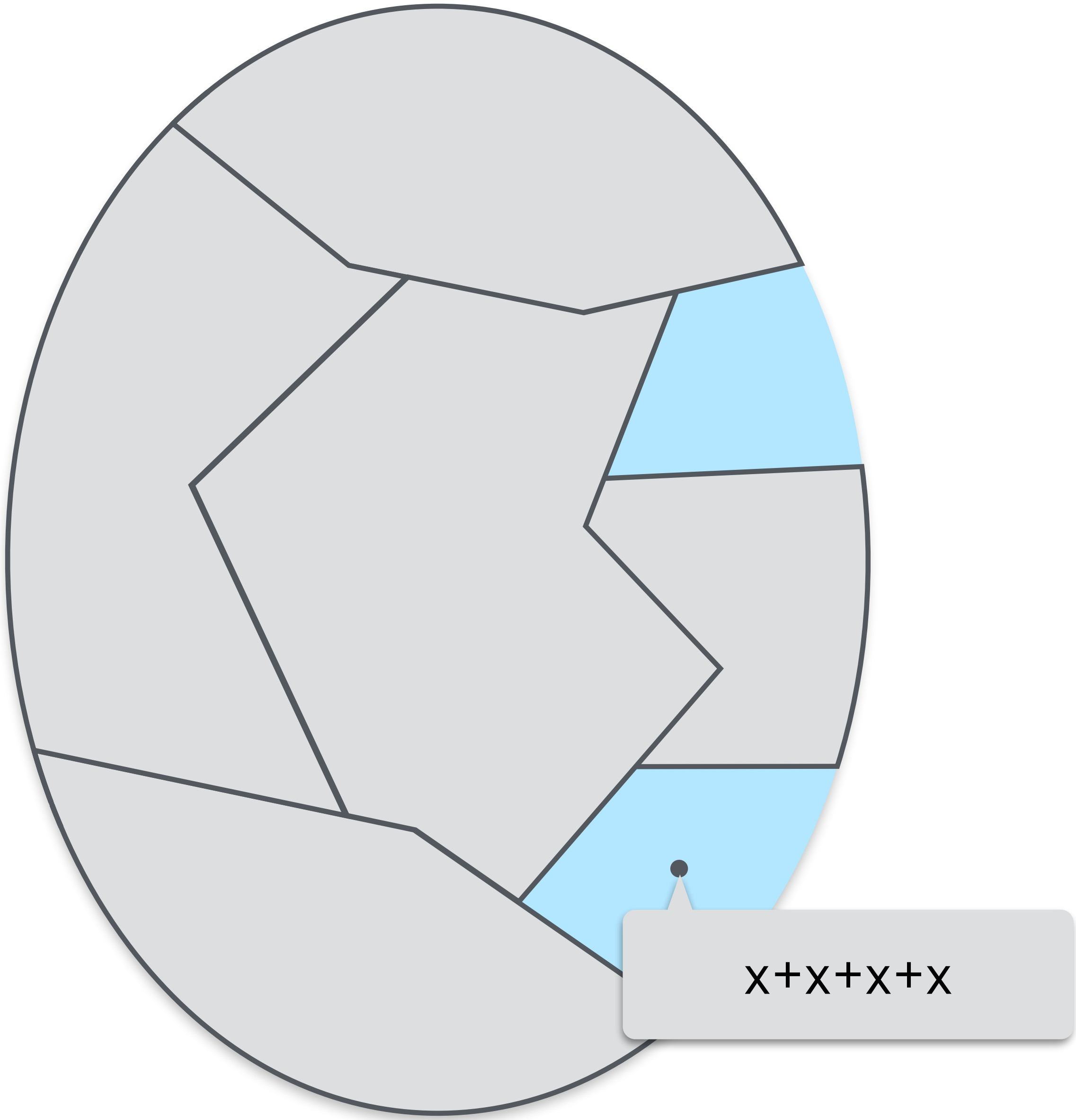

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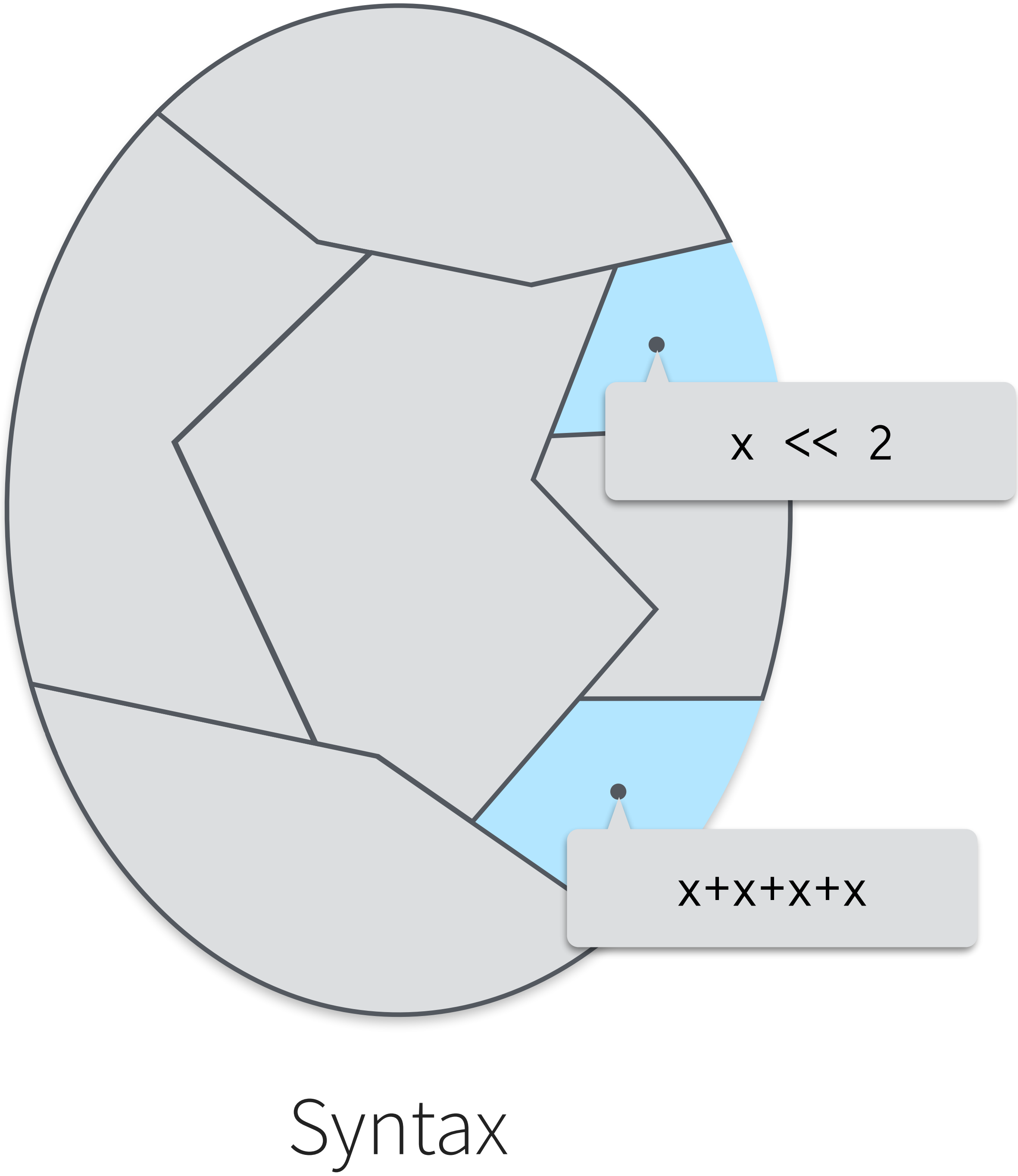
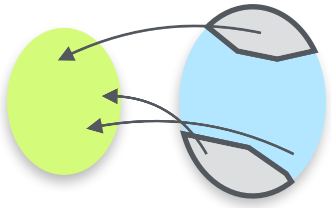
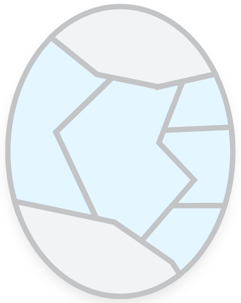




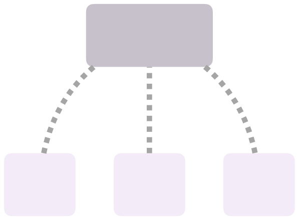
Background

Syntax-guided synthesis



Metasketches

Design and structure

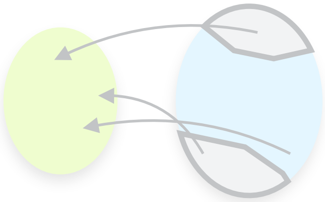


Synapse

A metasketch solver

Results

Better solutions, faster



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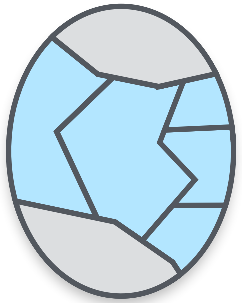

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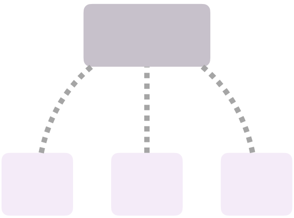

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Metasketches express structure and strategy

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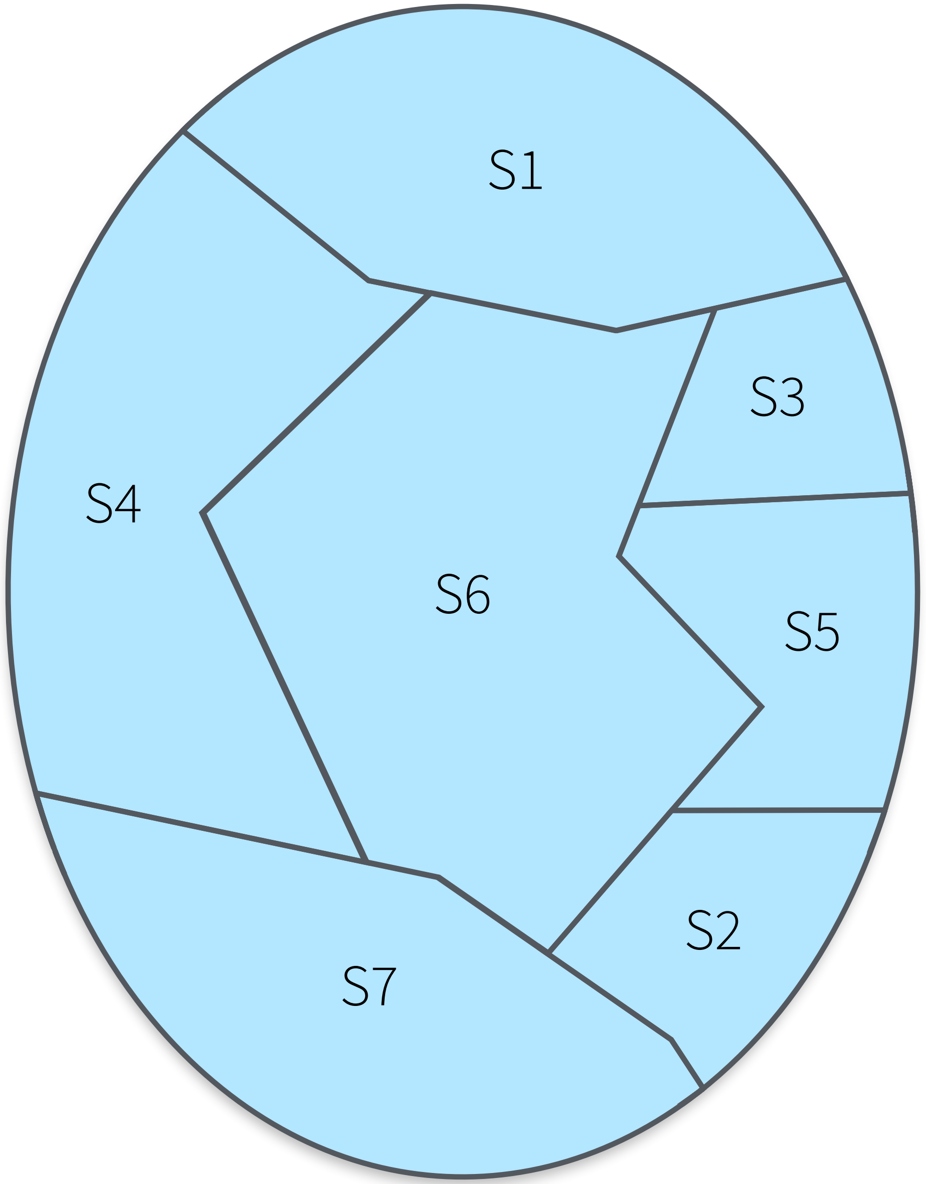
A metasketch contains:

1. structured candidate space ($\mathcal{S}$, $\preccurlyeq$)



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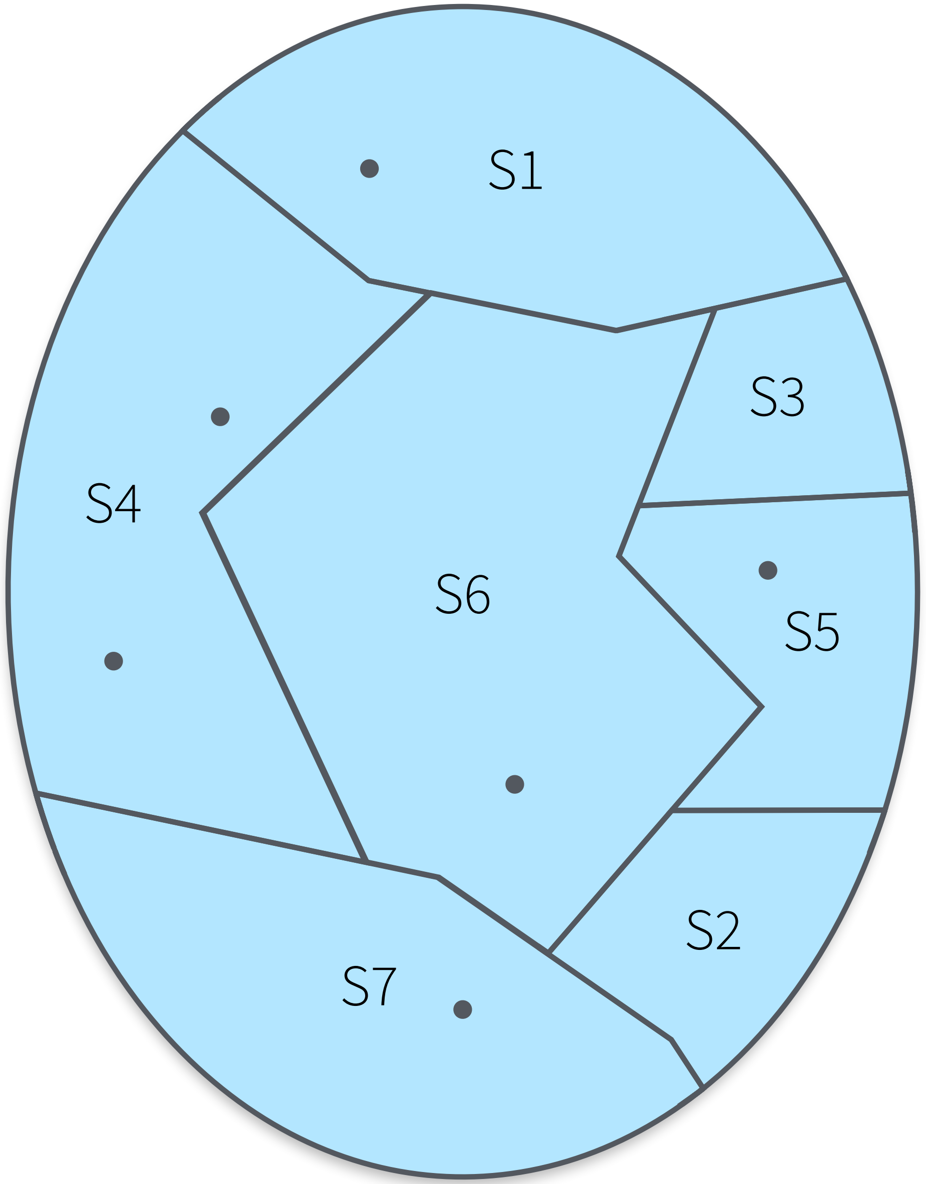

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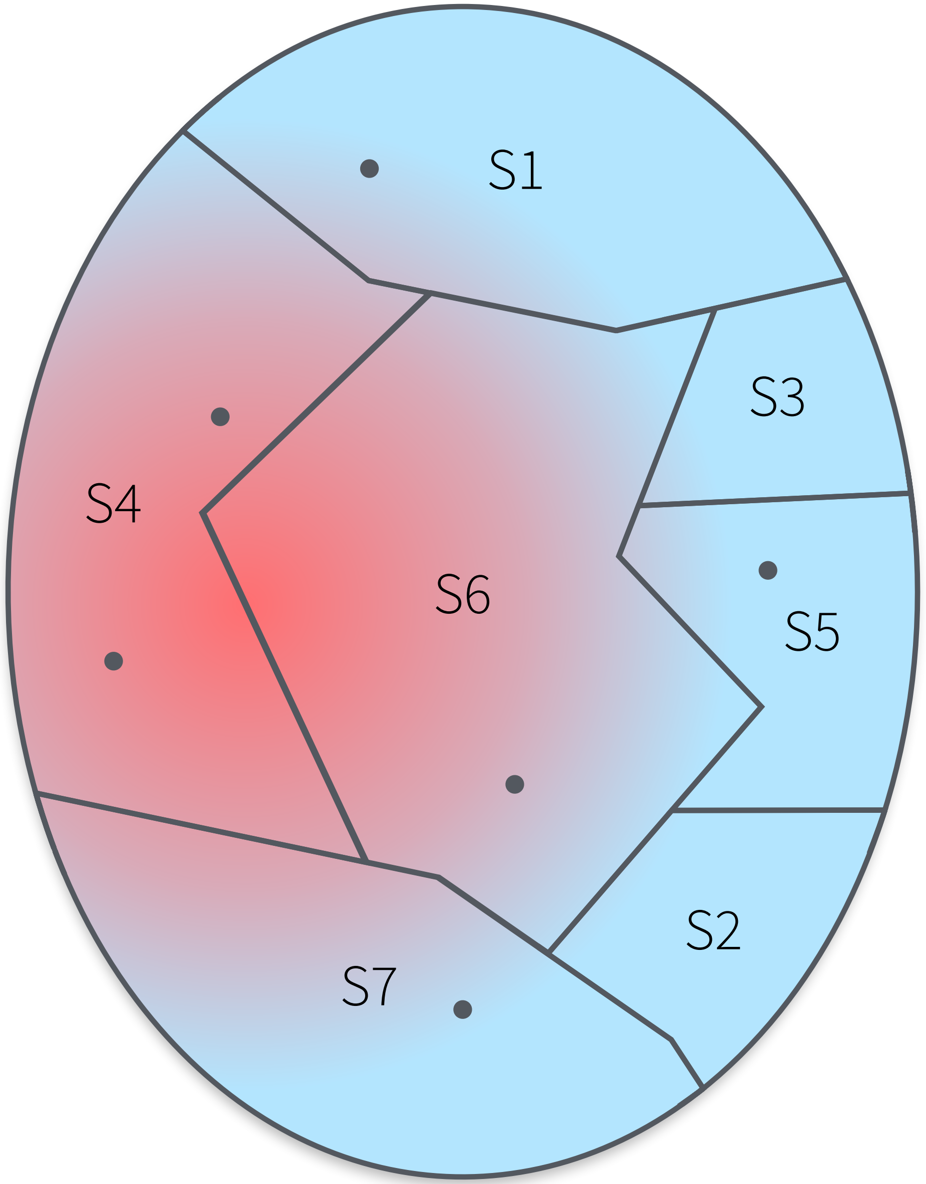

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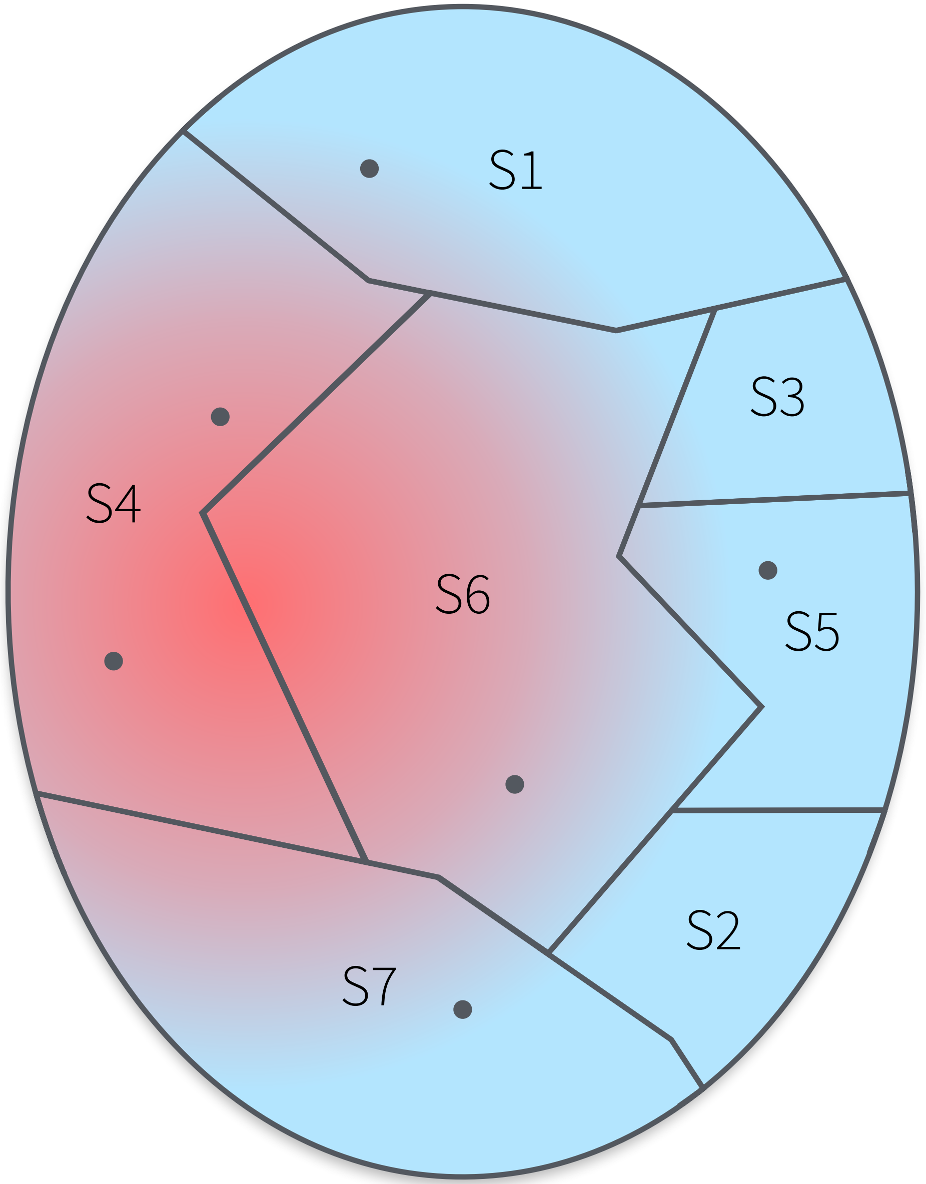

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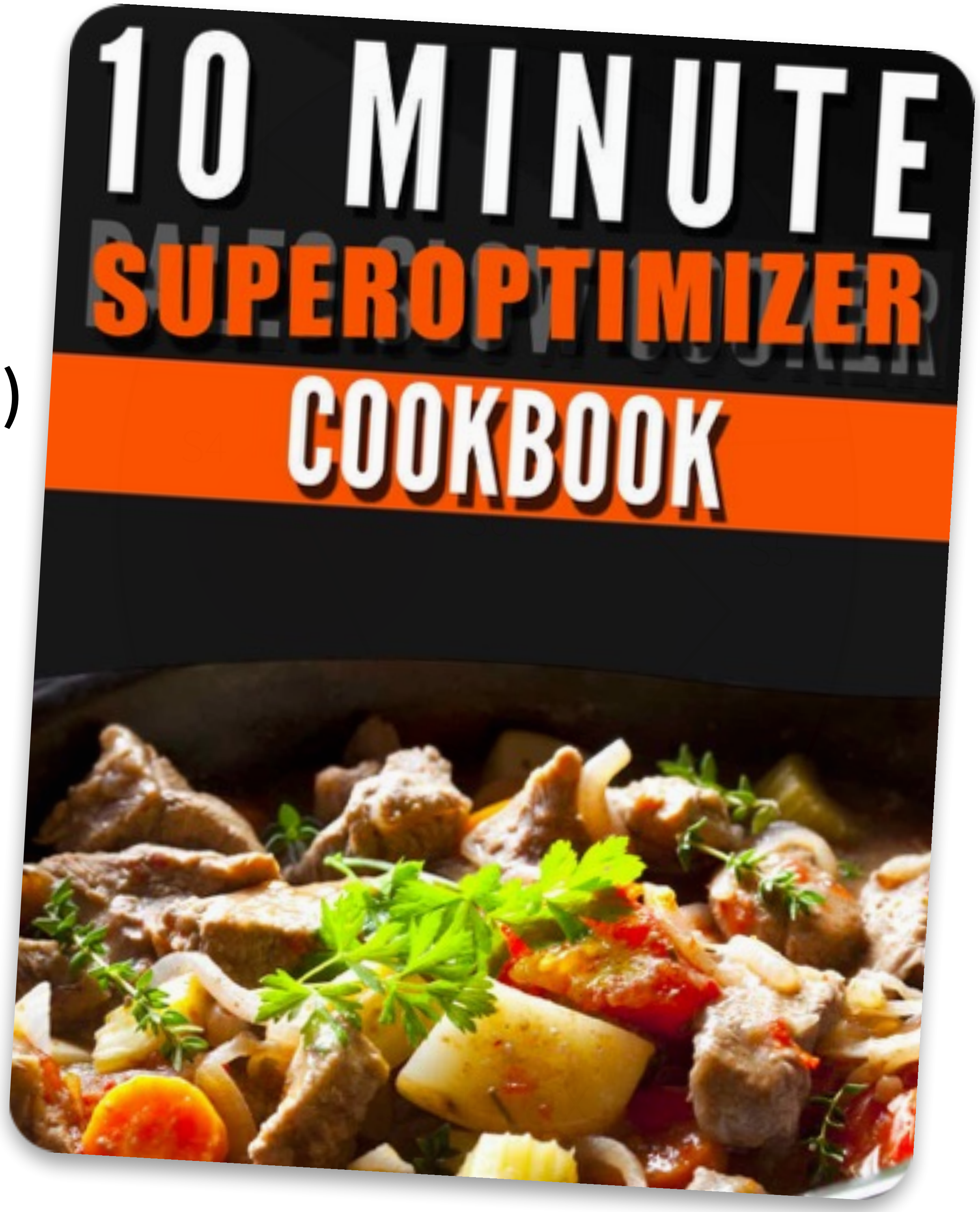

