# Program Synthesis in the Industrial World: Inductive, Incremental, Interactive

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# PROgram Synthesis using Examples

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R&D team, MSR → industrial Microsoft

We are hiring! Interns or full-time ☺

# This talk

# Outline

- Programming by Examples (PBE) & PROSE: Quick Background
- Mass-Market Deployment
  - ↪ Goals
    - ↪ Challenges
      - ↪ Solutions
- Discussion

# PBE & PROSE

A 3-slide Background

# Motivation

**99% of spreadsheet users do not know programming**


**Data scientists spend 80% time wrangling raw data**

# PROSE Timeline




**FlashFill** (text transformations) 2010-2012 [POPL 11]

**FlashExtract** (text extraction) 2012-2014 [PLDI 14]

**FlashRelate** (table transformations) 2012-2015 [PLDI 15]

… **FlashMeta** (PBE framework) 2014-2015 [OOPSLA 15]

**PROSE SDK** 2015-present

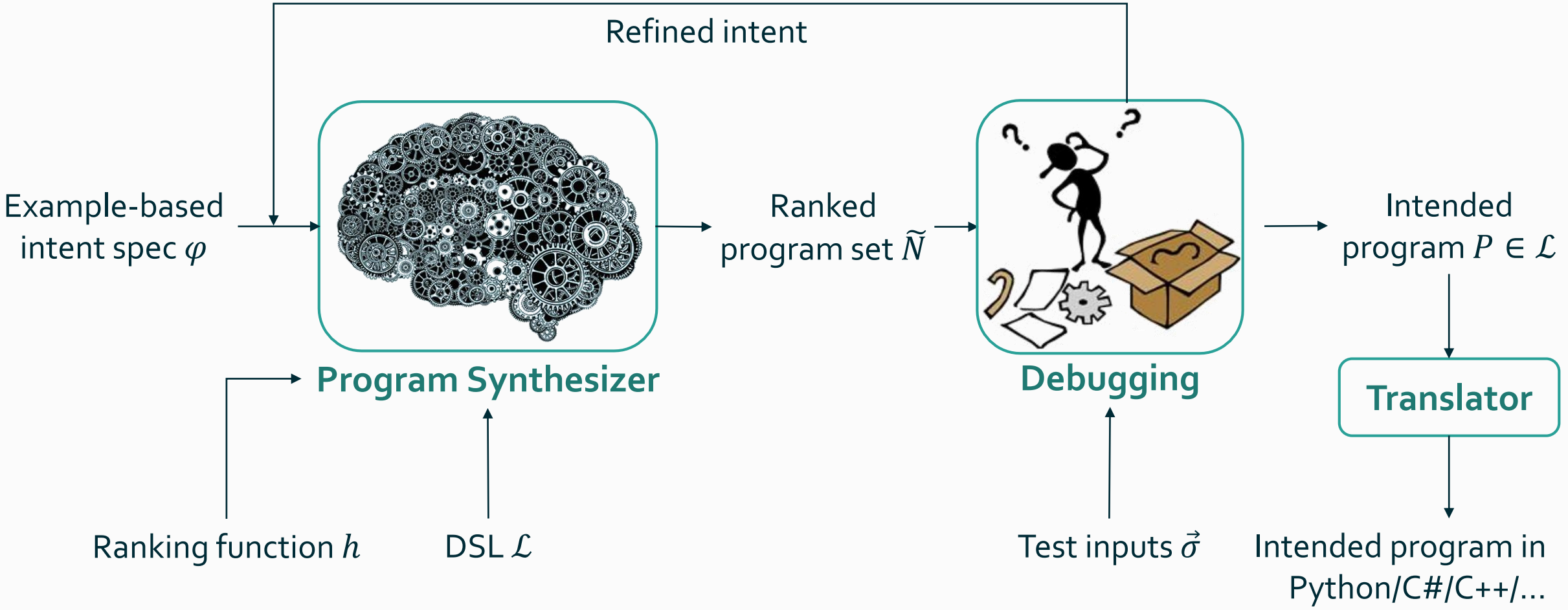
Excel

Exchange

Convert-String,
ConvertFrom-String

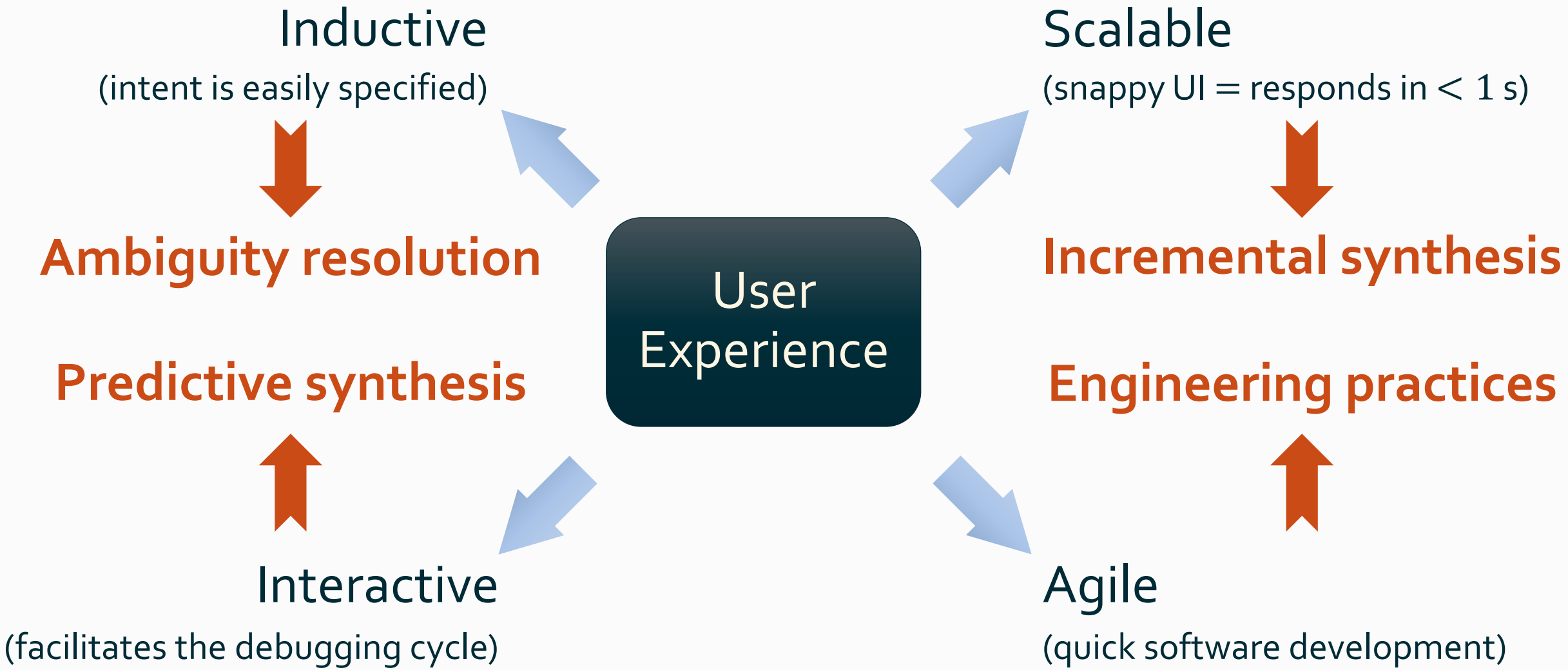
Microsoft Log Analytics

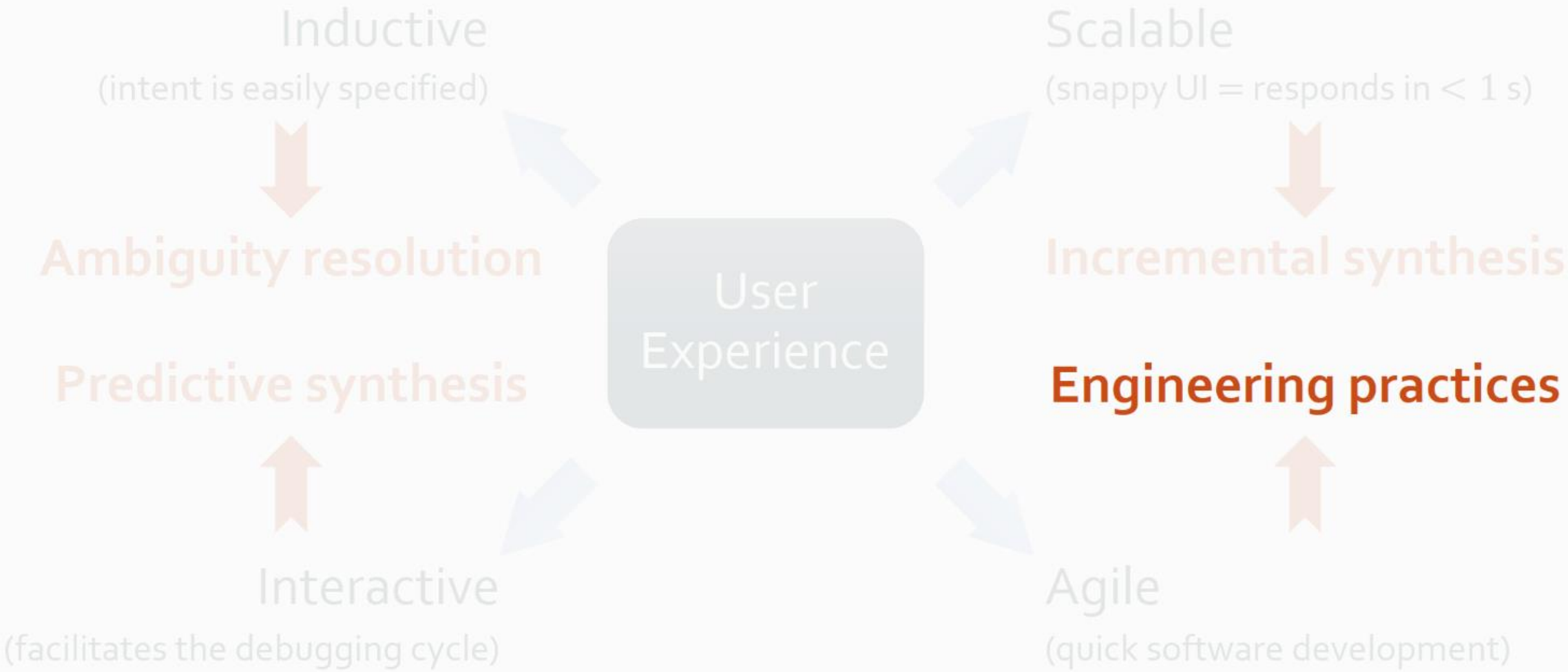
# PBE Architecture



# Mass-Market Deployment

Goals & Challenges


Inductive
(intent is easily specified)
Ambiguity resolution