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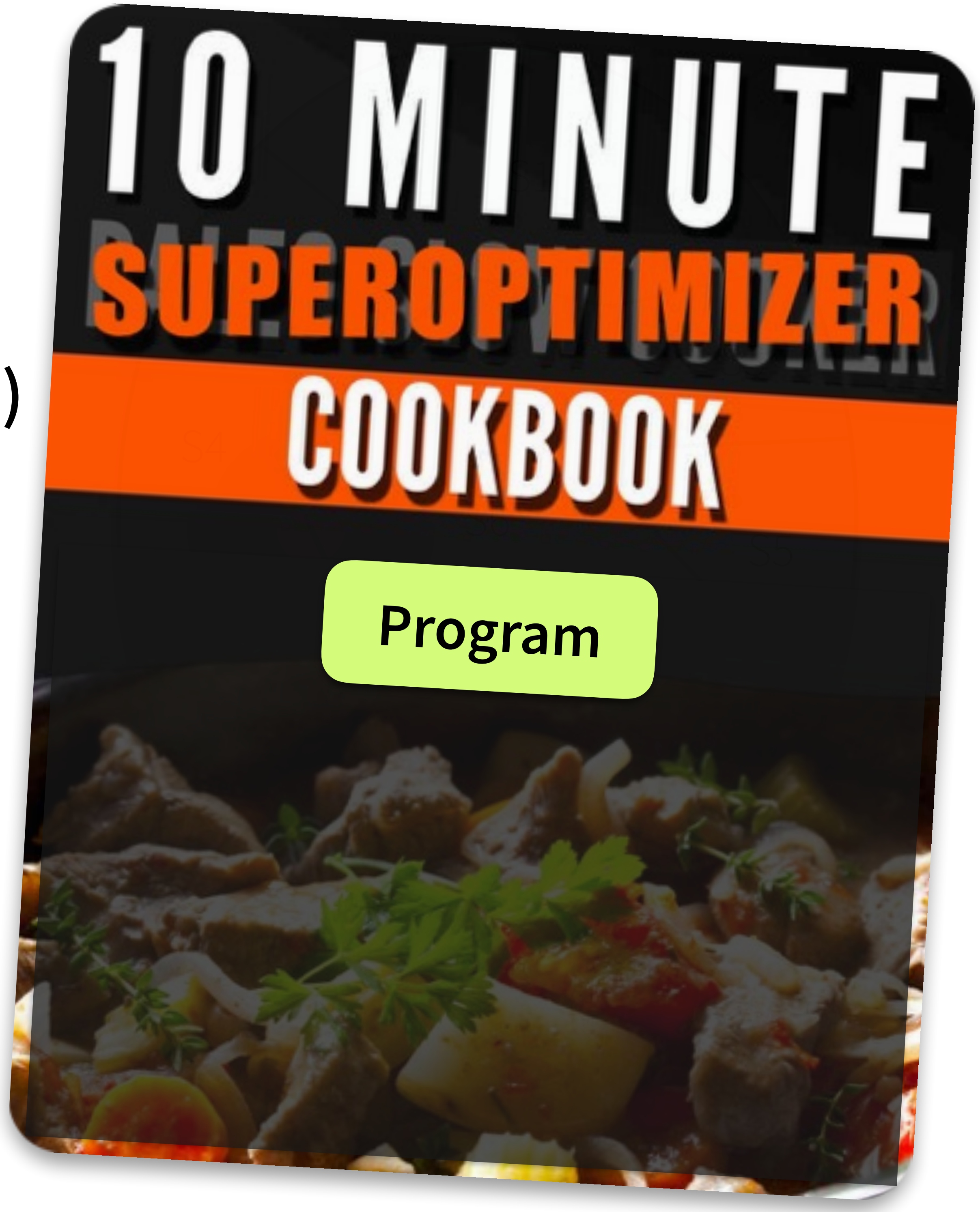

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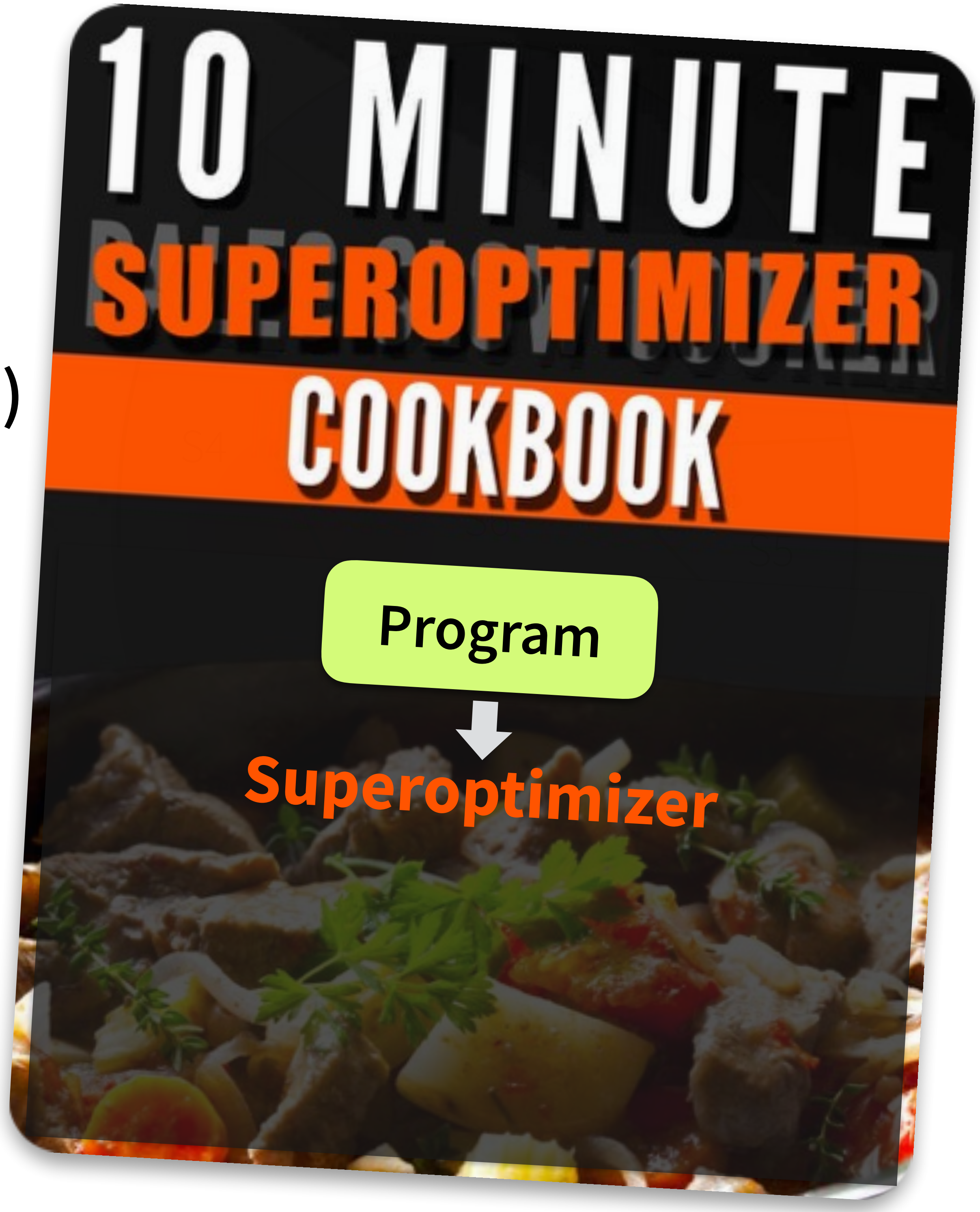

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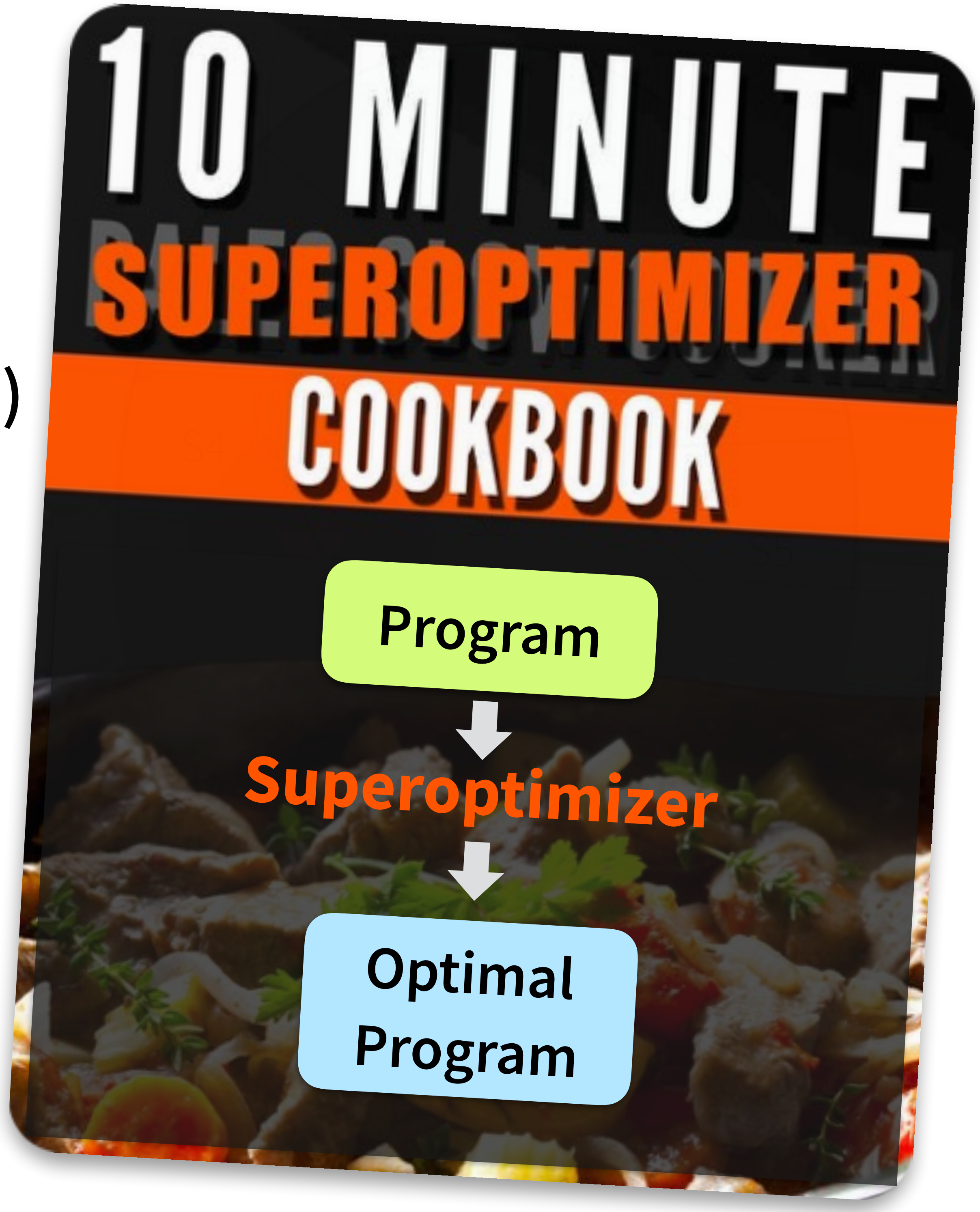

Program

Superoptimizer

Optimal Program

Metasketches express structure and strategy

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Metasketches express structure and strategy

1. structured candidate space ($\mathcal{S}$, $\preccurlyeq$)

A fragmentation of the candidate space, and an ordering on those fragments.

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Metasketches express structure and strategy

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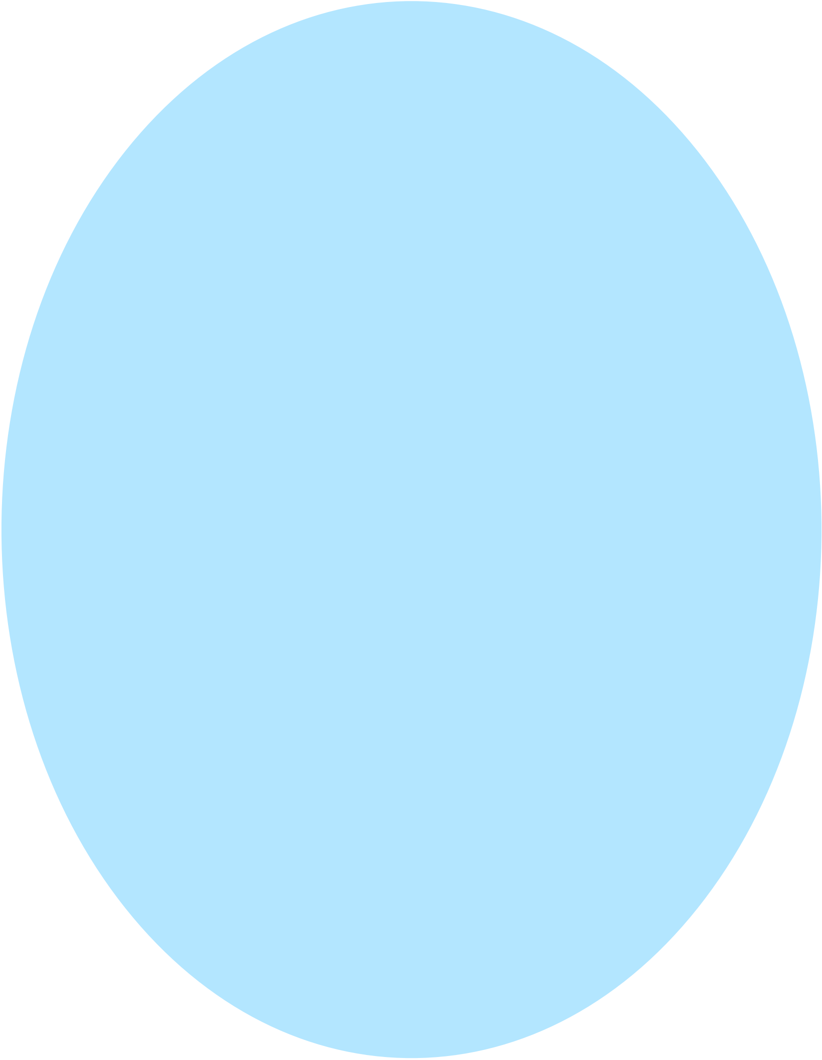
$\mathcal{S}$ = set of all SSA programs



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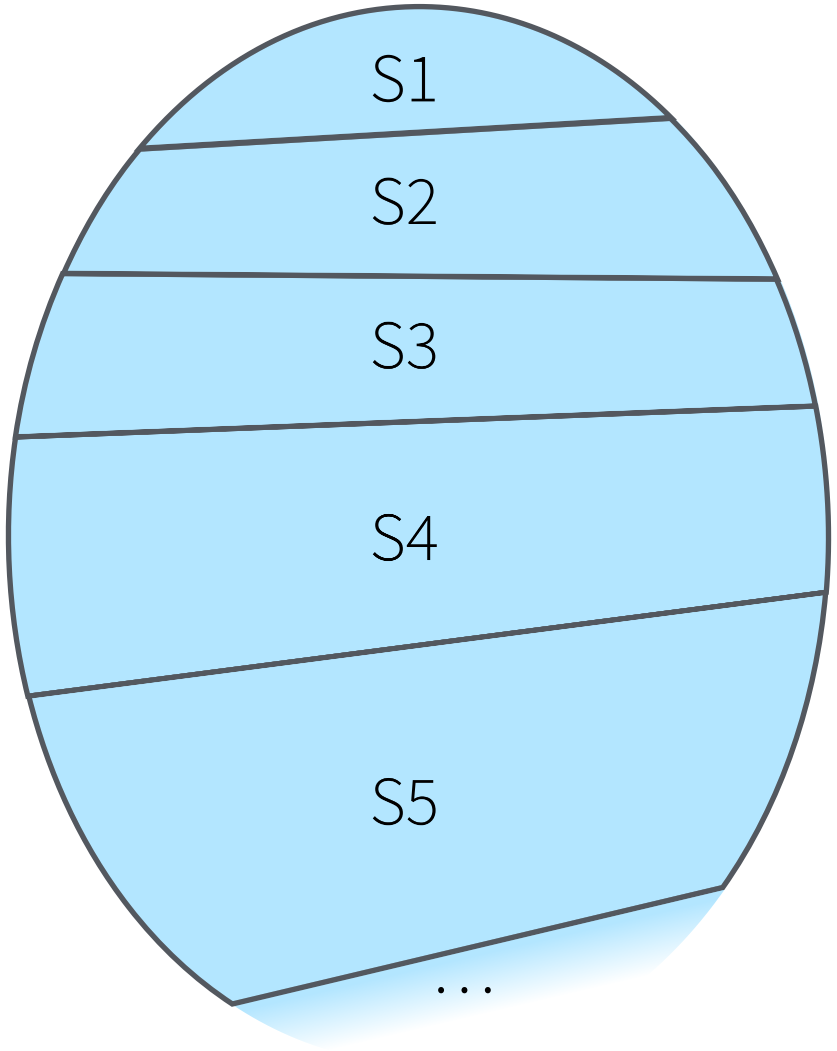

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Metasketches express structure and strategy

1. structured candidate space ($\mathcal{S}$, $\preccurlyeq$)

- a countable set $\mathcal{S}$ of sketches
- a total order $\preccurlyeq$ on $\mathcal{S}$

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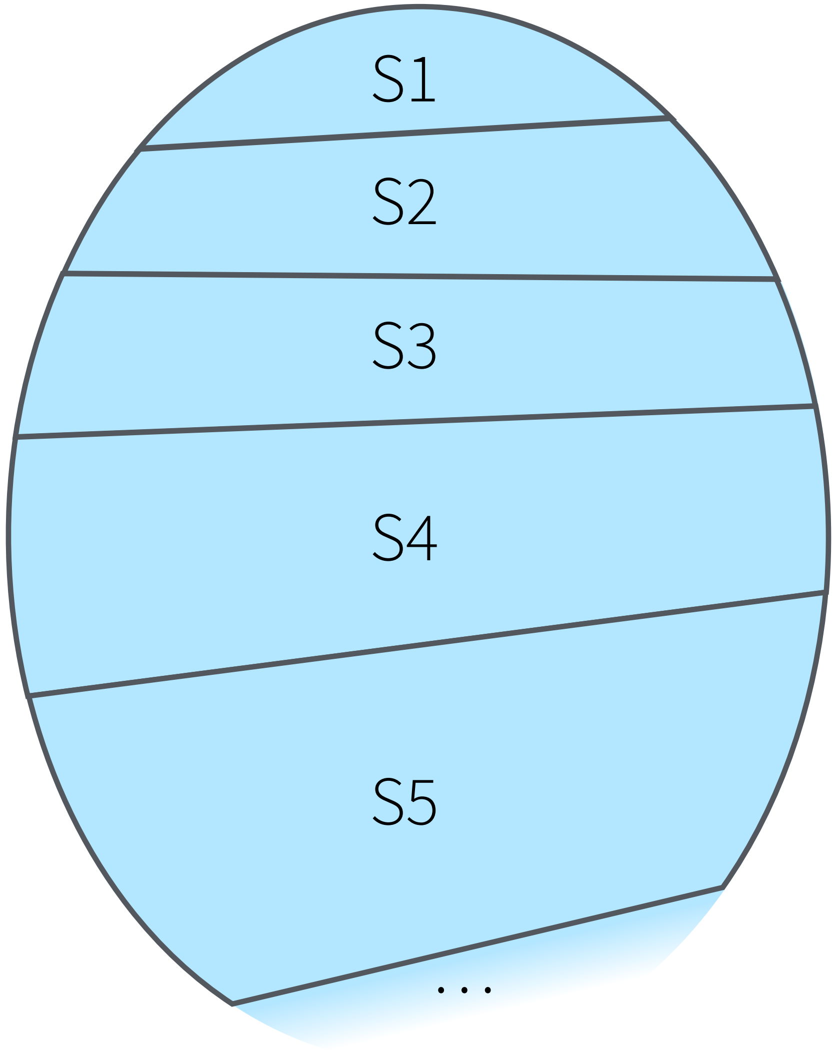

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S₃ (SSA programs of length 3)

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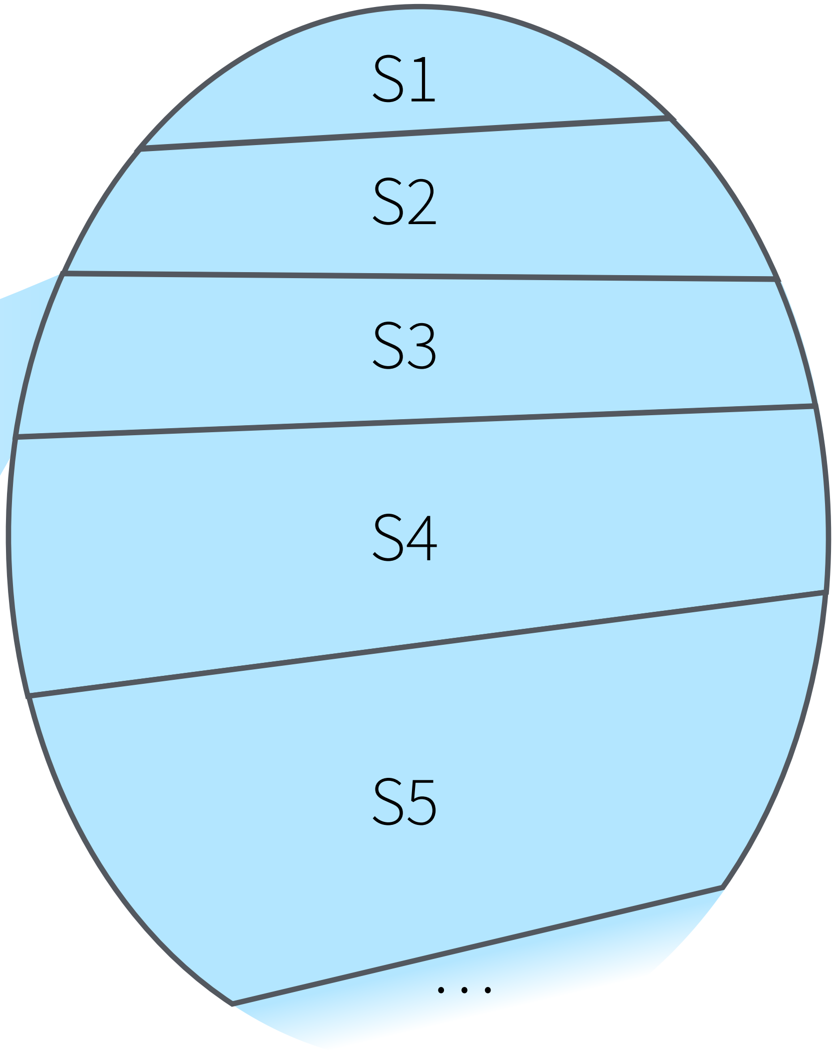
def f(x):
  r1 = ??op(??{x})
  r2 = ??op(??{x,r1})
  r3 = ??op(??{x,r1,r2})
  return r3
```

$\mathcal{S}$ = set of all SSA programs



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+, -, <, if, . . .

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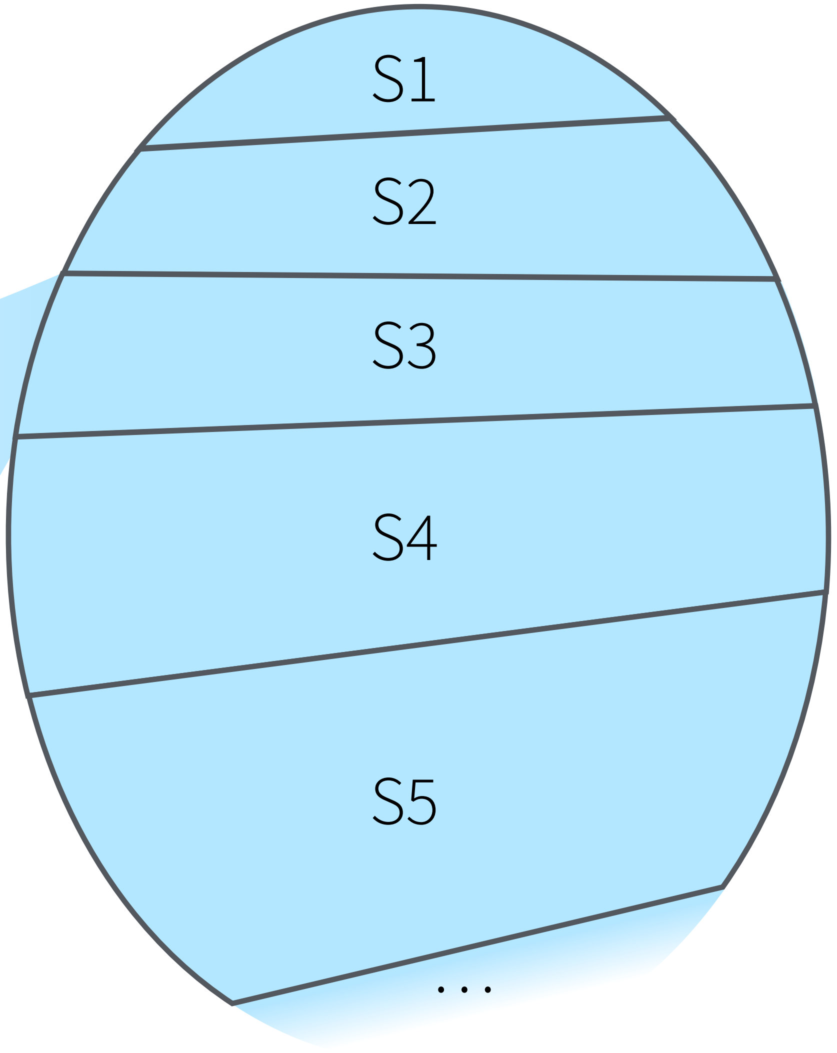

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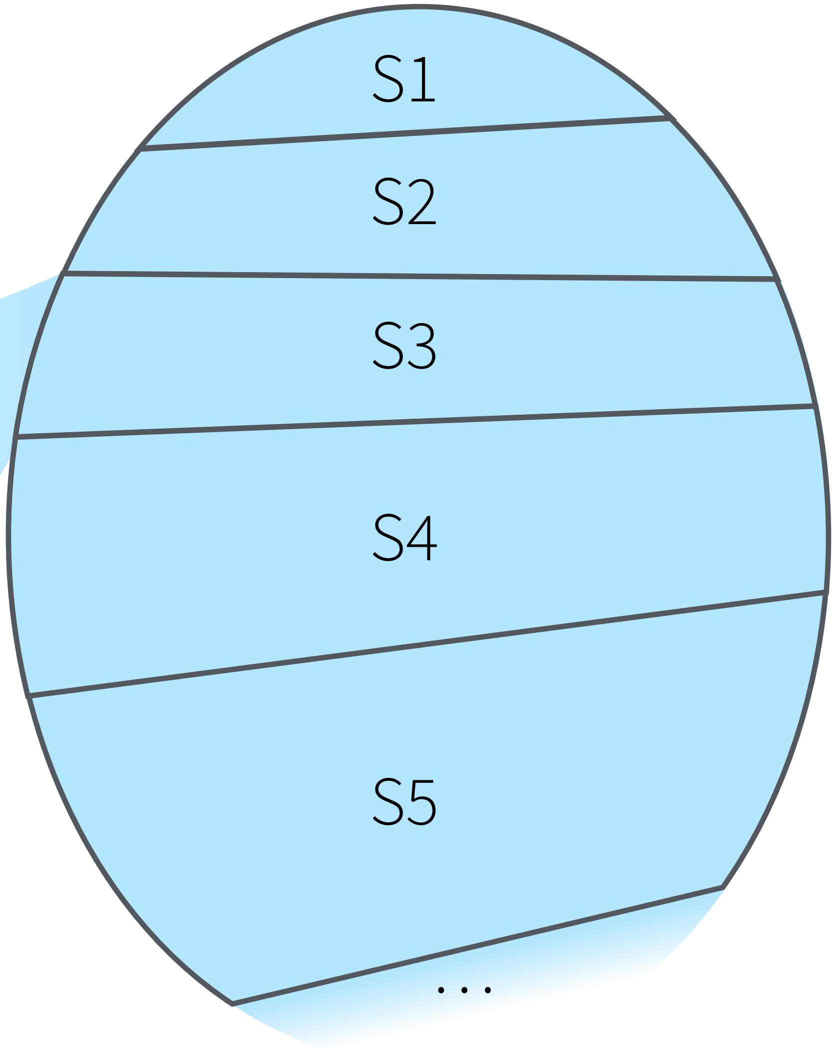
Vars & constants

$\mathcal{S}$ = set of all SSA programs



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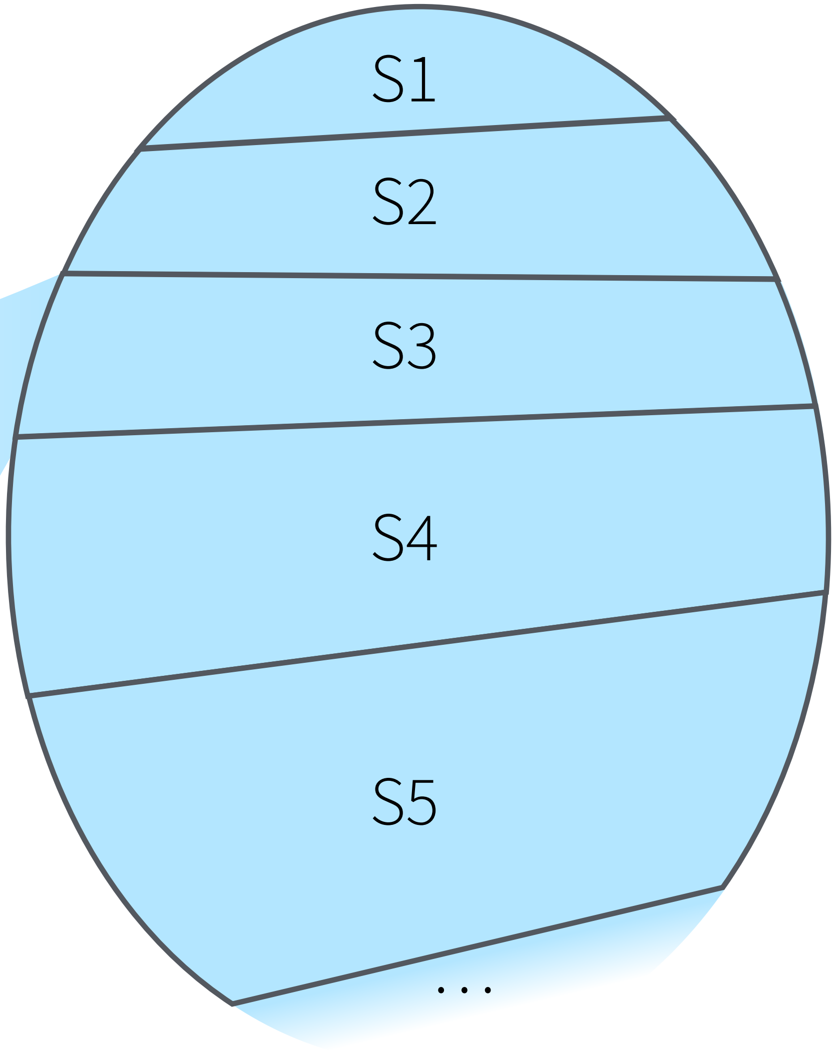
def f(x):
   r1 = ??op(??{x})
   r2 = ??op(??{x,r1})
   r3 = ??op(??{x,r1,r2})
   return r3
```

$\mathcal{S}$ = set of all SSA programs



2. cost function (κ)

3. gradient function (g)

Metasketches express structure and strategy

1. structured candidate space ($\mathcal{S}$, $\preccurlyeq$)

- a countable set $\mathcal{S}$ of sketches
- a total order $\preccurlyeq$ on $\mathcal{S}$

Ordering expresses high-level search strategy.

A fragmentation of the candidate space, and an ordering on those fragments.

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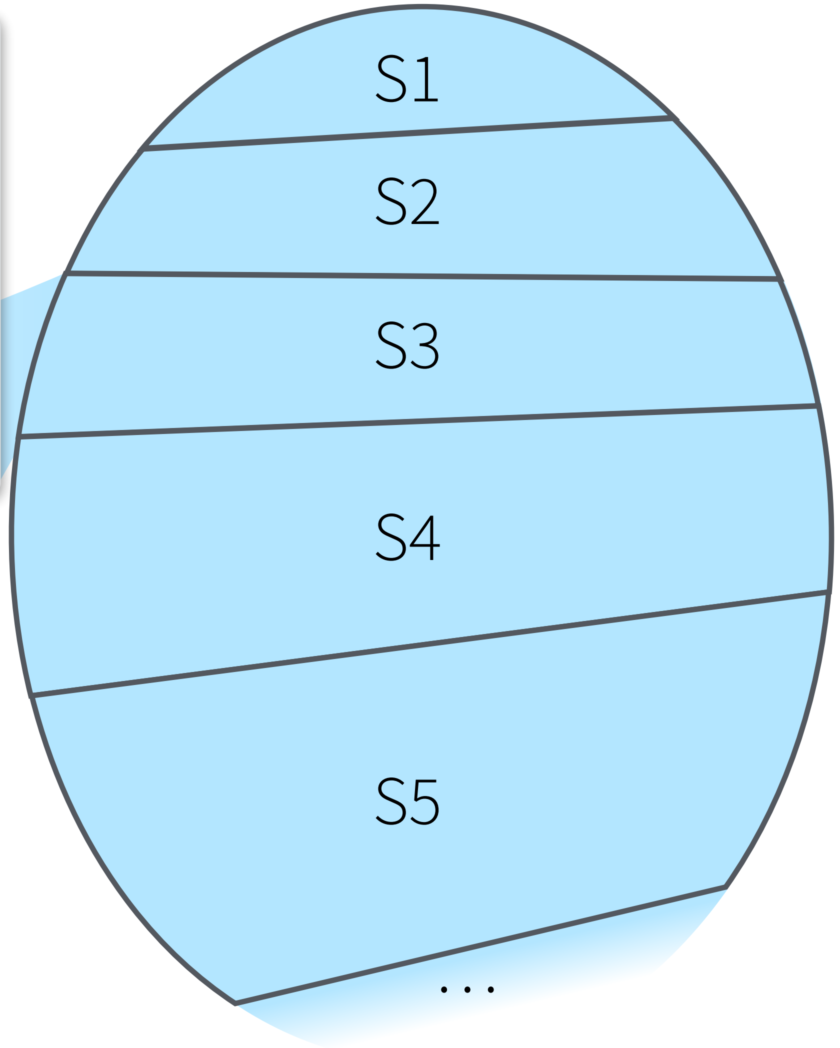

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Ordering expresses high-level search strategy.

Here, $\preccurlyeq$ expresses iterative deepening.

S_3 (SSA programs of length 3)

```
def f(x):
   r_1 = ??_op(??_{x})
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```

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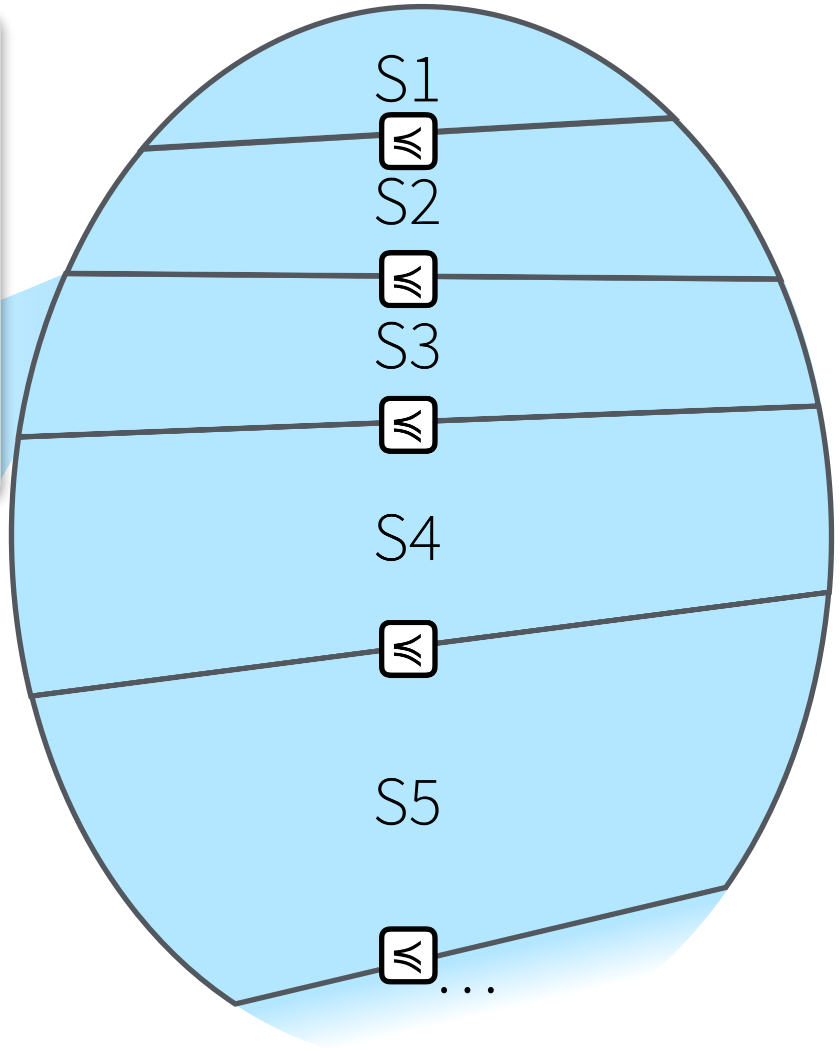

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A fragmentation of the candidate space, and an ordering on those fragments.

$\mathcal{S}$ = set of all SSA programs

S_1

```
def f(x):
  r1 = ??_op(??_{x})
  return r1
```

S_2

```
def f(x):
  r1 = ??_op(??_{x})
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  return r2
```

S_3

```
def f(x):
  r1 = ??_op(??_{x})
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```

...

Implemented as a generator that returns the next sketch in the space

2. cost function (κ)

3. gradient function (g)

Metasketches express structure and strategy

1. structured candidate space ($\mathcal{S}$, $\preccurlyeq$)

- a countable set $\mathcal{S}$ of sketches
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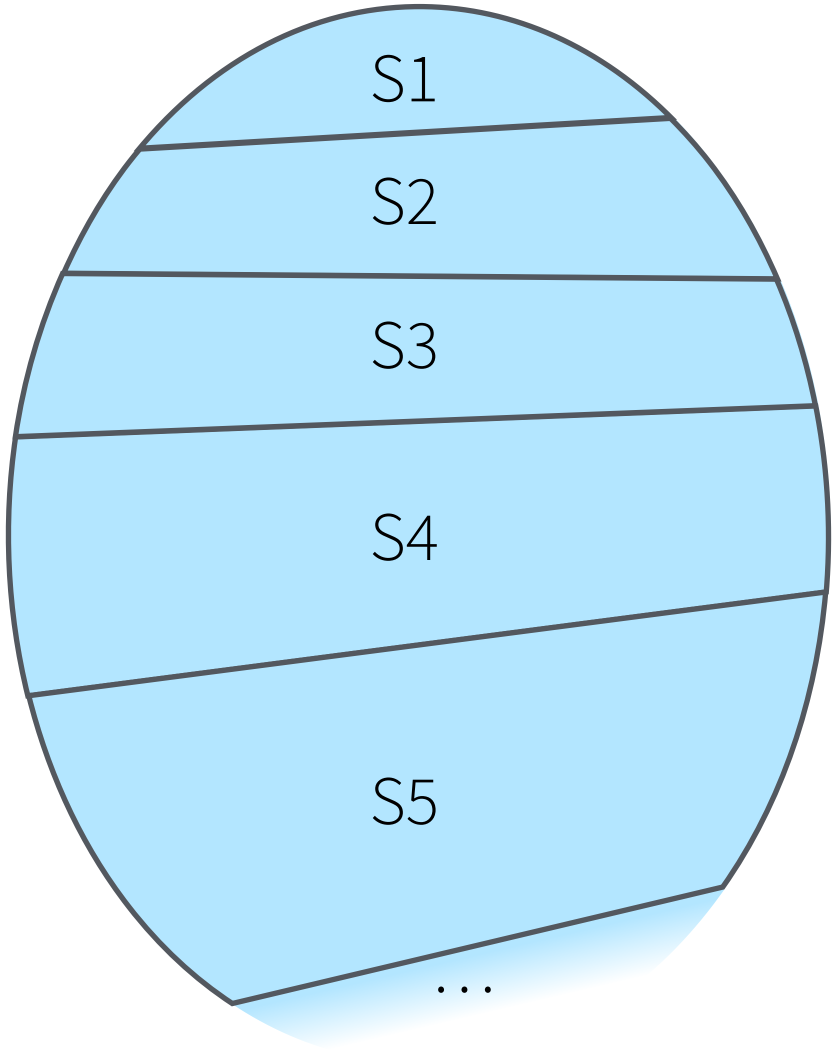
Semantics

$\mathcal{S}$ = set of all SSA programs



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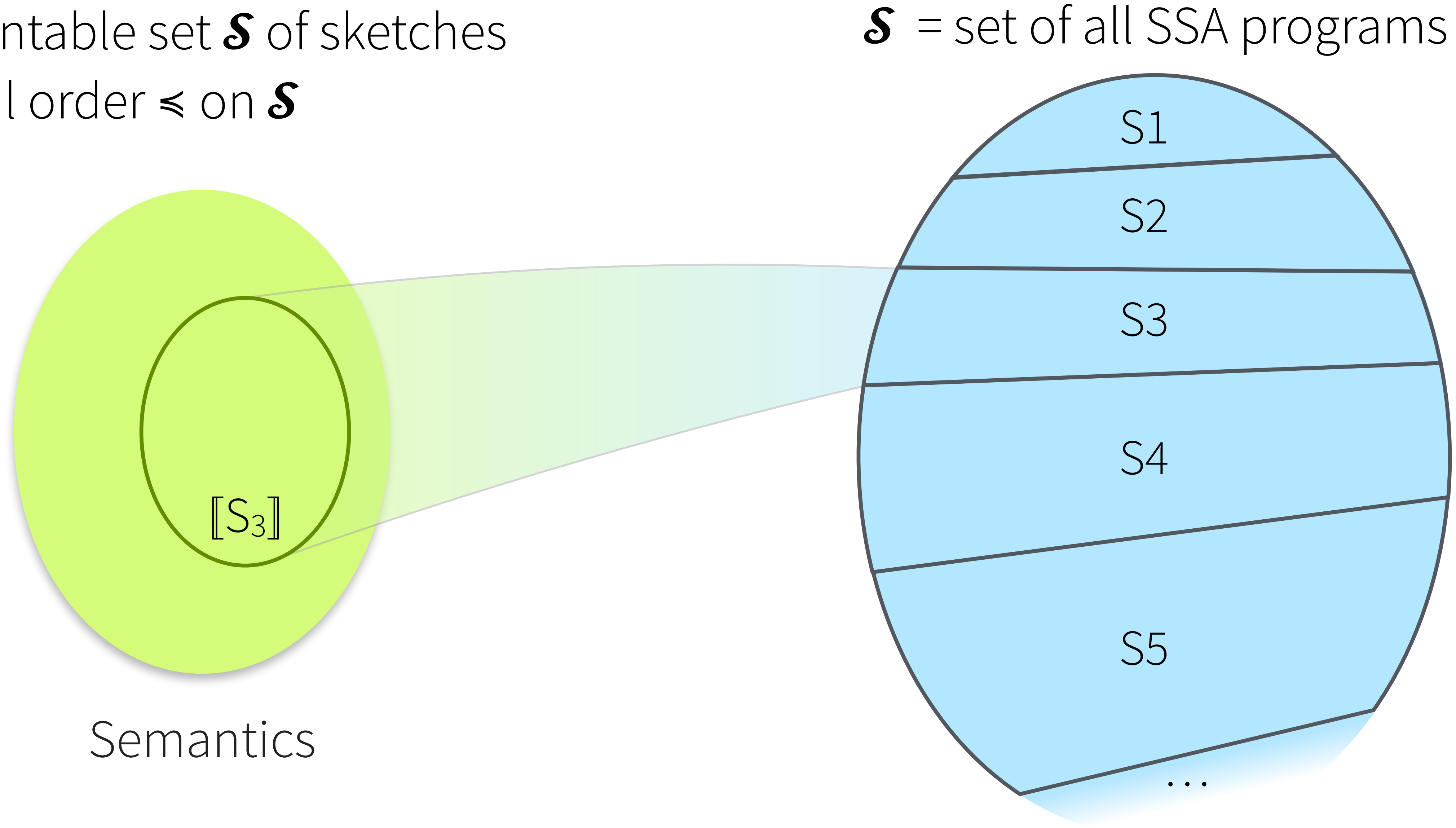

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Metasketches express structure and strategy

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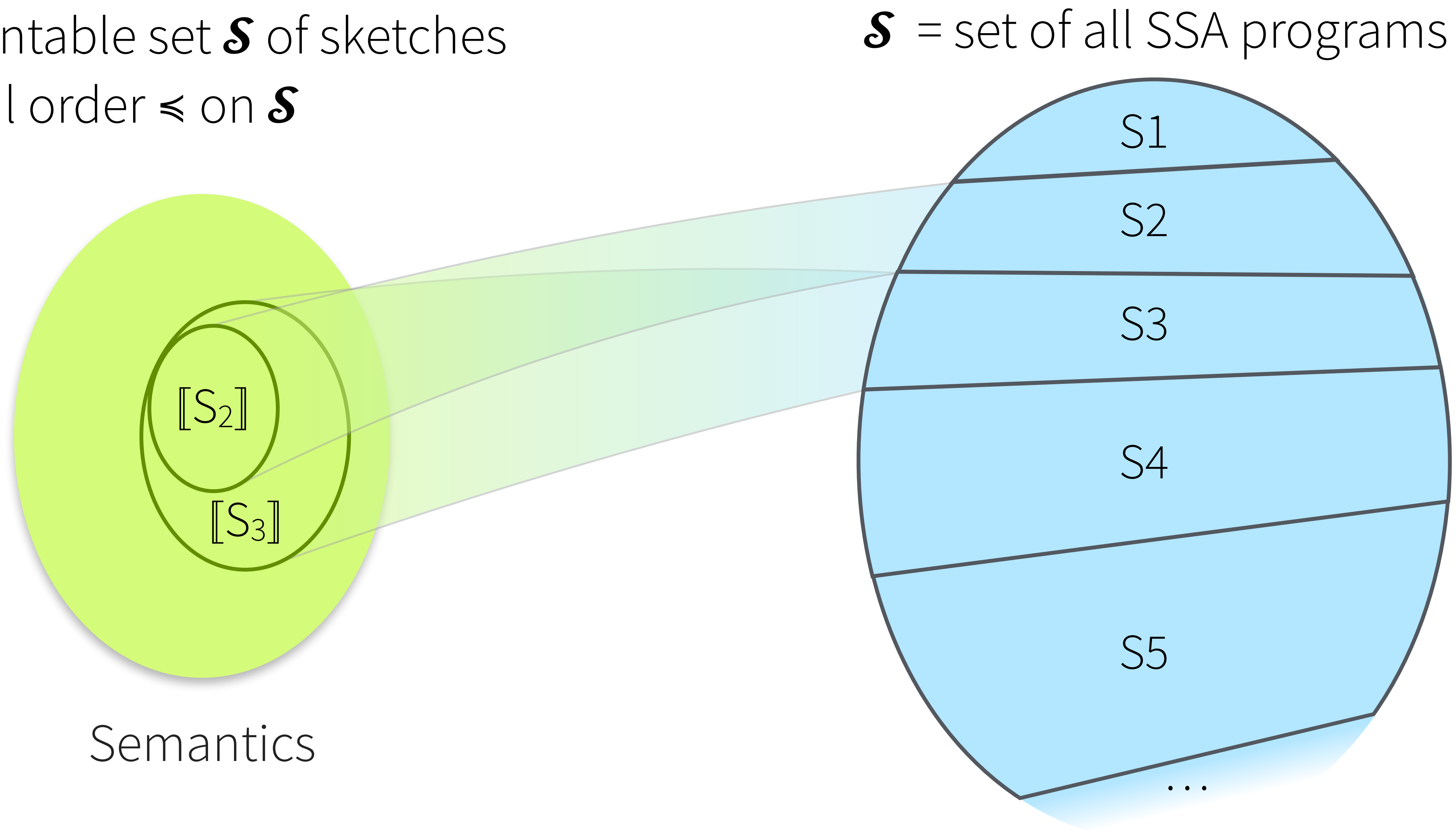

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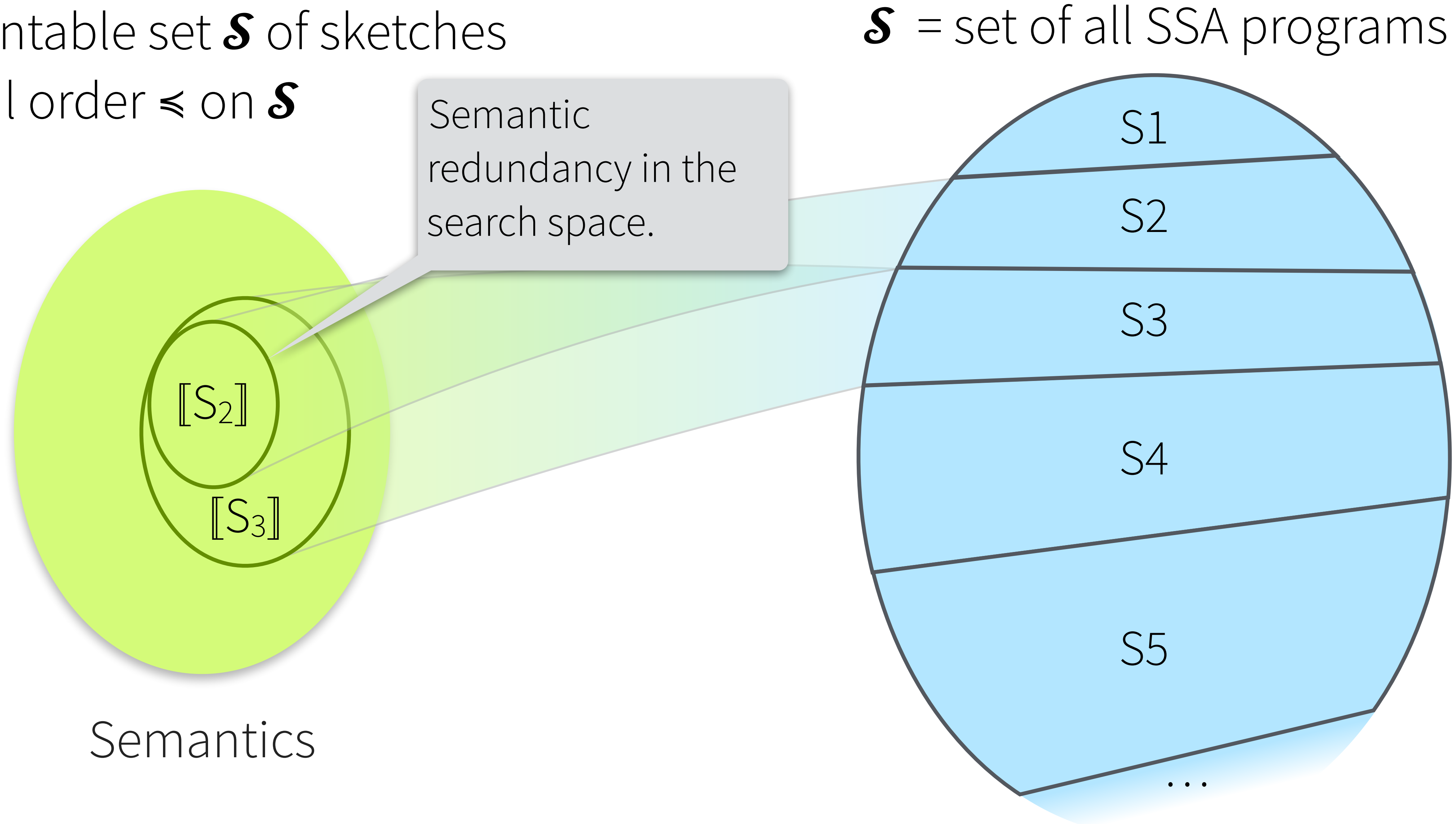

$\mathcal{S}$ = set of all SSA programs
Semantic redundancy in the search space.
⟦S₂⟧
⟦S₃⟧
S1
S2
S3
S4
S5
...

Semantics

2. cost function (κ)

3. gradient function (g)

Metasketches express structure and strategy

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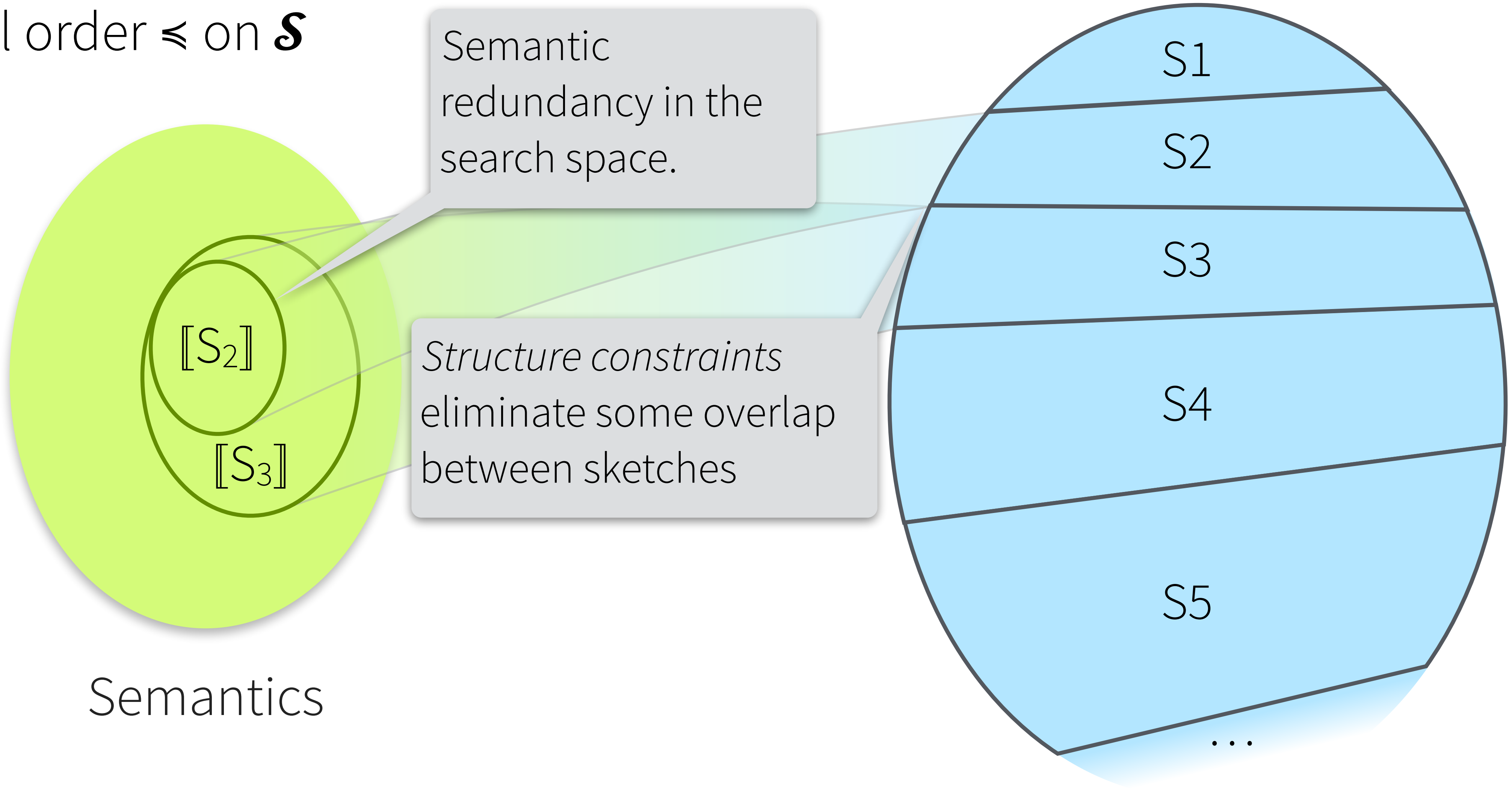

Semantic redundancy in the search space.

Structure constraints eliminate some overlap between sketches

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Metasketches express structure and strategy

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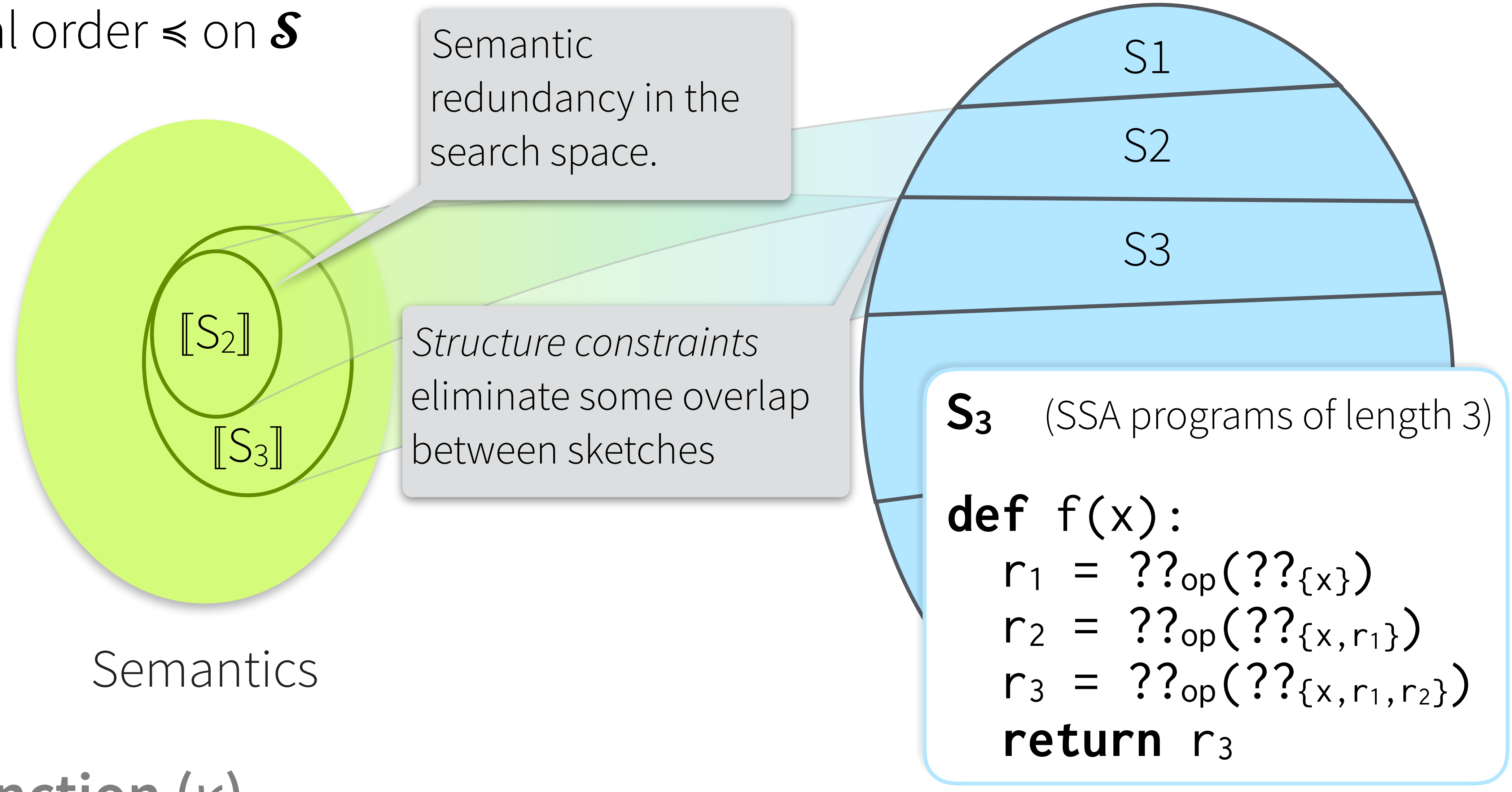

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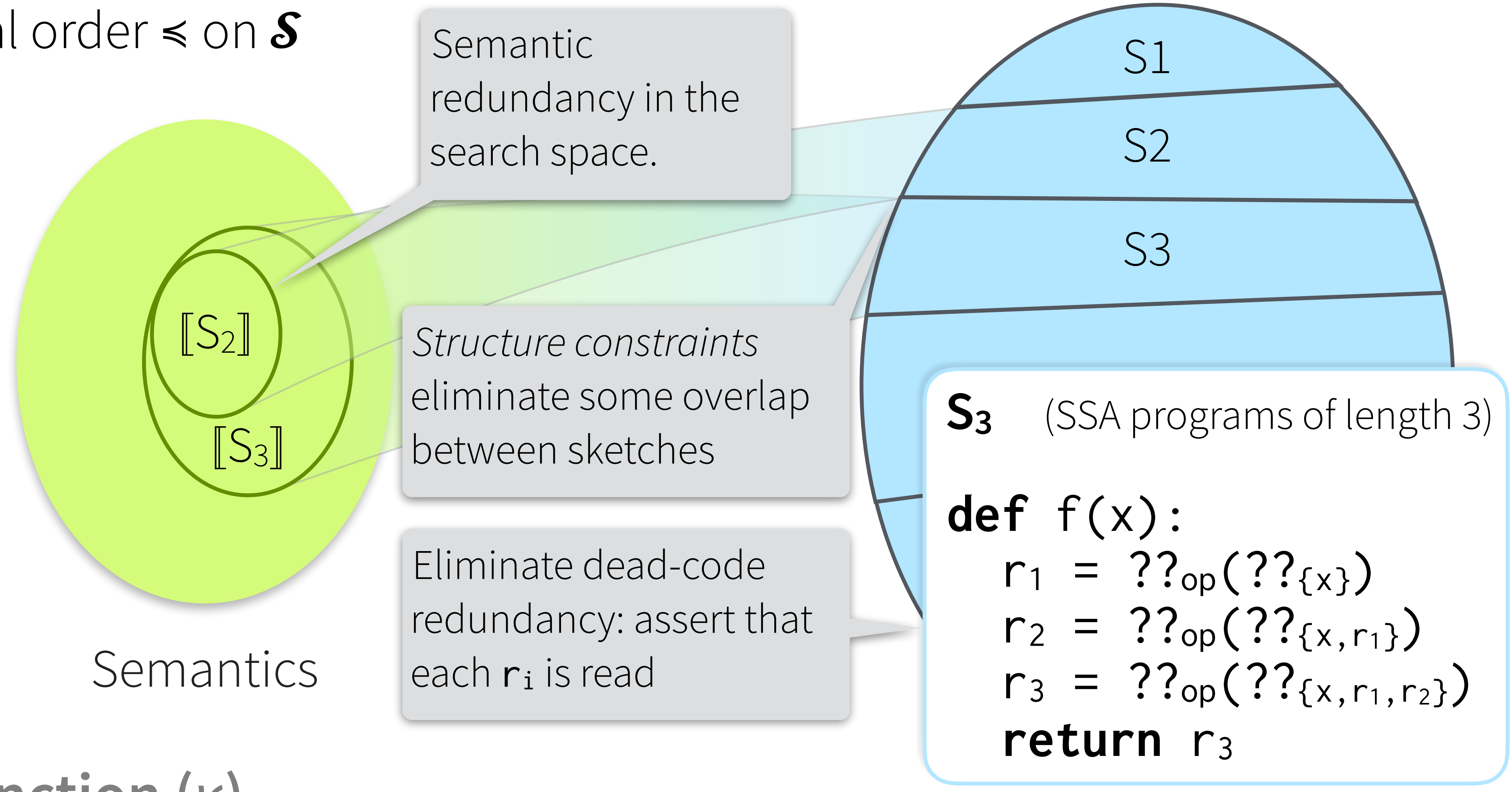

Semantic redundancy in the search space.

Structure constraints eliminate some overlap between sketches

Eliminate dead-code redundancy: assert that each r_i is read

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2. cost function (κ)

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Cost functions rank candidate programs

1. **structured candidate space ($\mathcal{S}$, ≼)**

2. **cost function (κ)**

   $\kappa : \mathcal{L} \to \mathbb{R}$

   assigns a numeric cost to each program in the language $\mathcal{L}$

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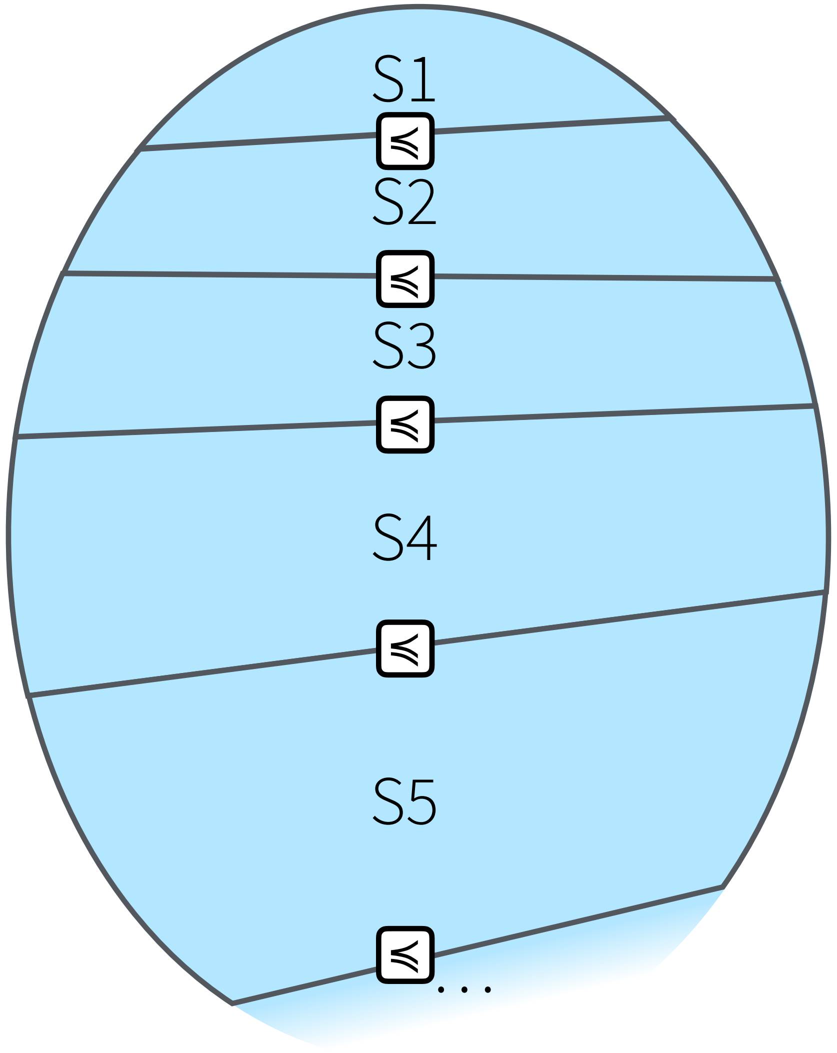

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Cost functions can be based on both syntax and semantics (dynamic behavior)

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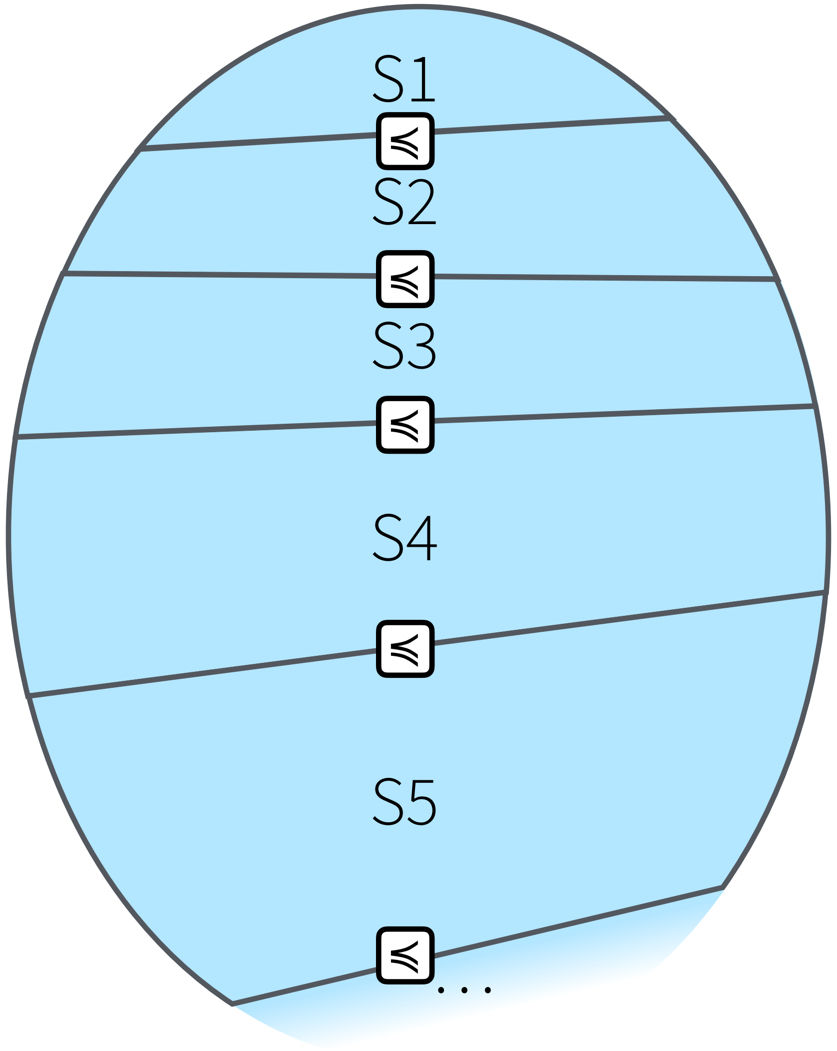

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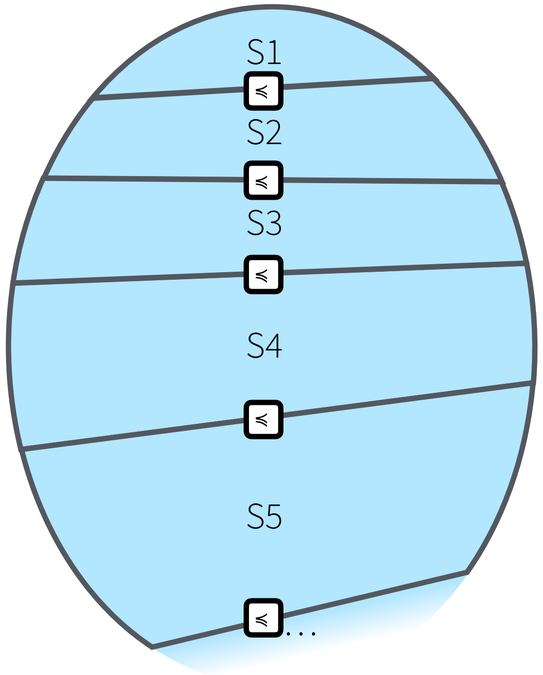


$\kappa(P) = i \quad$ for $P \in S_i \in \mathcal{S}$

The number of variables defined in P

3. **gradient function (g)**

Gradient functions provide cost structure

1. structured candidate space ($\mathcal{S}$, ≼)

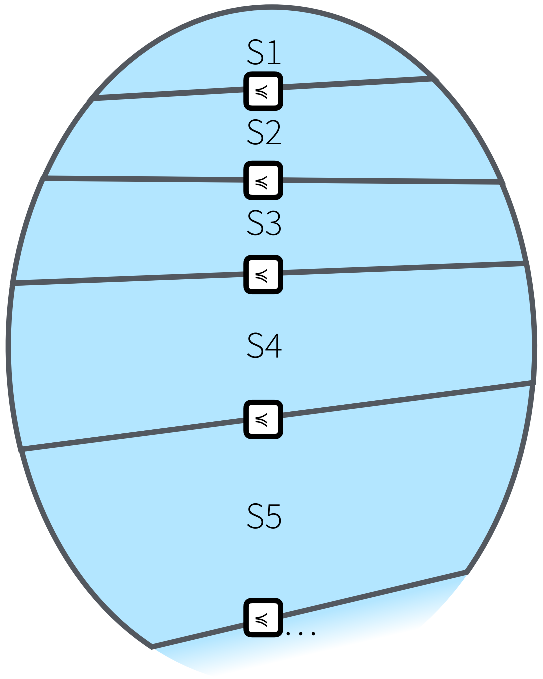
2. cost function (κ)

3. **gradient function (g)**

$g : \mathbb{R} \to 2^{\mathcal{S}}$

$g(c)$ is the set of sketches in $\mathcal{S}$ that *may* contain a solution P with $\kappa(P) < c$

$\mathcal{S}$ = set of all SSA programs



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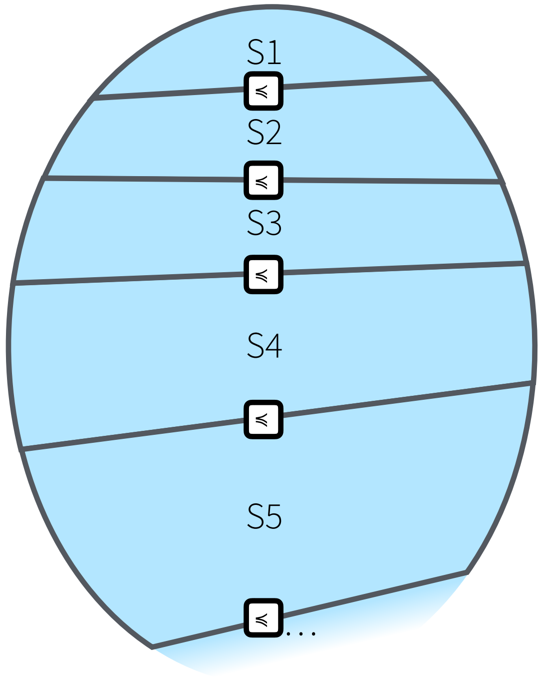
The gradient function overapproximates the behavior of **κ** on $\mathcal{S}$

$\mathcal{S}$ = set of all SSA programs



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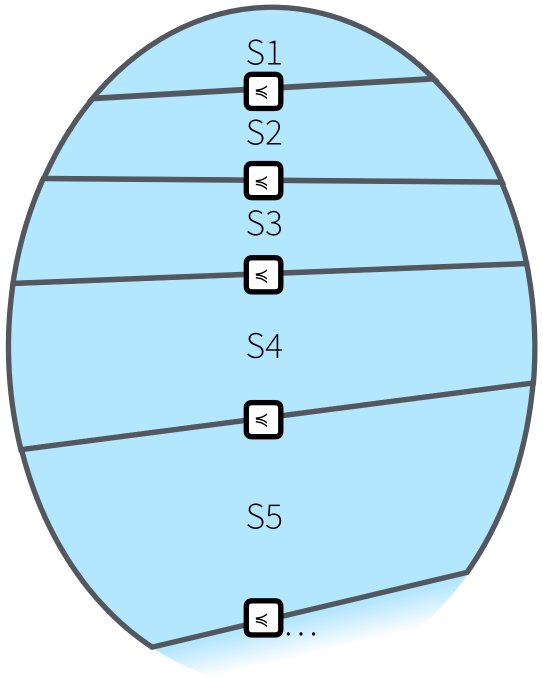

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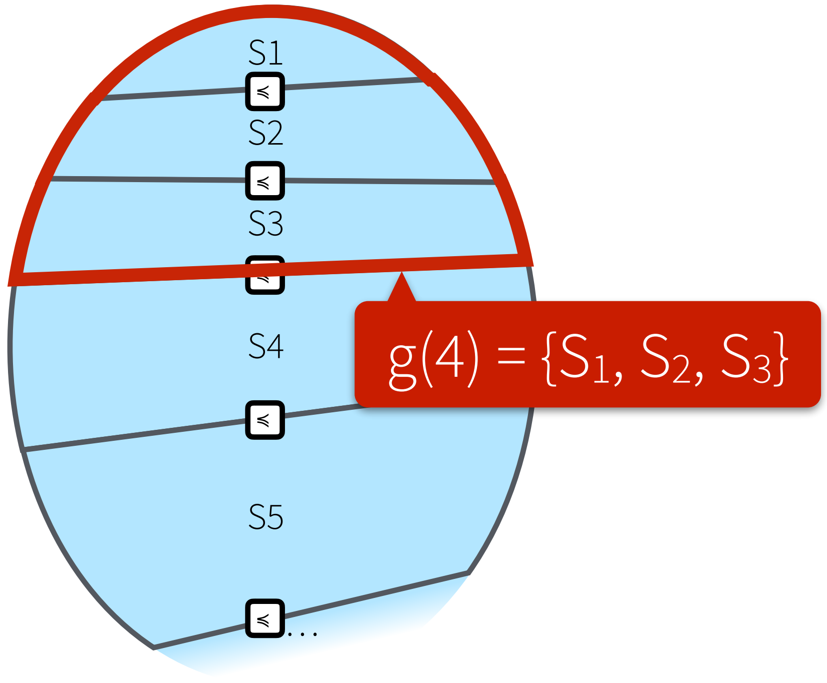

$g(4) = \{S_1, S_2, S_3\}$

$\kappa(P) = i \quad \text{for } P \in S_i \in \mathcal{S}$

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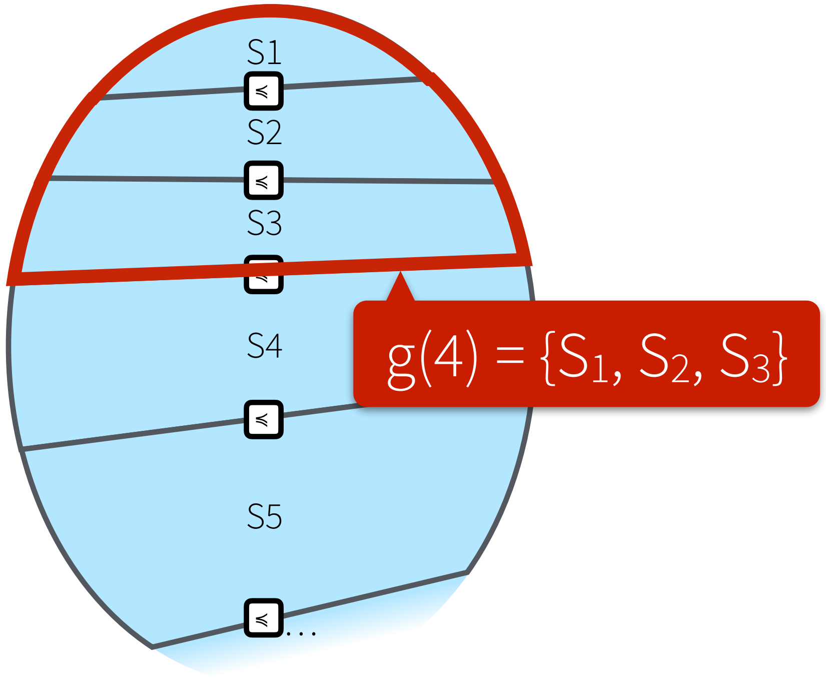
The gradient function overapproximates the behavior of κ on $\mathcal{S}$

Always sound for g to return all of $\mathcal{S}$ if a tighter bound is unavailable.

$\mathcal{S}$ = set of all SSA programs



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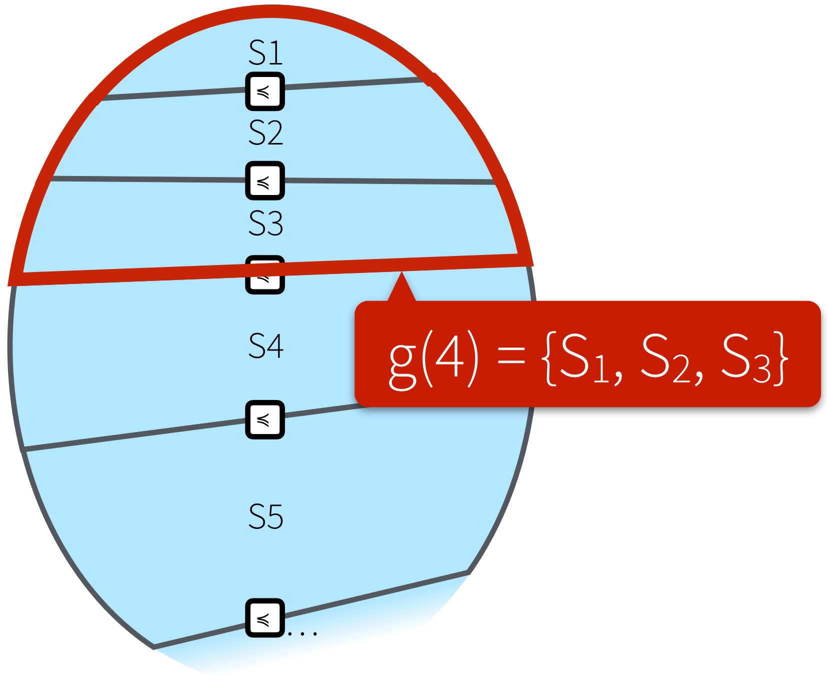
The gradient function overapproximates the behavior of κ on $\boldsymbol{\mathcal{S}}$

Always sound for g to return all of $\boldsymbol{\mathcal{S}}$ if a tighter bound is unavailable.

g(c) always being finite is sufficient (not necessary) to guarantee termination.

$\boldsymbol{\mathcal{S}}$ = set of all SSA programs



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Metasketches

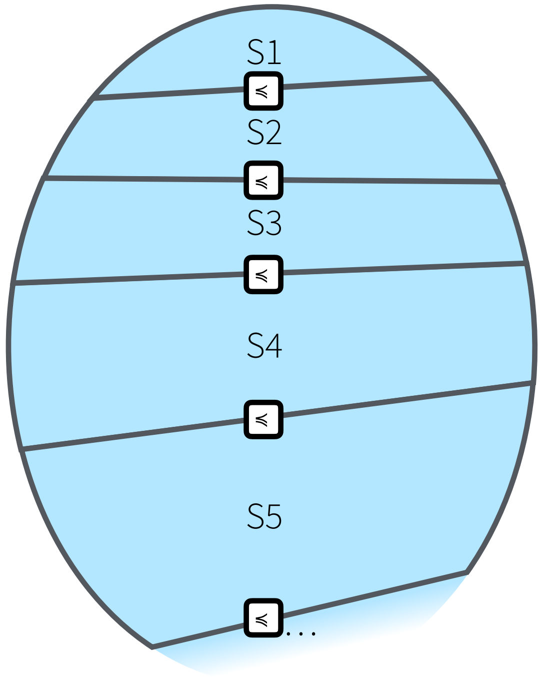
Design and structure

1. **structured candidate space ($\mathcal{S}$, ≼)**

2. **cost function (κ)**

3. **gradient function (g)**

$\boldsymbol{\mathcal{S}}$ = set of all SSA programs



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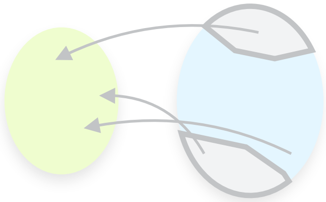
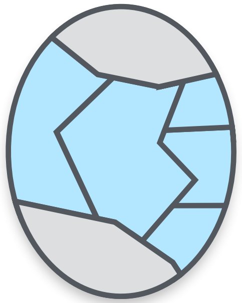


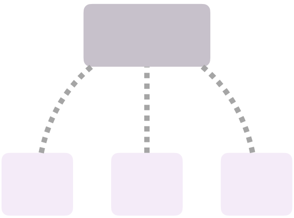
Background

Syntax-guided synthesis



Metasketches

Design and structure

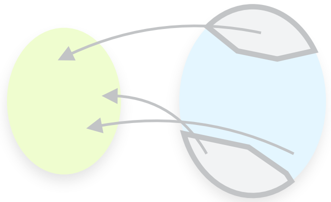


Synapse

A metasketch solver

Results

Better solutions, faster



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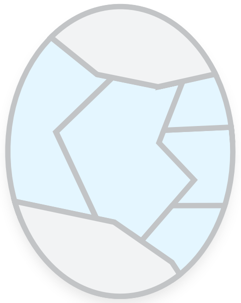
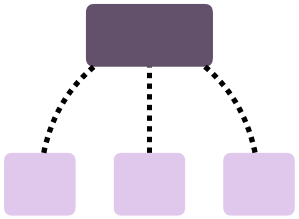


Metasketches

Design and structure



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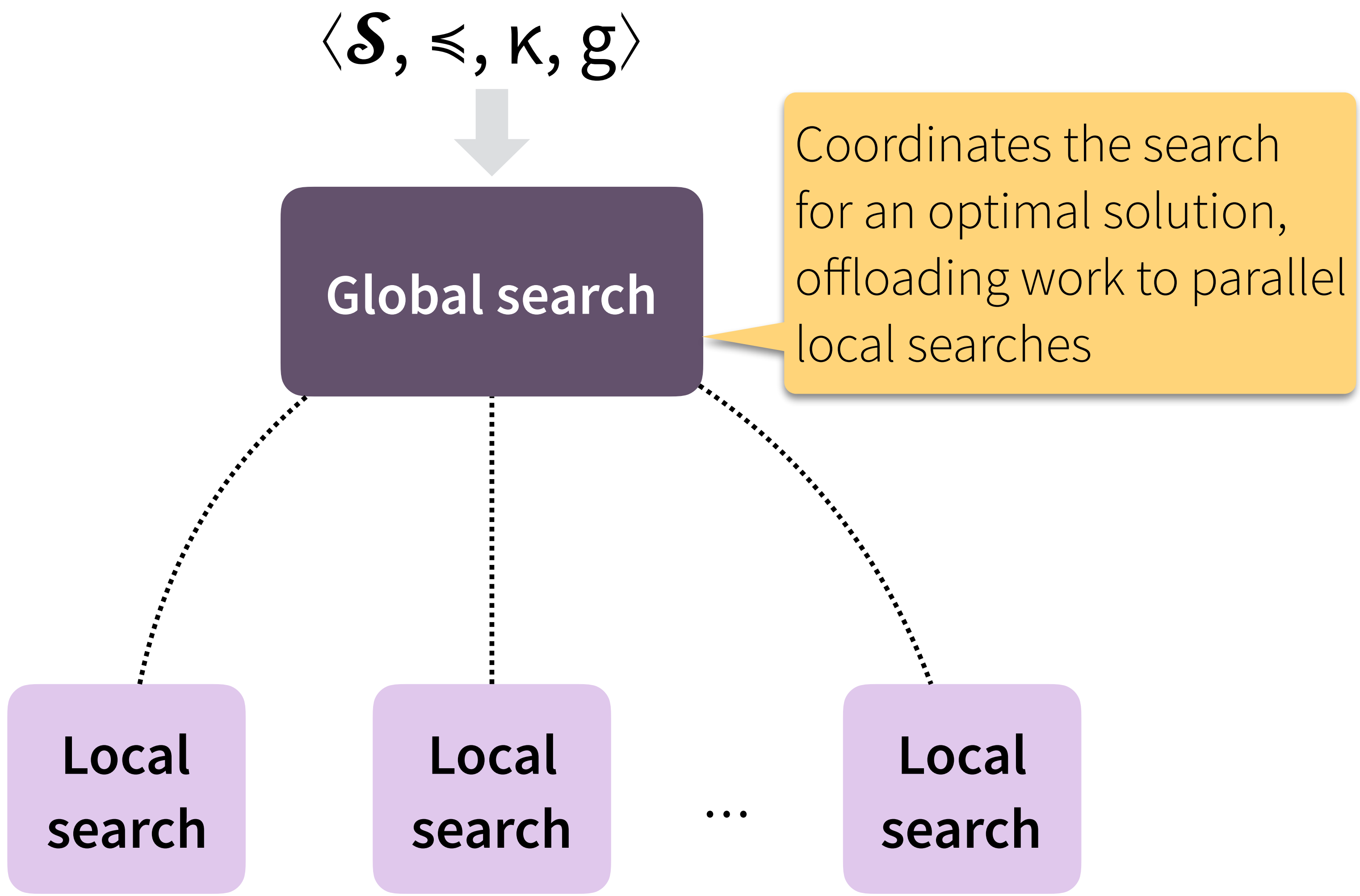
Solving with two cooperative searches



$\langle \mathcal{S}, \preccurlyeq, \kappa, g \rangle$

Global search

Local search

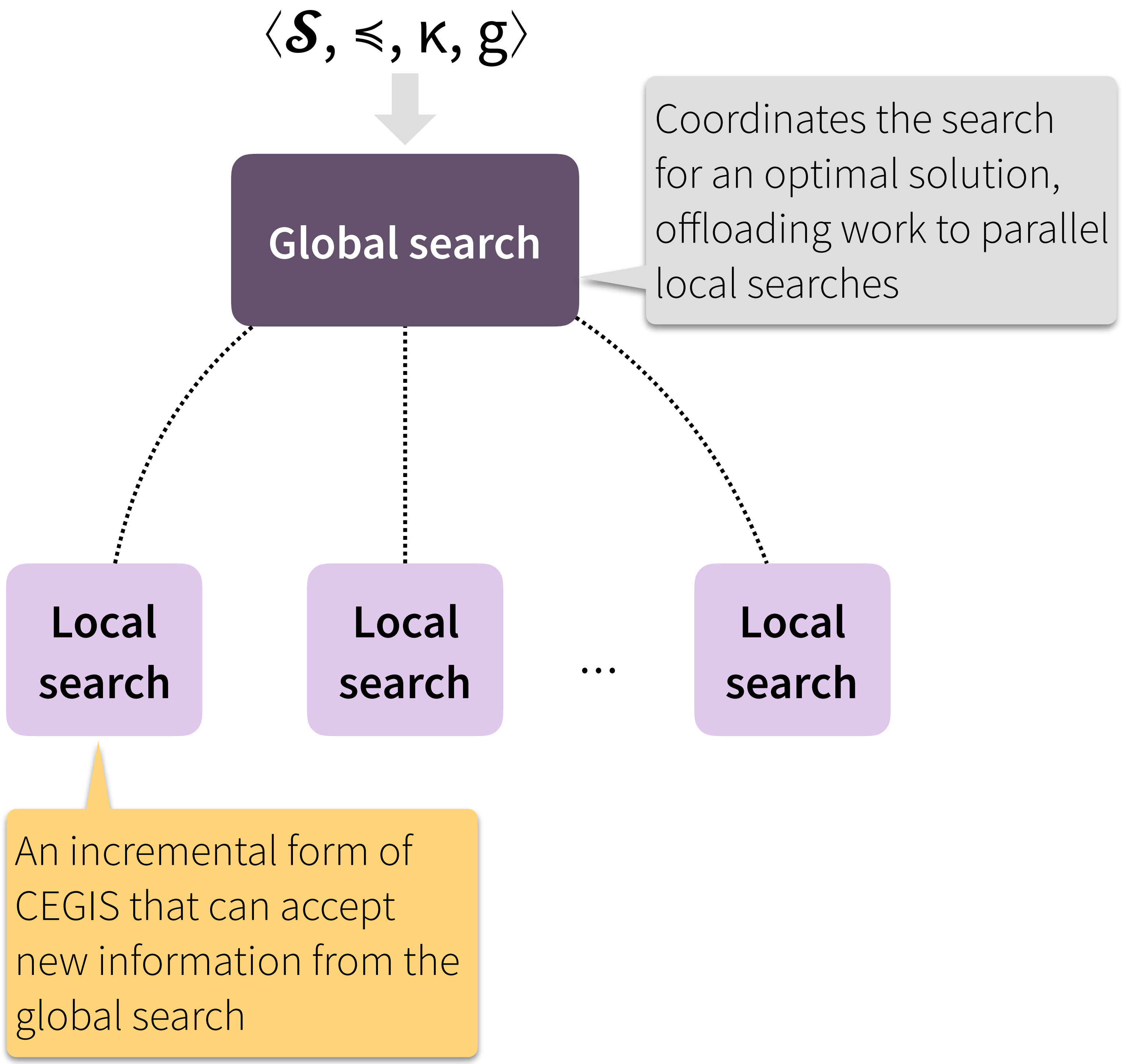
Local search

…

Local search

Coordinates the search for an optimal solution, offloading work to parallel local searches

Solving with two cooperative searches



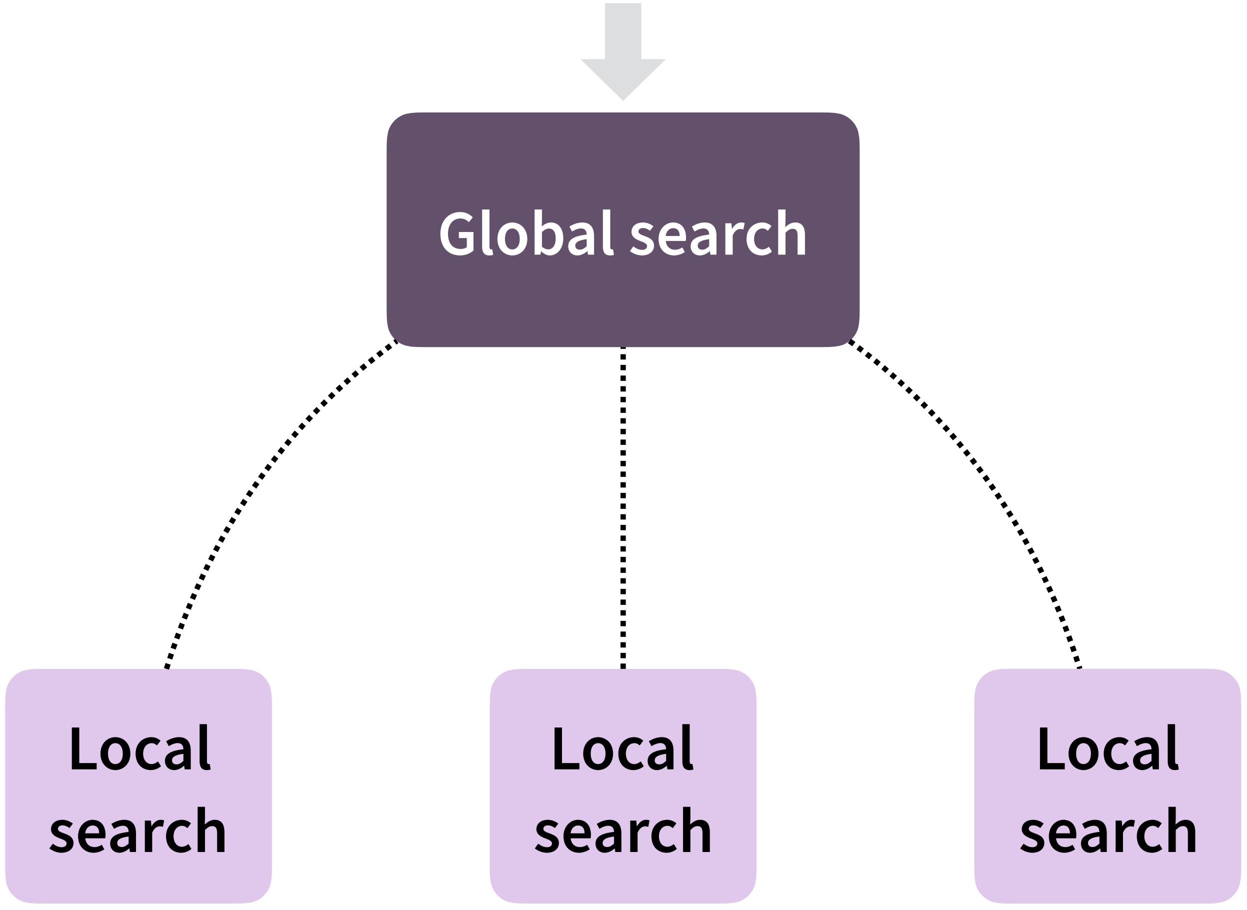
$\langle \mathcal{S}, \preccurlyeq, \kappa, g \rangle$

Coordinates the search for an optimal solution, offloading work to parallel local searches

An incremental form of CEGIS that can accept new information from the global search

Solving with two cooperative searches

$\langle \boldsymbol{\mathcal{S}}, \preccurlyeq, \kappa, g \rangle$

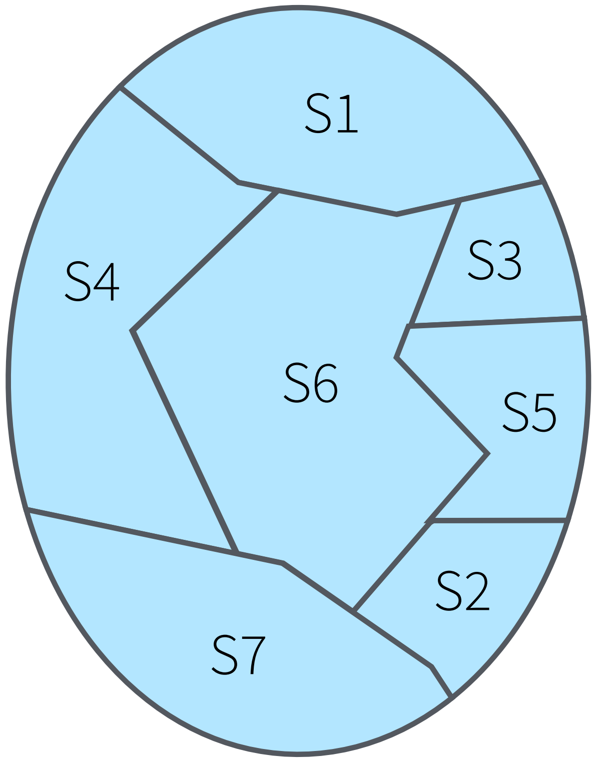


Global search

Local search

Local search

Local search



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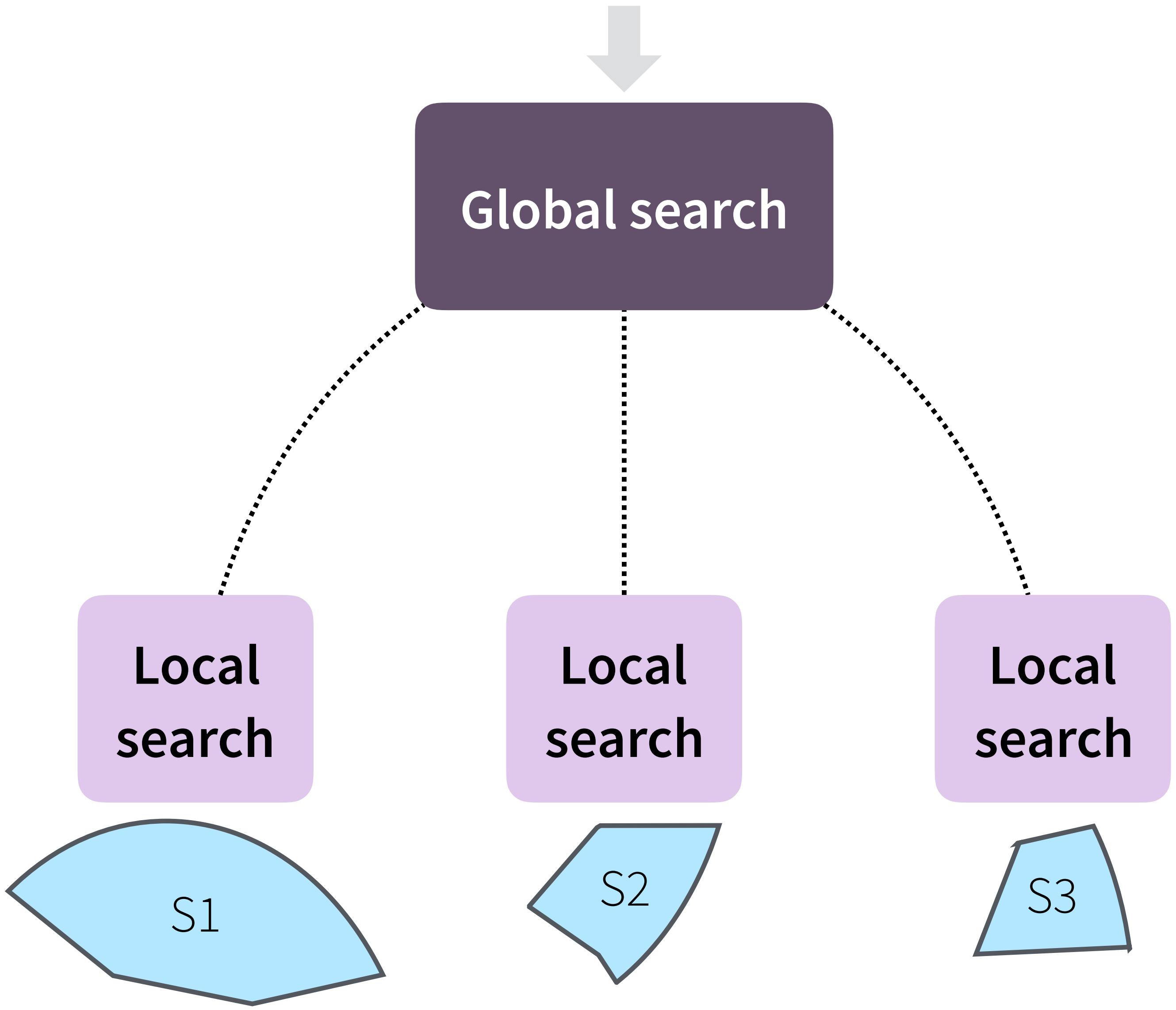
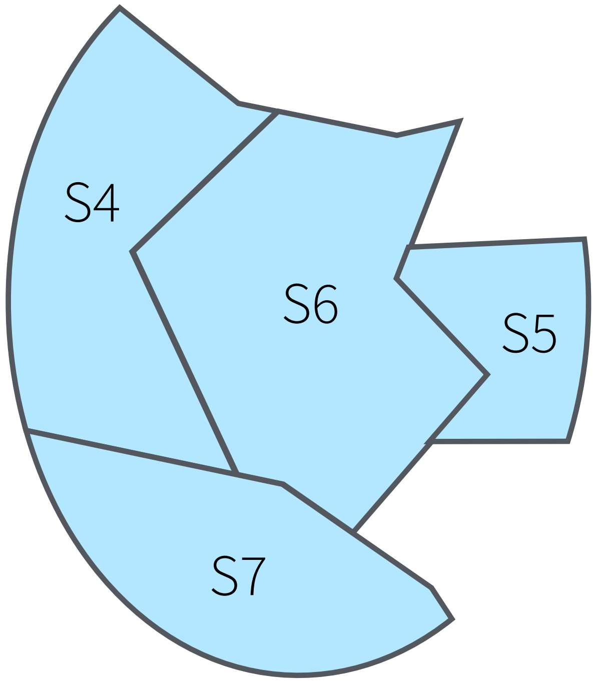


Global search

Local search

Local search

Local search



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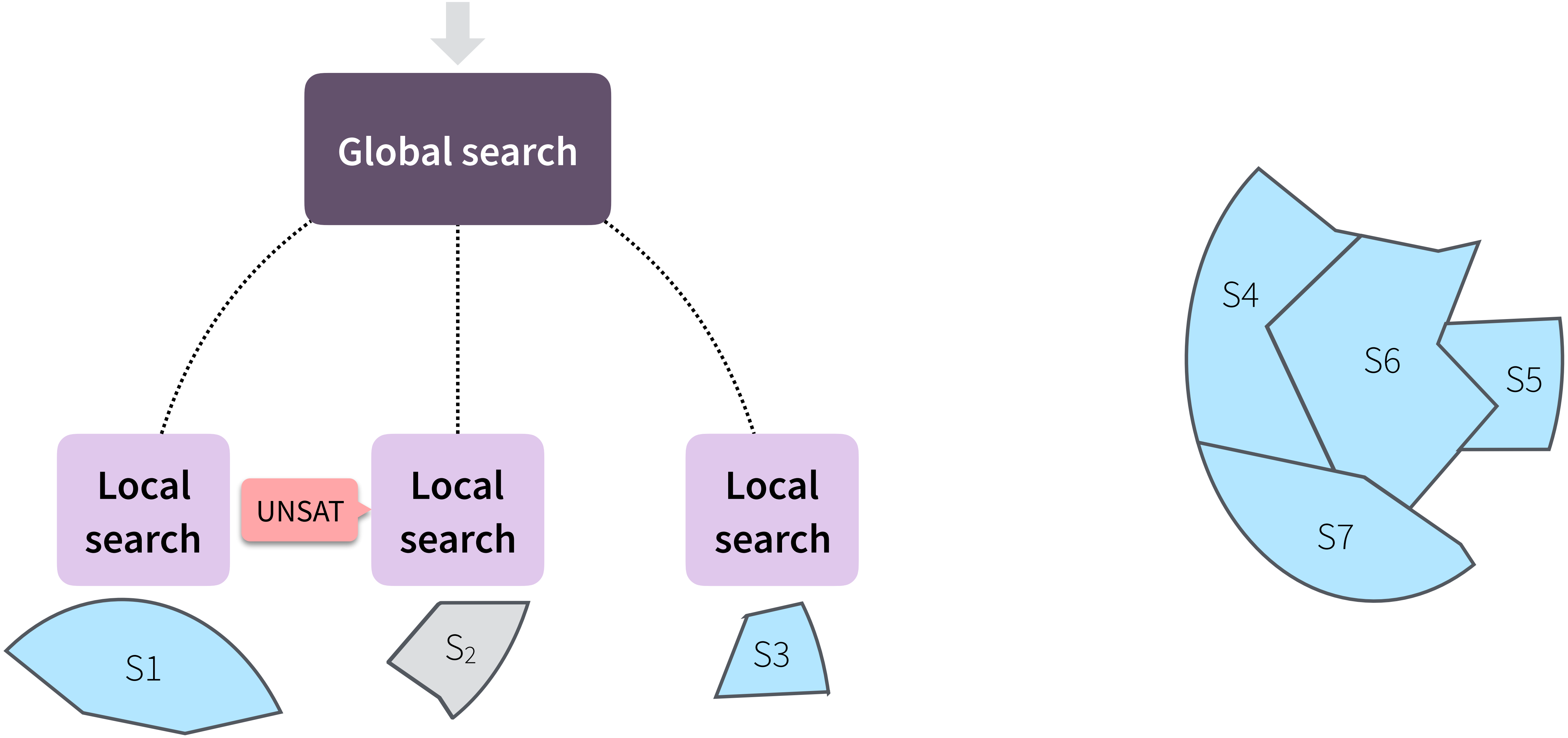

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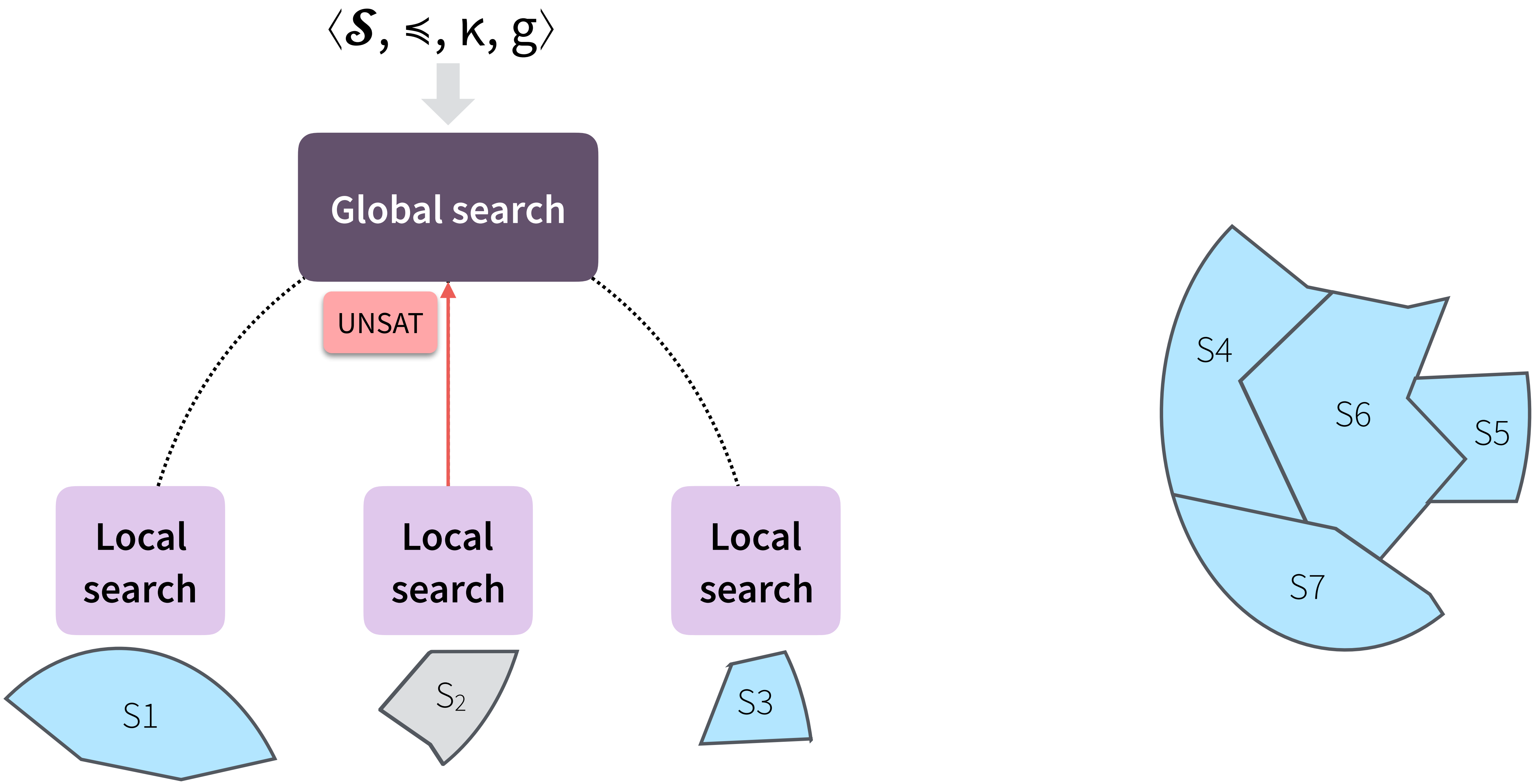

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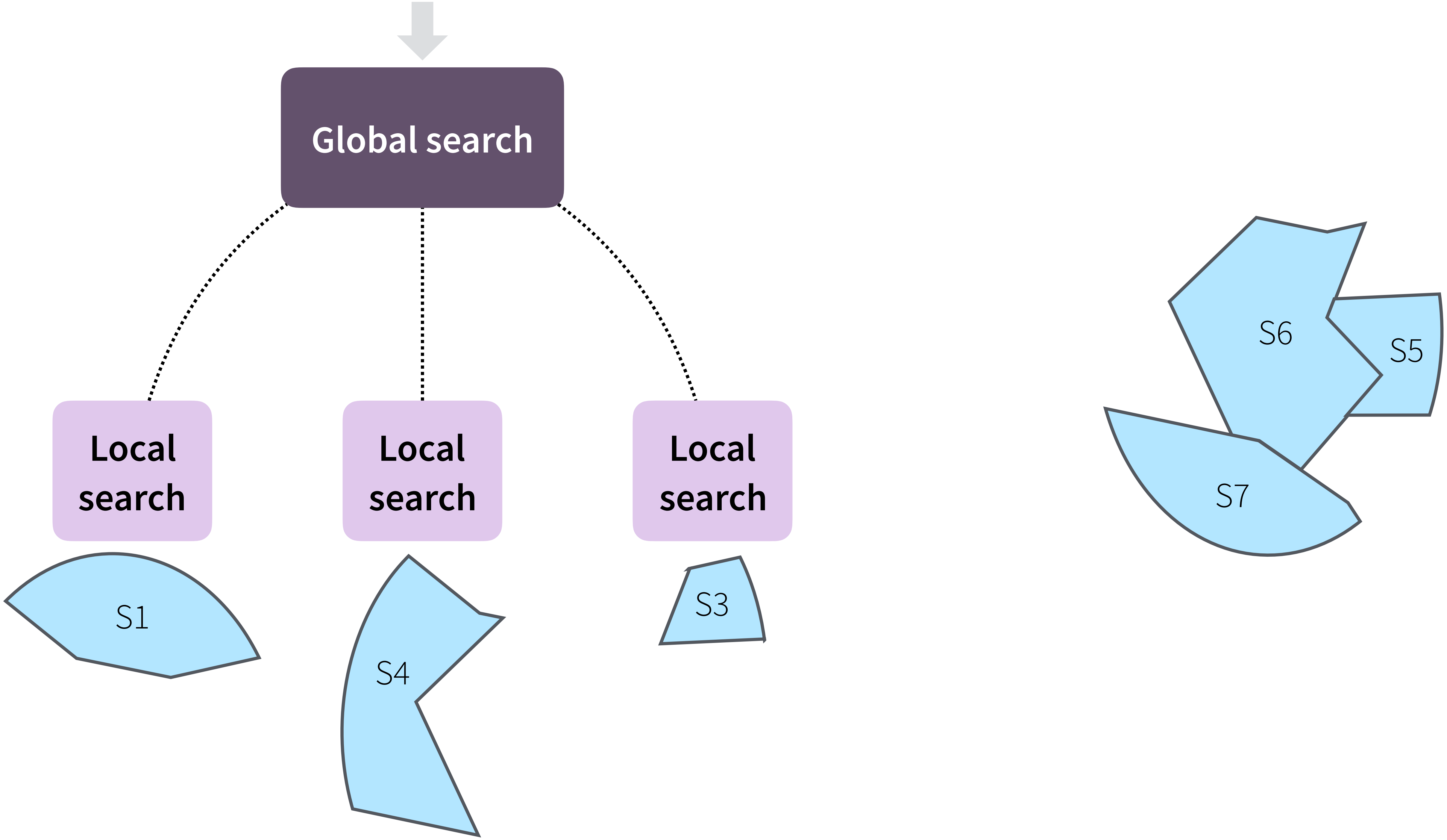

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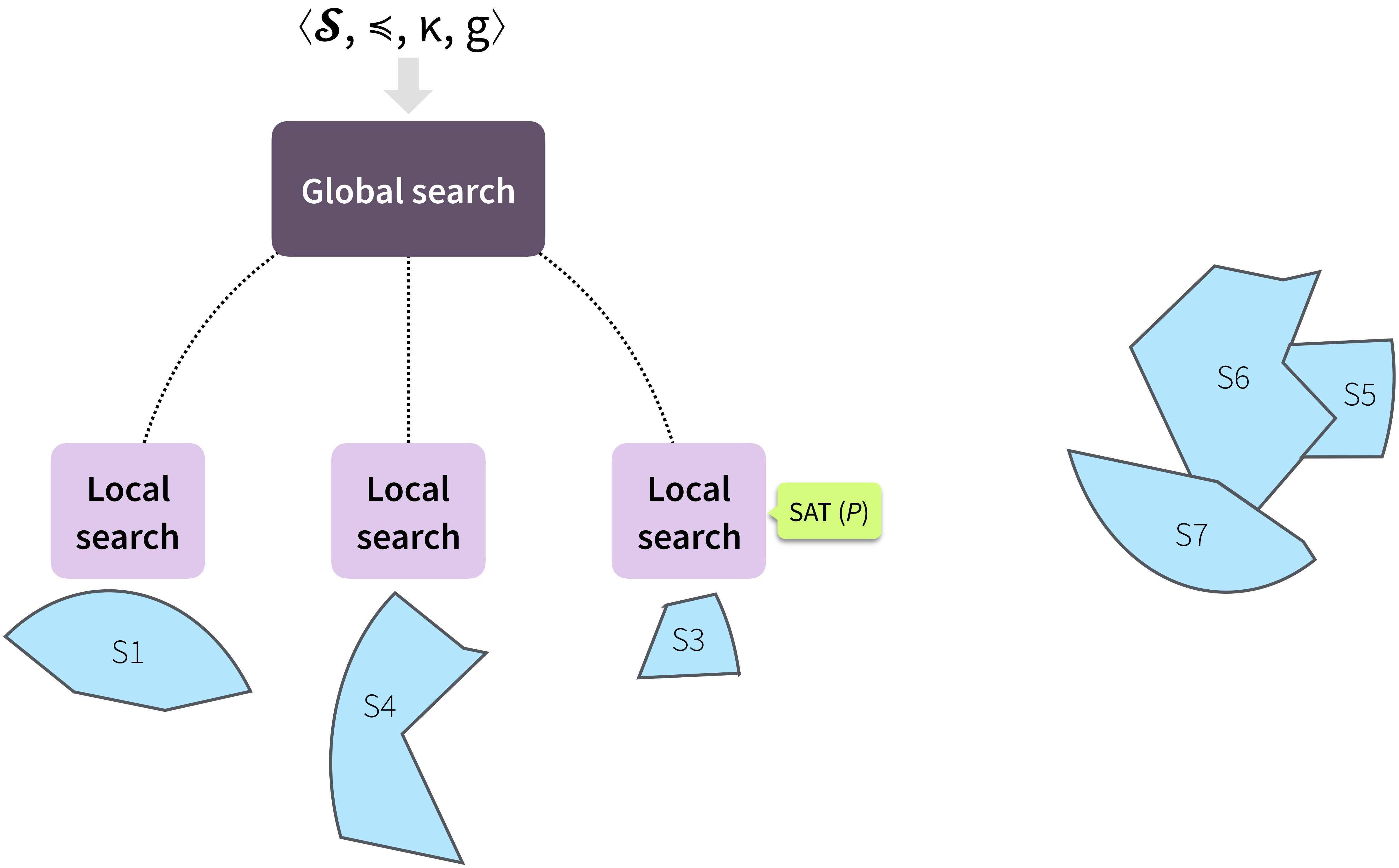


$\langle \mathcal{S}, \preccurlyeq, \kappa, g \rangle$

Global search

Local search

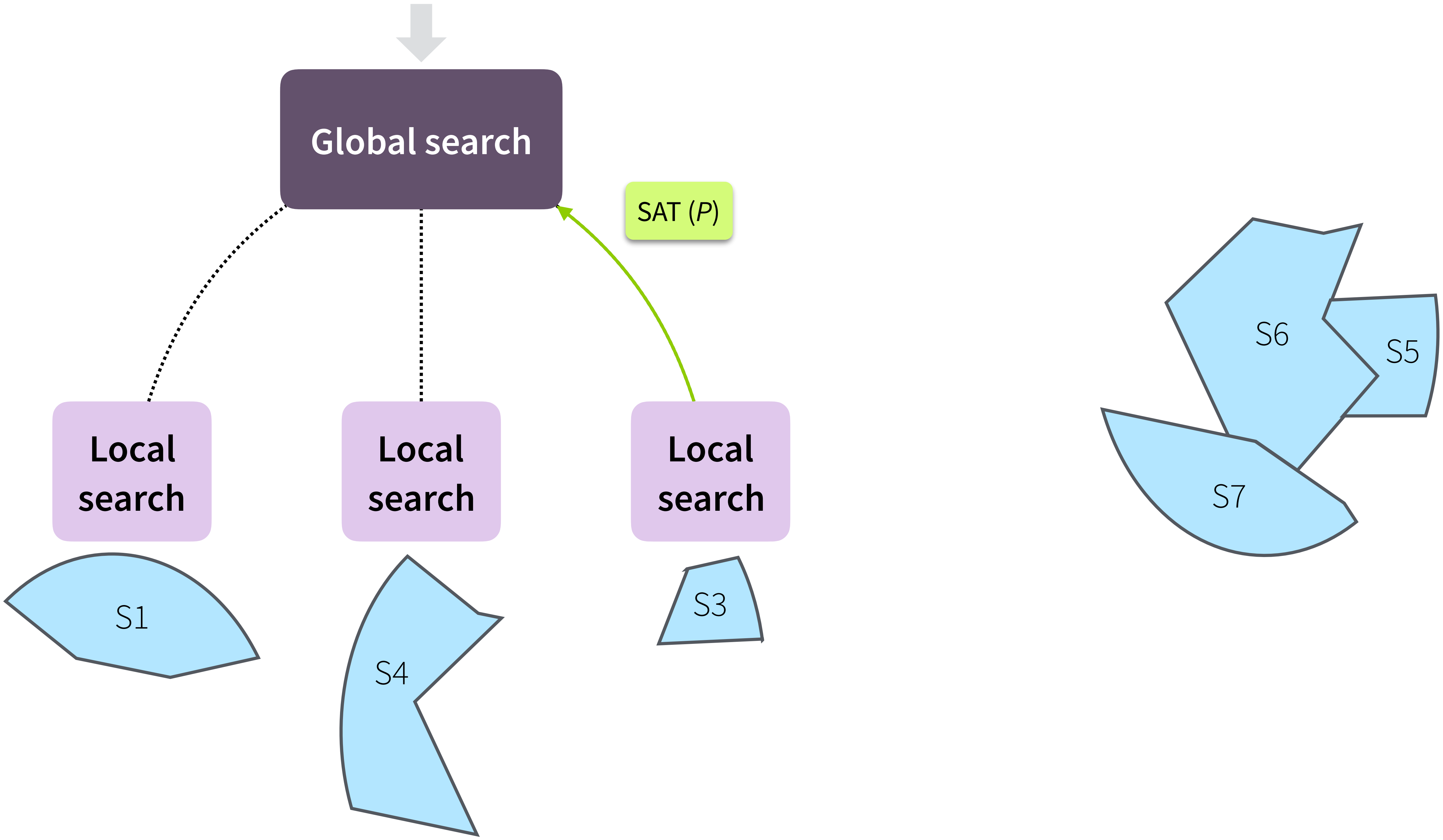
Local search

Local search

SAT (*P*)

Solving with two cooperative searches

$\langle \mathcal{S}, \preccurlyeq, \kappa, g \rangle$



Global search

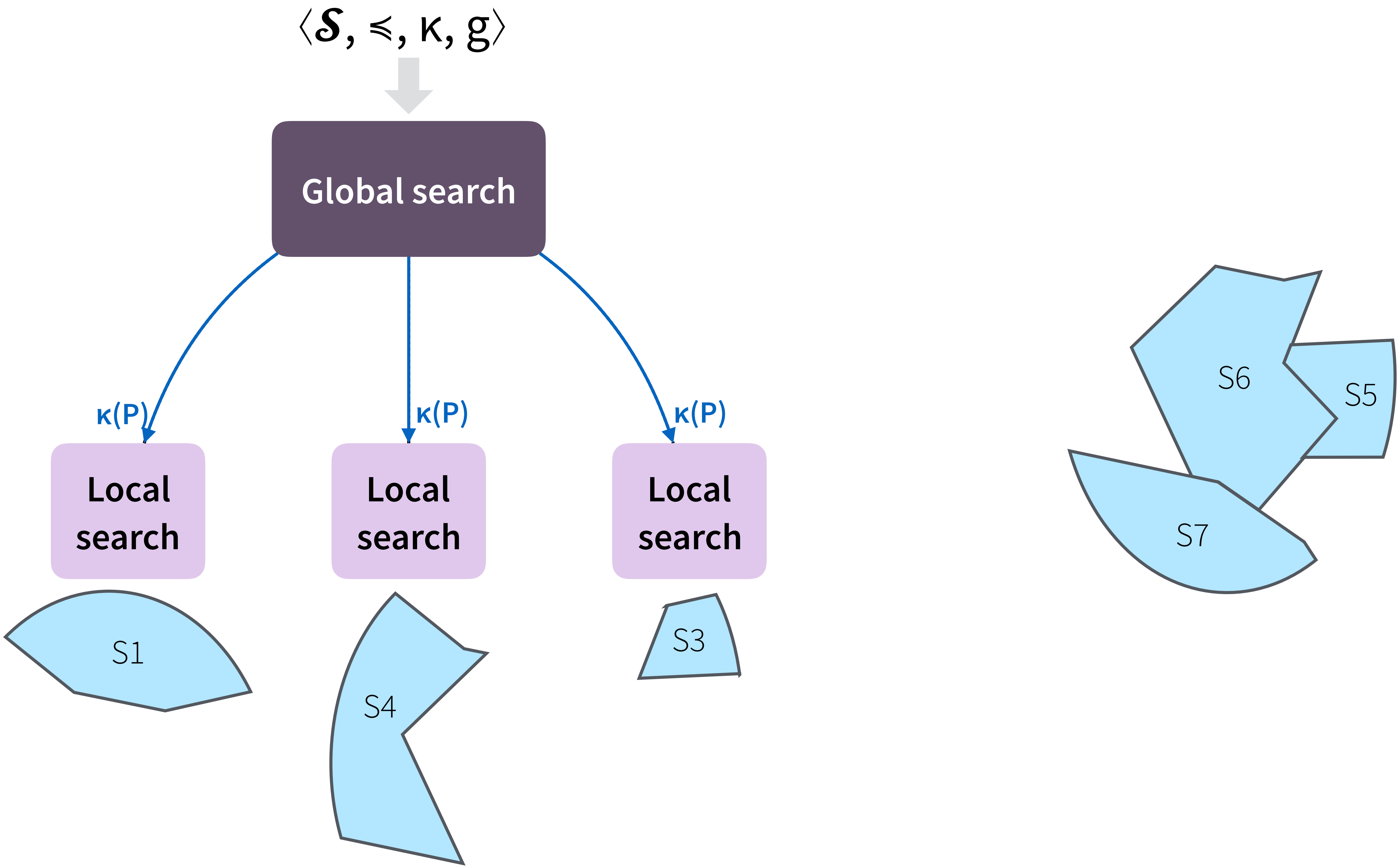
SAT (*P*)

Local search

Local search

Local search

Solving with two cooperative searches



$\langle \boldsymbol{\mathcal{S}}, \preccurlyeq, \kappa, g \rangle$

Global search

$\kappa(P)$

$\kappa(P)$

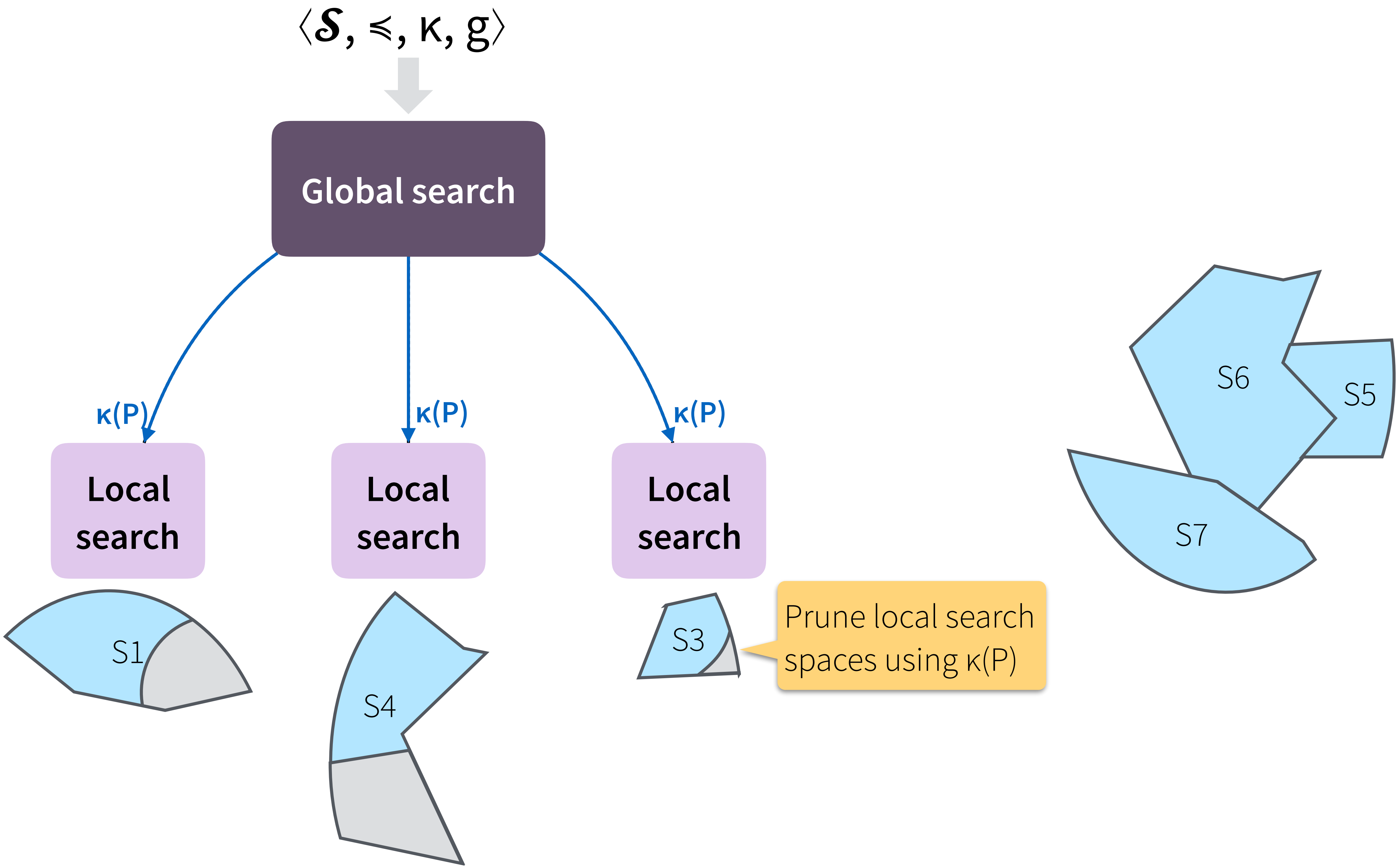
$\kappa(P)$

Local search

Local search

Local search

Solving with two cooperative searches



$\langle \mathcal{S}, \preccurlyeq, \kappa, g \rangle$

Global search

κ(P)

κ(P)

κ(P)

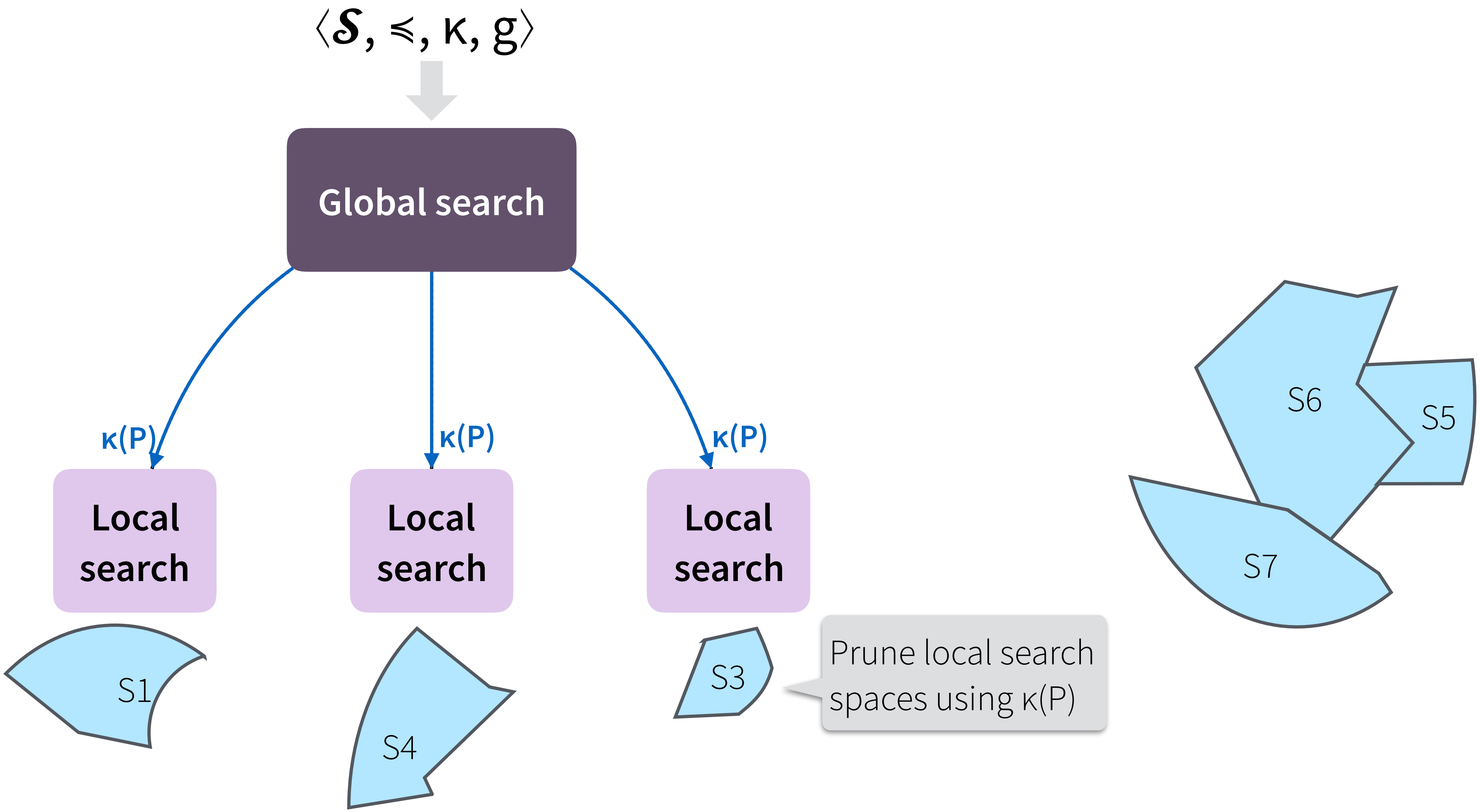
Local search

Local search

Local search

Prune local search spaces using κ(P)

Solving with two cooperative searches



$\langle \mathcal{S}, \preccurlyeq, \kappa, g \rangle$

Global search

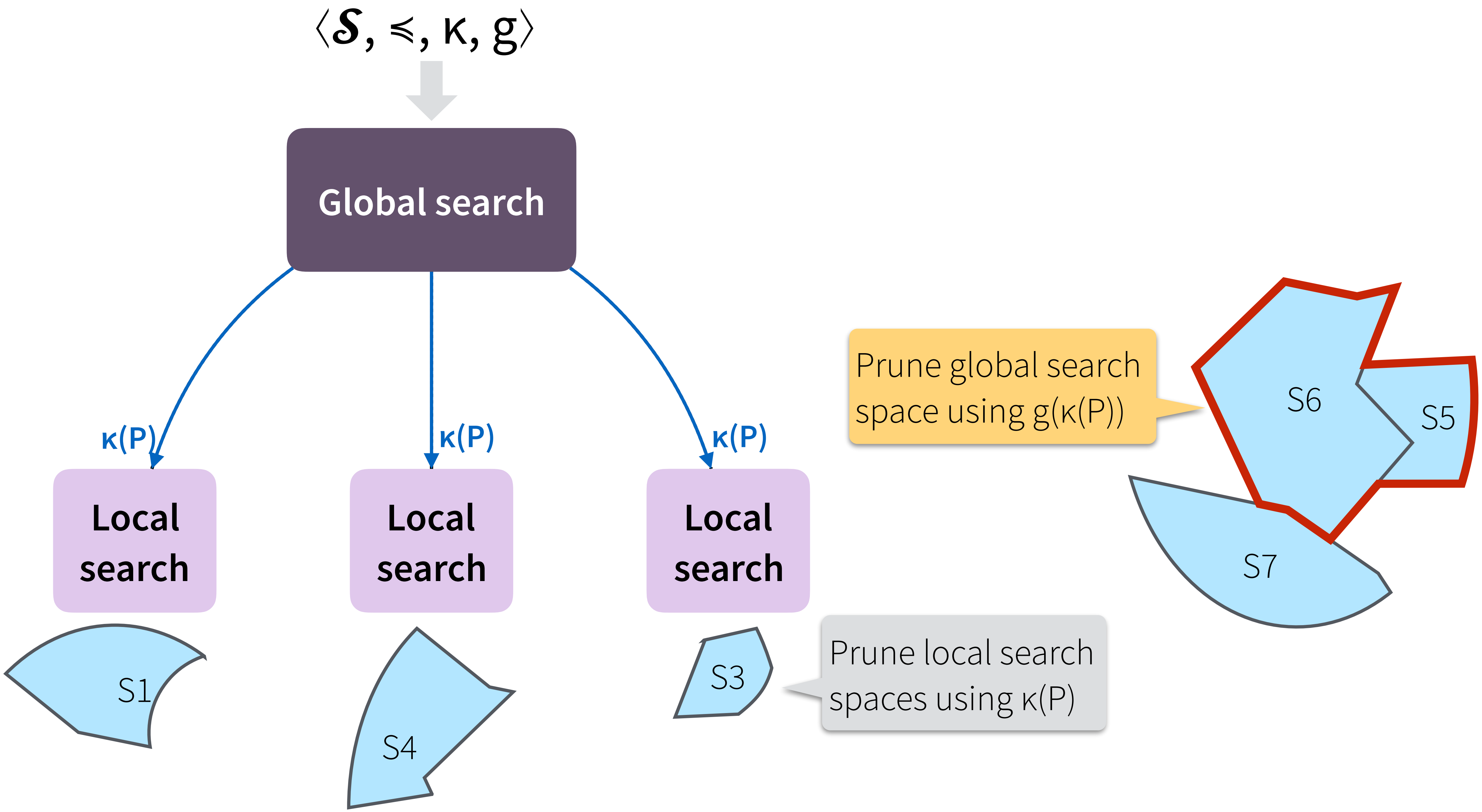
Local search

Local search

Local search

Prune local search spaces using κ(P)

Solving with two cooperative searches

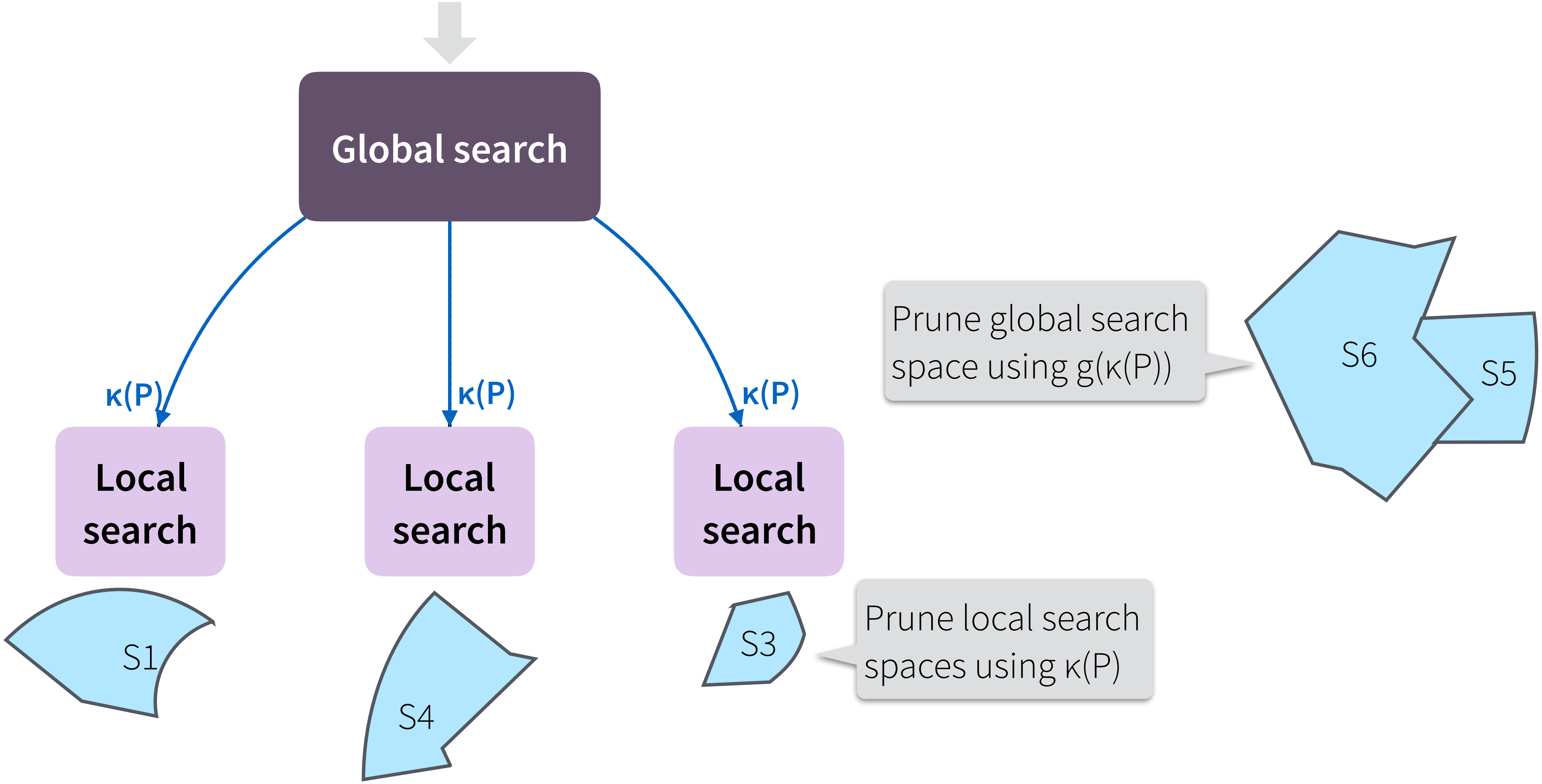


Prune global search space using g(κ(P))

Prune local search spaces using κ(P)

Solving with two cooperative searches

$\langle \mathcal{S}, \preccurlyeq, \kappa, g \rangle$



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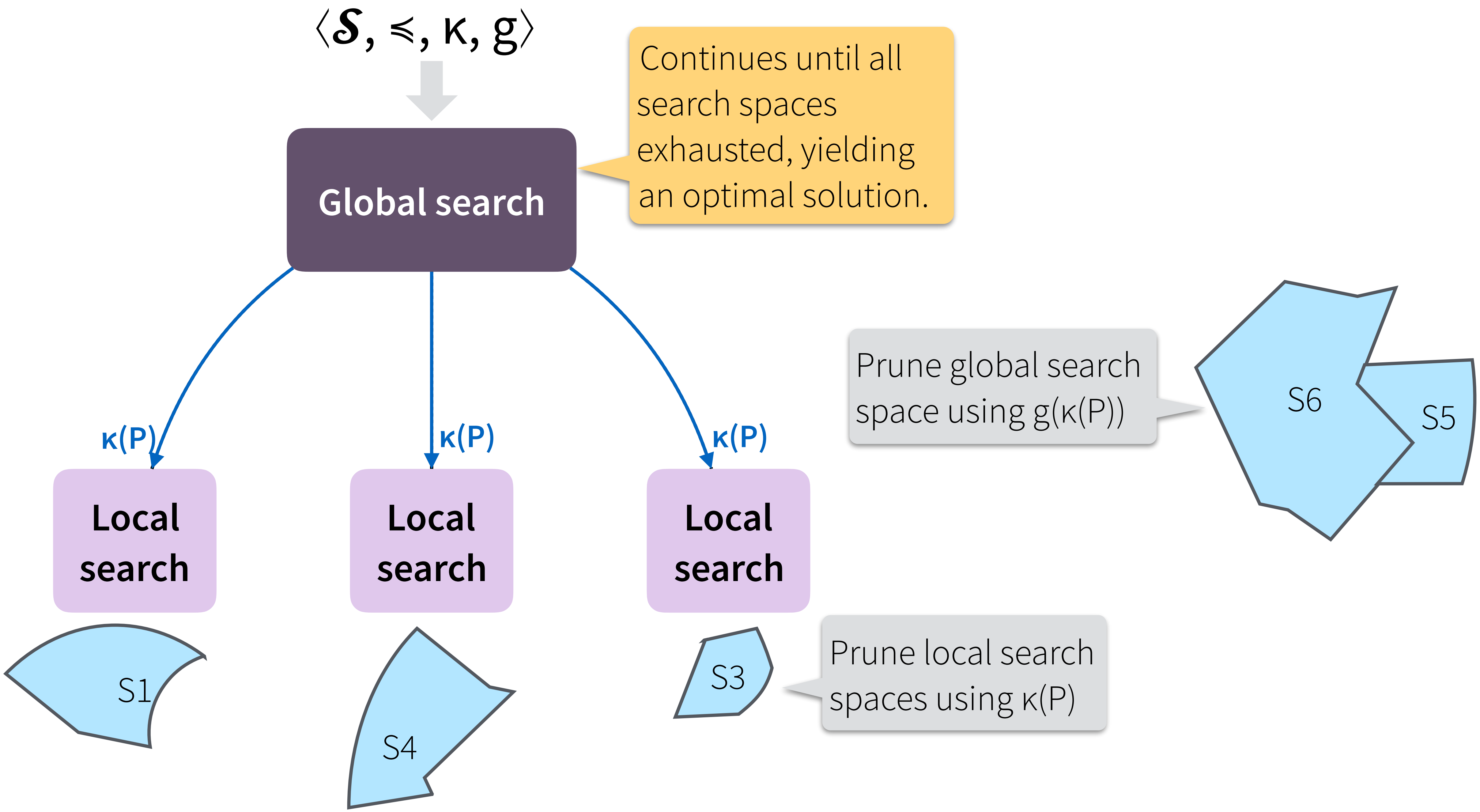

$\langle \mathcal{S}, \preccurlyeq, \kappa, g \rangle$

Global search

Continues until all search spaces exhausted, yielding an optimal solution.

κ(P)

Local search

Local search

Local search

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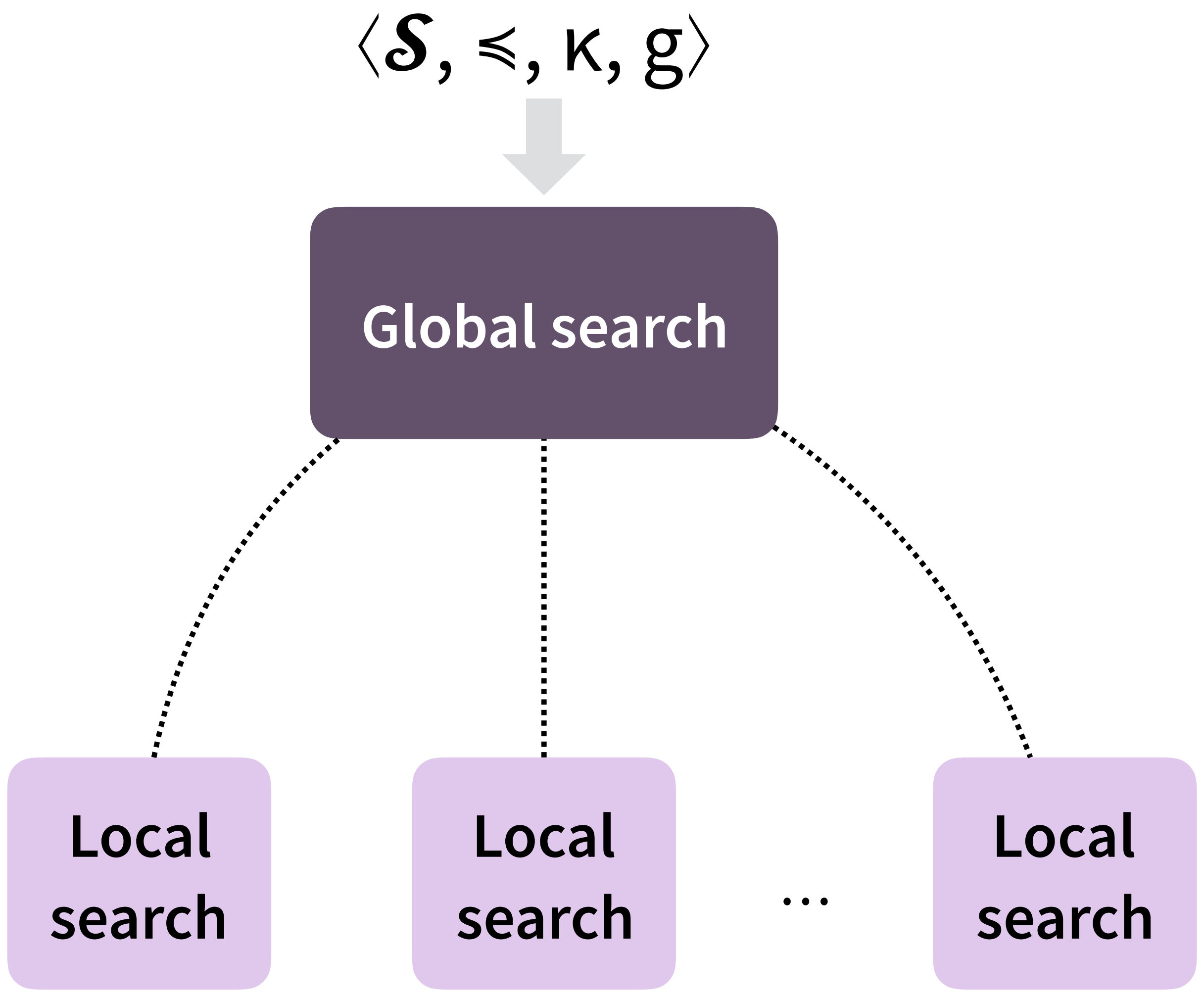
Synapse implementation



Implemented in Rosette, a solver-aided extension of Racket

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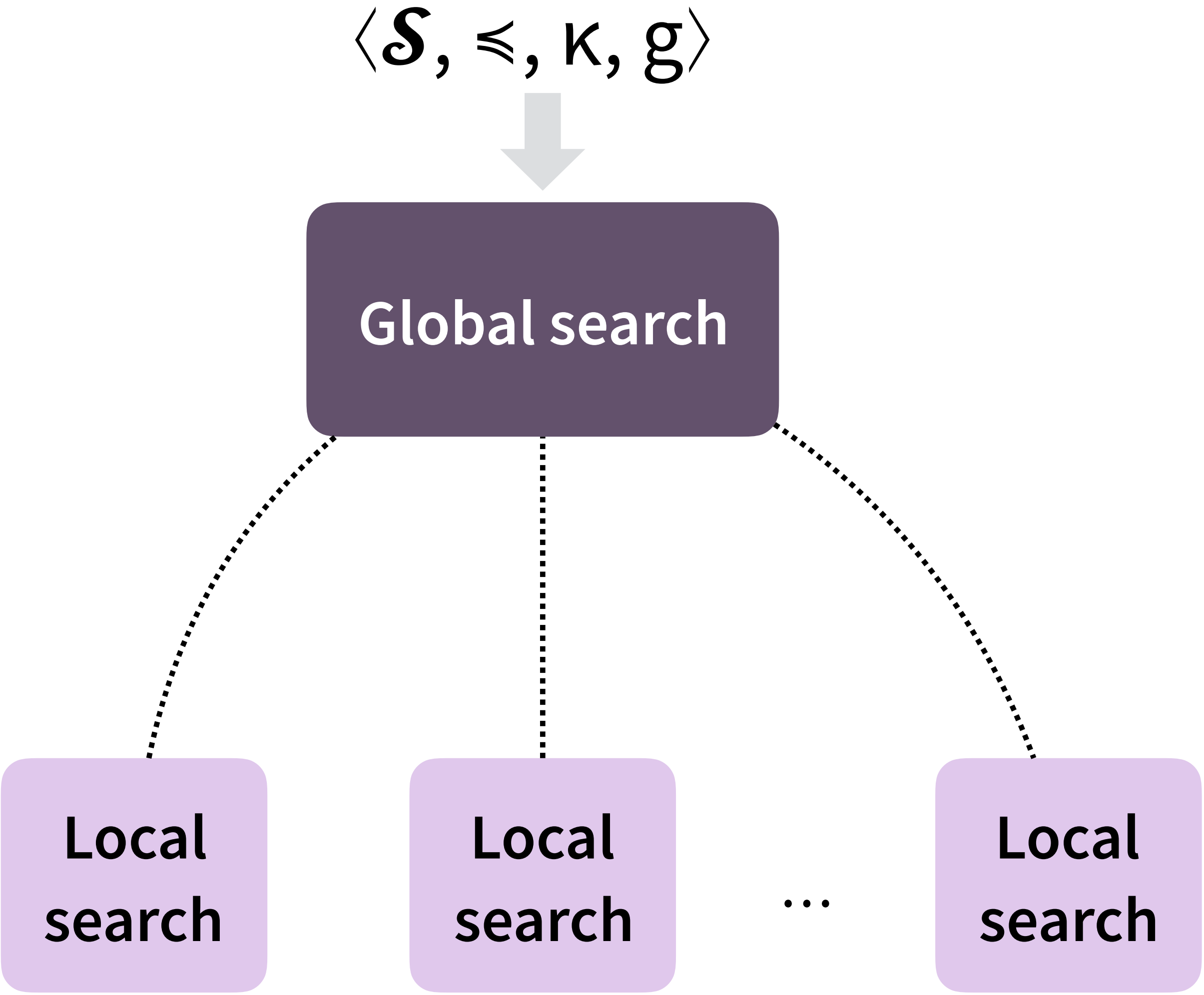

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Local CEGIS searches can share counterexamples

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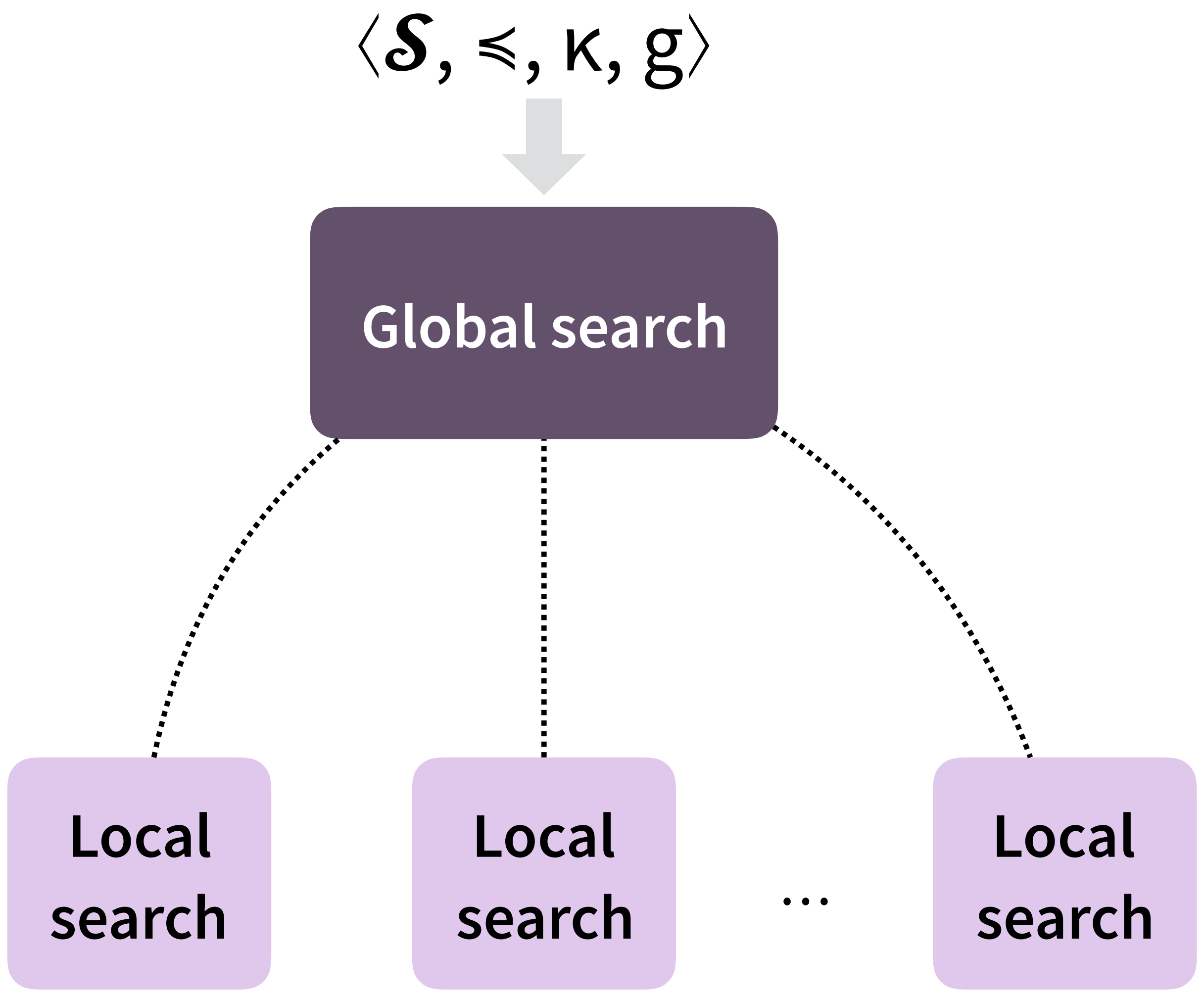

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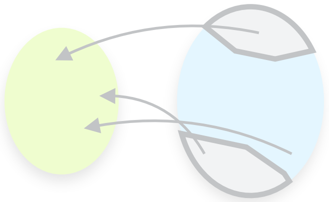
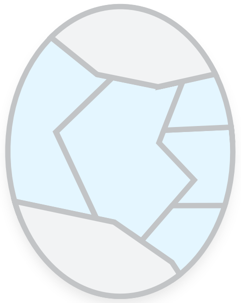
Local CEGIS searches can share counterexamples

Local searches can time out, which weakens optimality



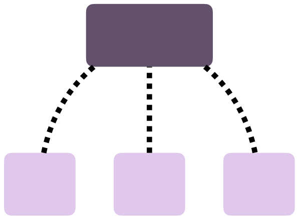
Background

Syntax-guided synthesis



Metasketches

Design and structure

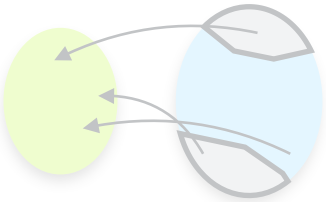


Synapse

A metasketch solver

Results

Better solutions, faster



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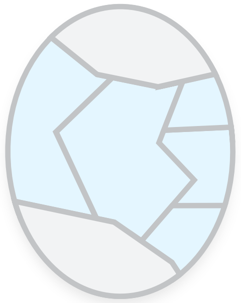

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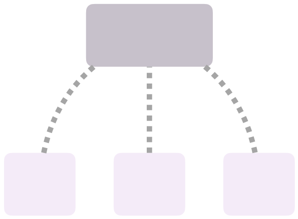

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Evaluation questions

Is Synapse a practical approach to solving different kinds of synthesis problems?

- Approximate computing, array programs

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Evaluation questions

Is Synapse a practical approach to solving different kinds of synthesis problems?

Approximate computing, array programs

Can Synapse reason about complex cost functions?

In the paper:

- Parallel speedup
- Optimizations (structure constraints, sharing)
- More kinds of problems
- More complex cost functions

Synapse solves previously-intractable problems

Parrot benchmarks from approximate computing [Esmaelizadeh et al., 2012]

Find the most efficient approximate program within an error bound

Synapse solves previously-intractable problems

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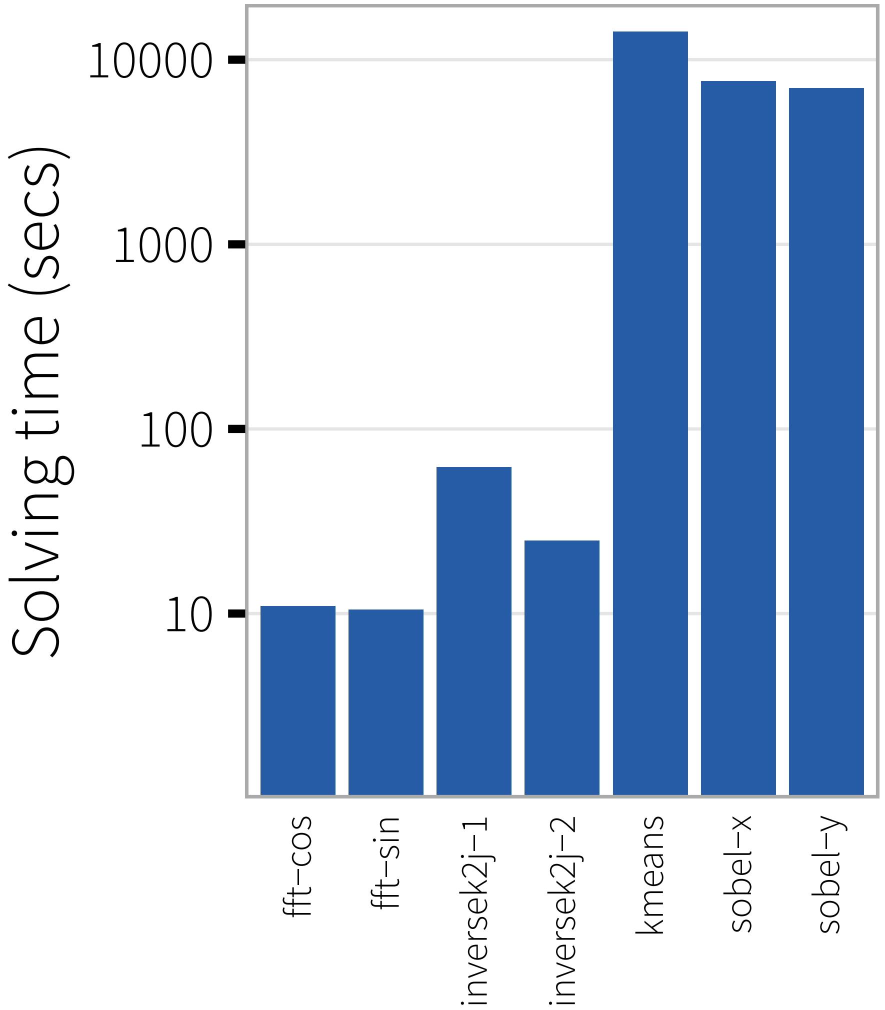

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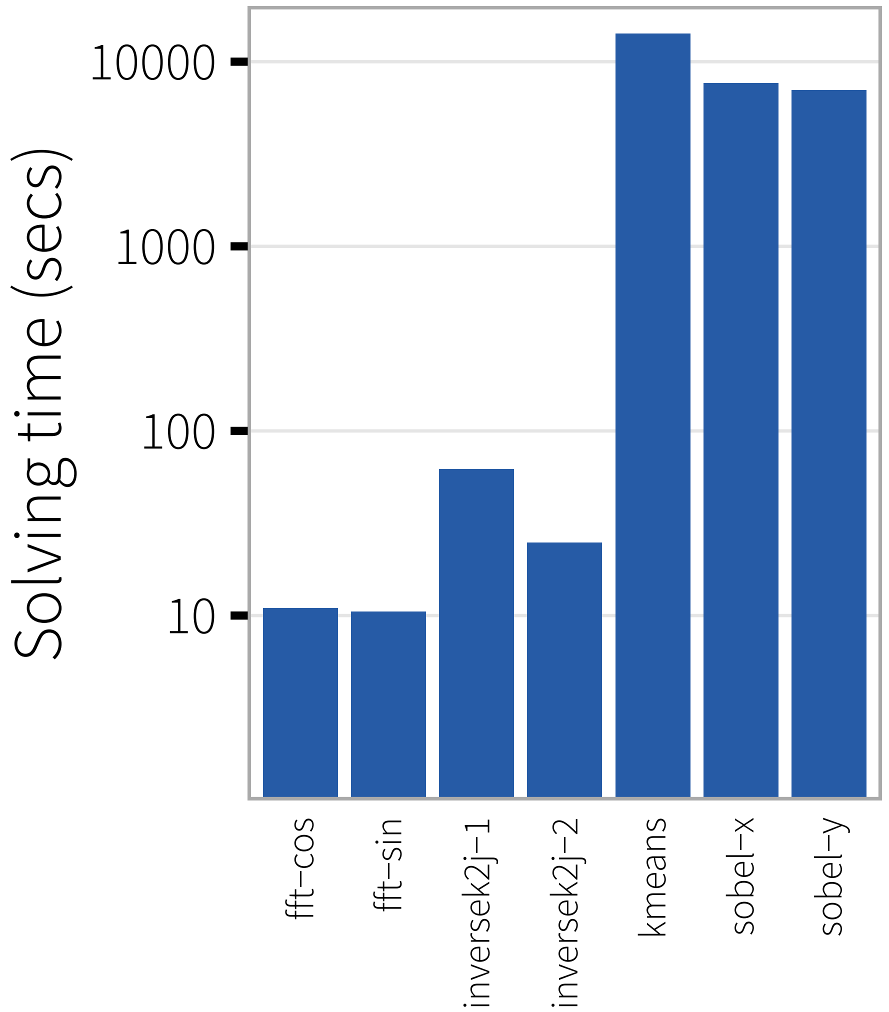

All intractable to Sketch and Stoke

Synapse solves standard benchmarks optimally

Array Search benchmarks from the syntax-guided synthesis (SyGuS) competition [Alur et al., 2015]

arraysearch-*n*: find program that searches lists of length *n*

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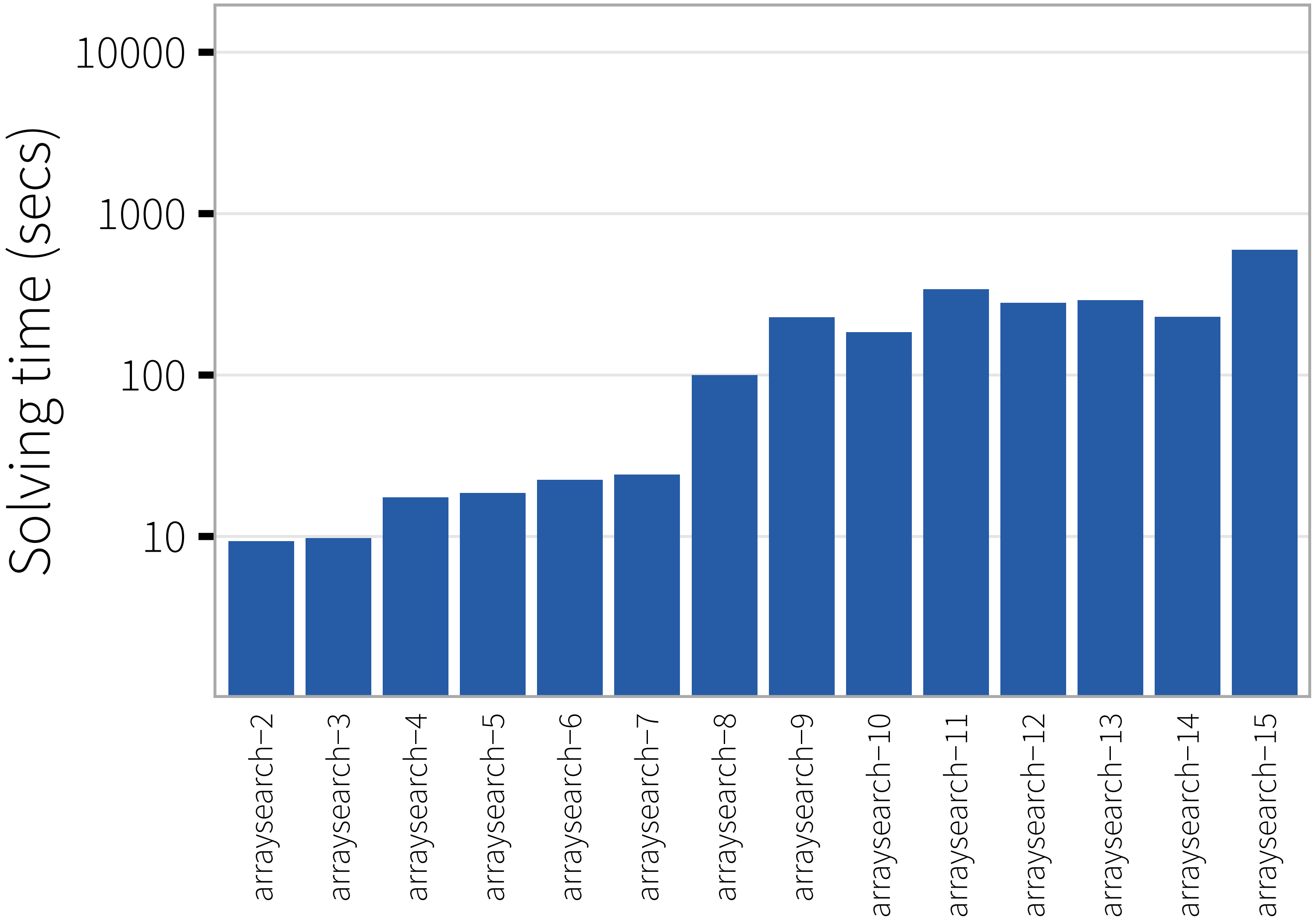

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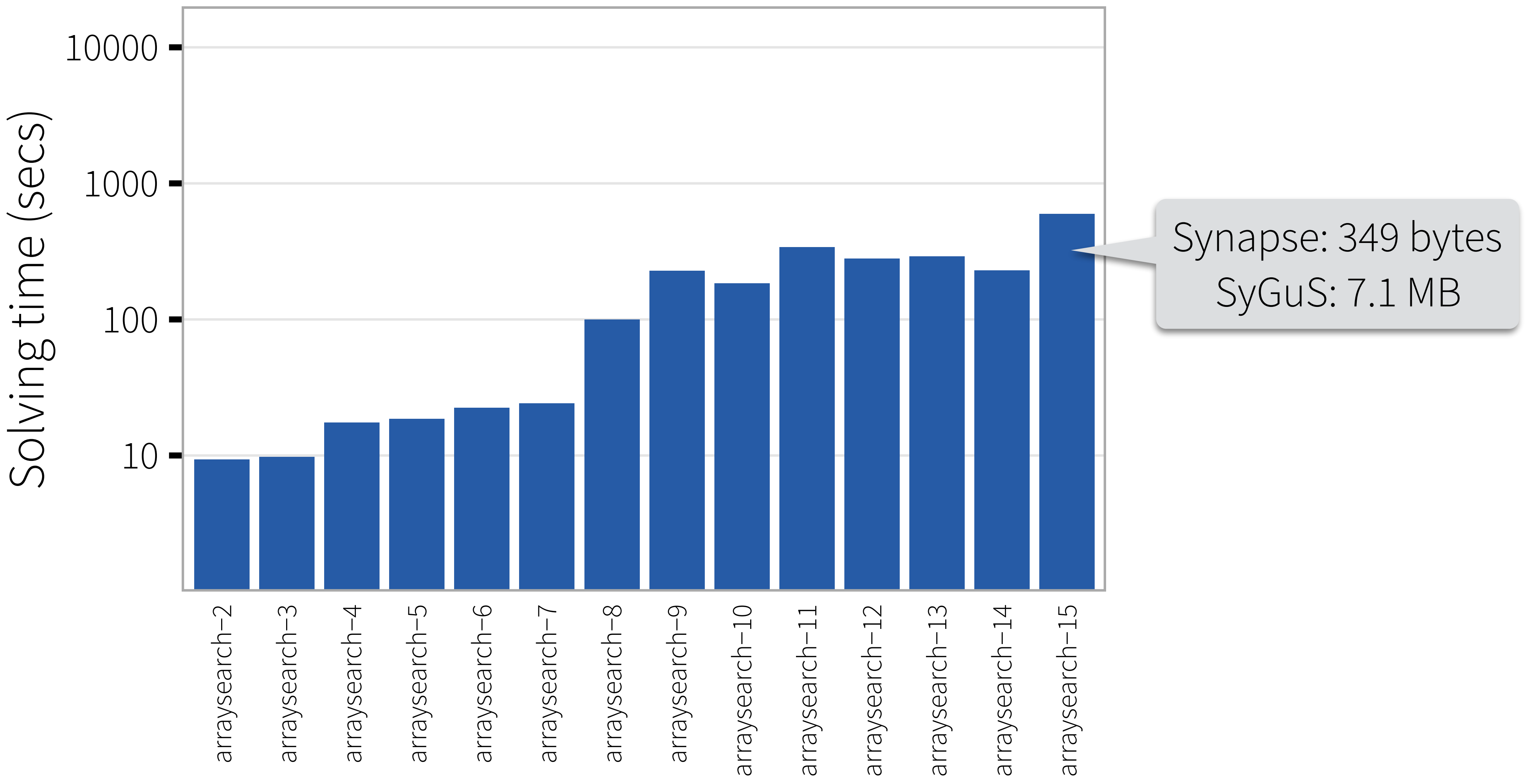
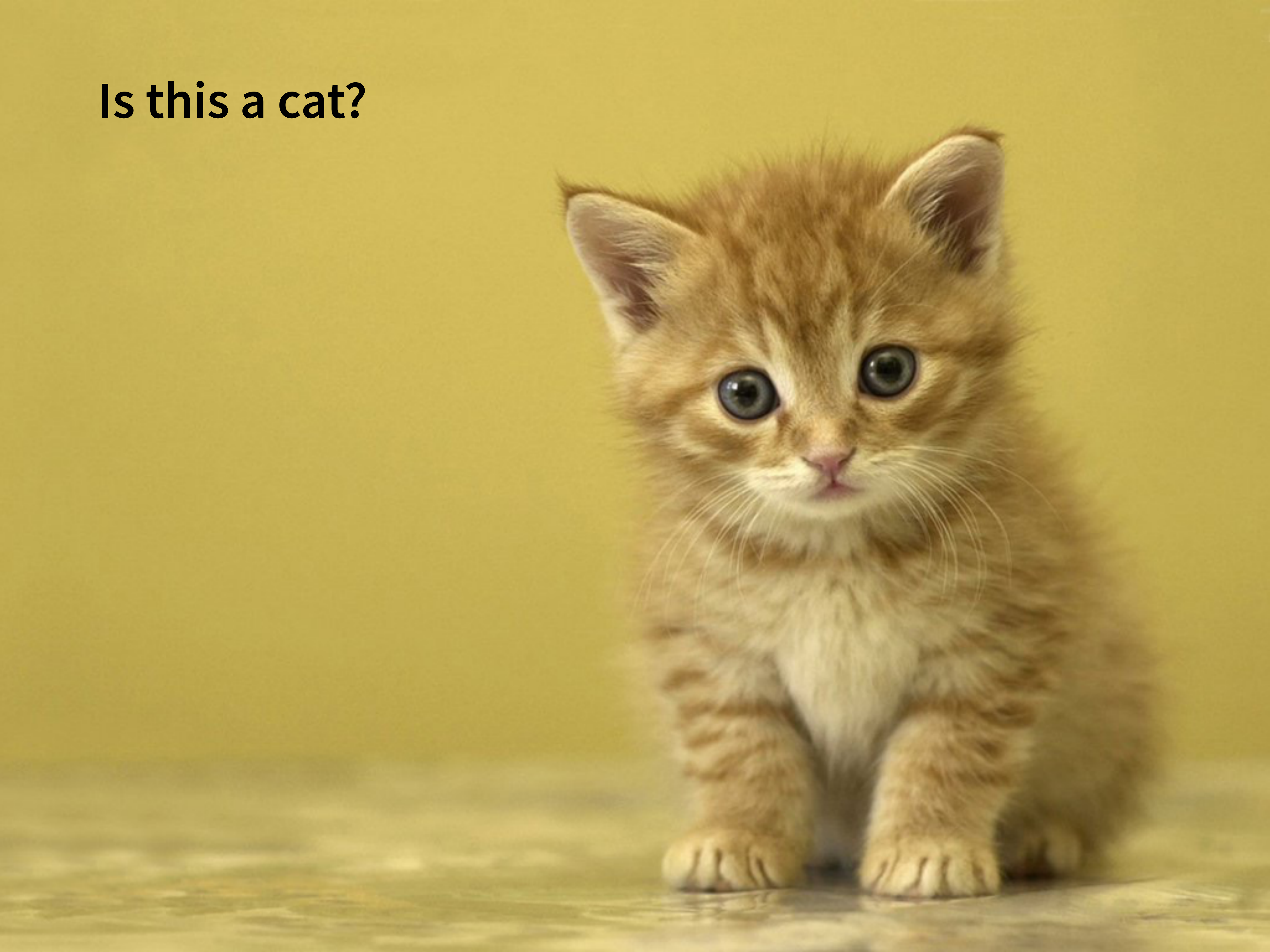
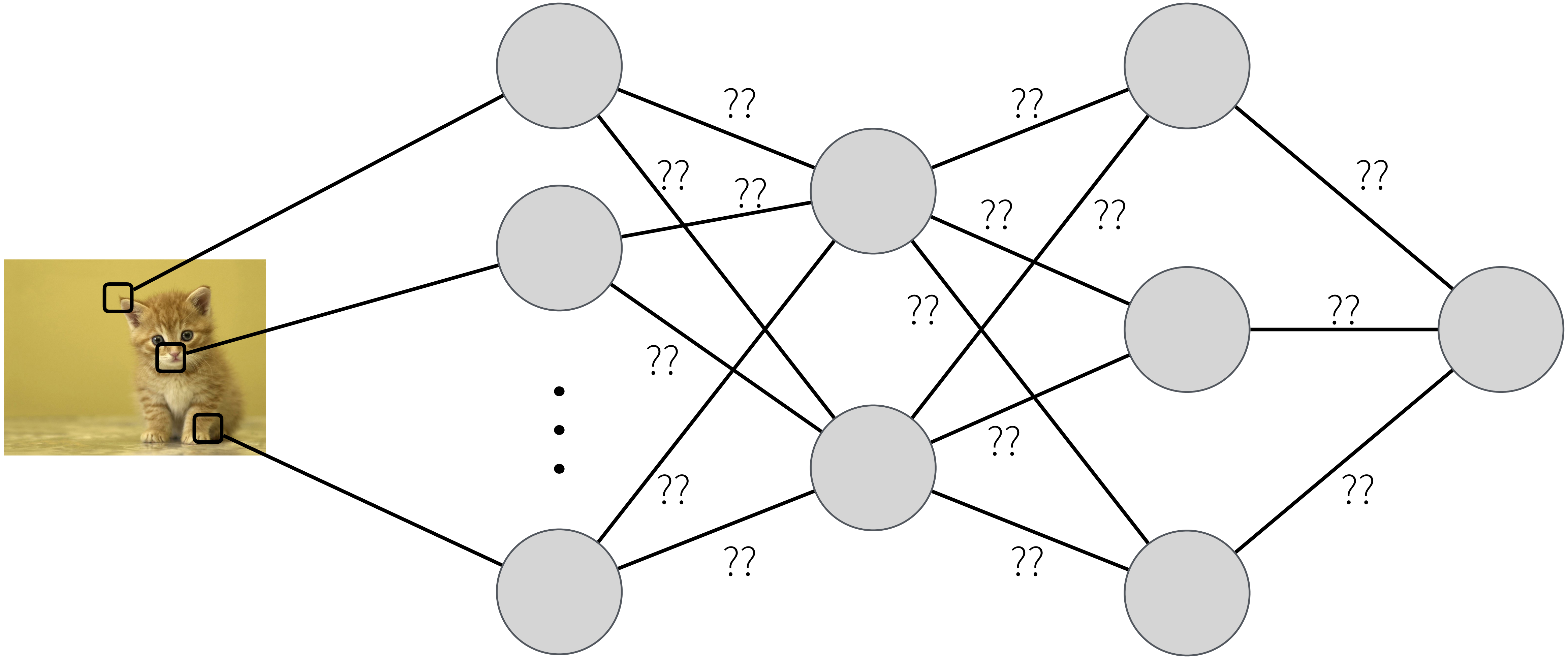


Synapse: 349 bytes
SyGuS: 7.1 MB

Is this a cat?



Synapse reasons about complex costs



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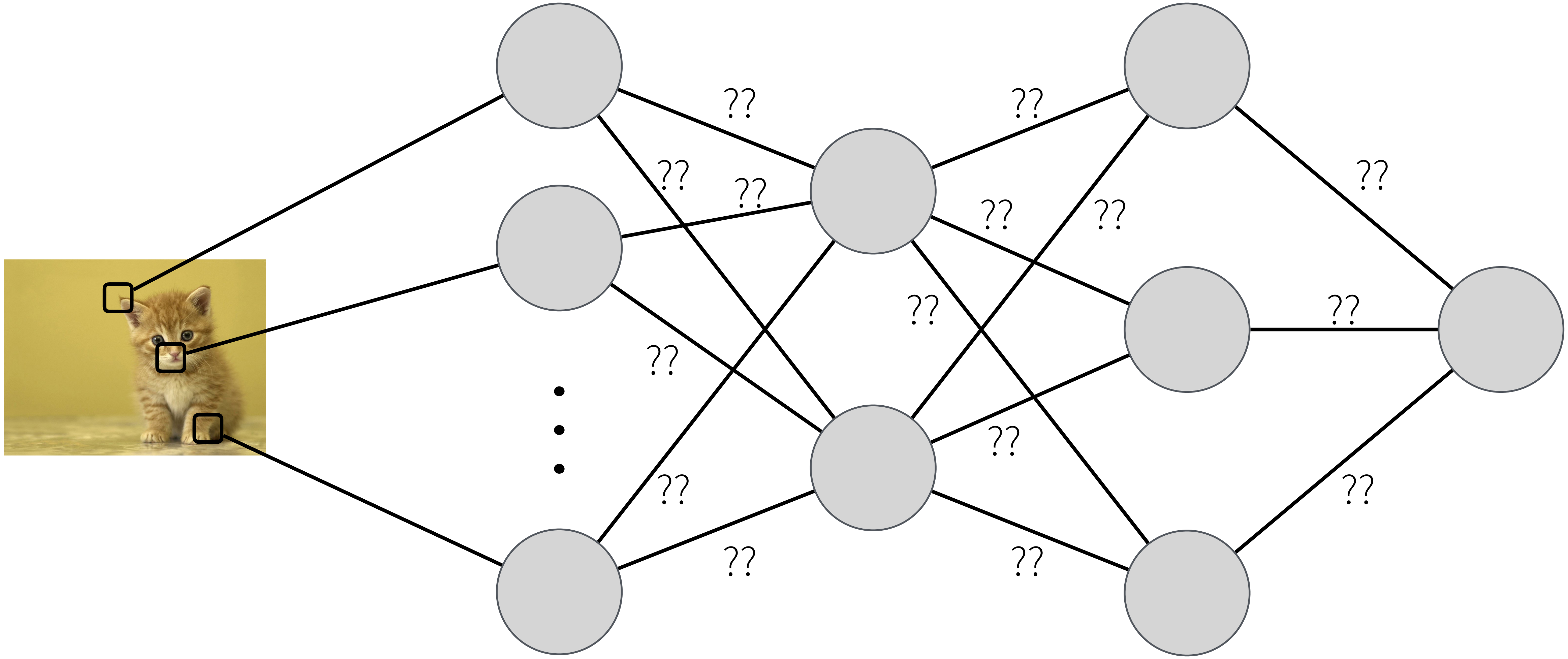

$$\kappa(P) = \sum_i |P(x_i) - y_i|$$

Classification error executes the program for each point in the training set

Metasketches

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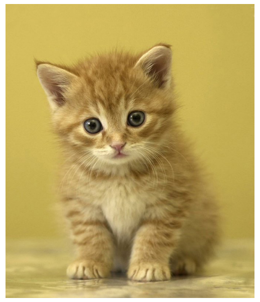

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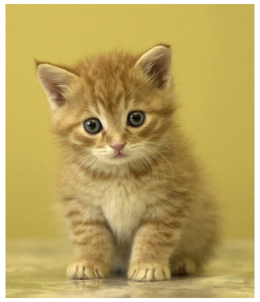
`synapse.uwplse.org`



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