Predictive synthesis
Interactive
(facilitates the debugging cycle)
Scalable
(snappy UI = responds in < 1 s)
Incremental synthesis
Engineering practices
Agile
(quick software development)
User Experience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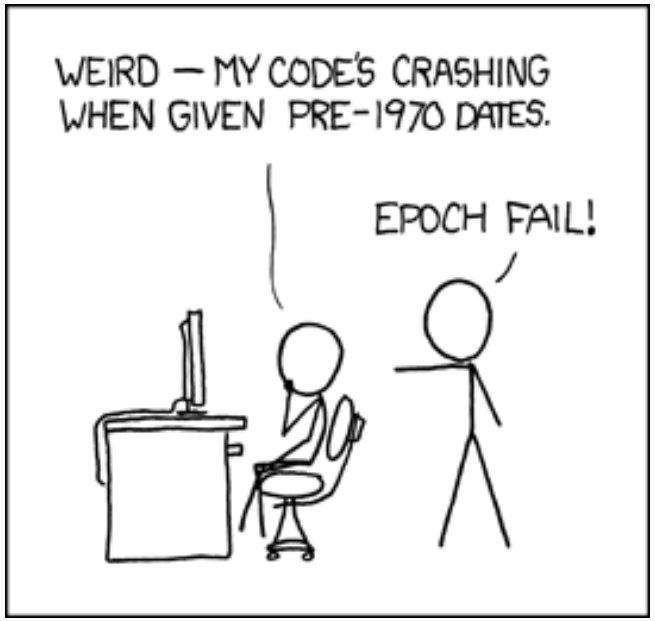
# Engineering practices




- Production-quality library code
  - Prototyping still exists, but it's not the final form
- Unit tests & TDD
- Integration tests: real-life scenarios
  - Close to 8K for all DSLs in total
  - Most are mined from *public* sources (e.g. help forums)
  - In preparation: benchmark suite release for the community

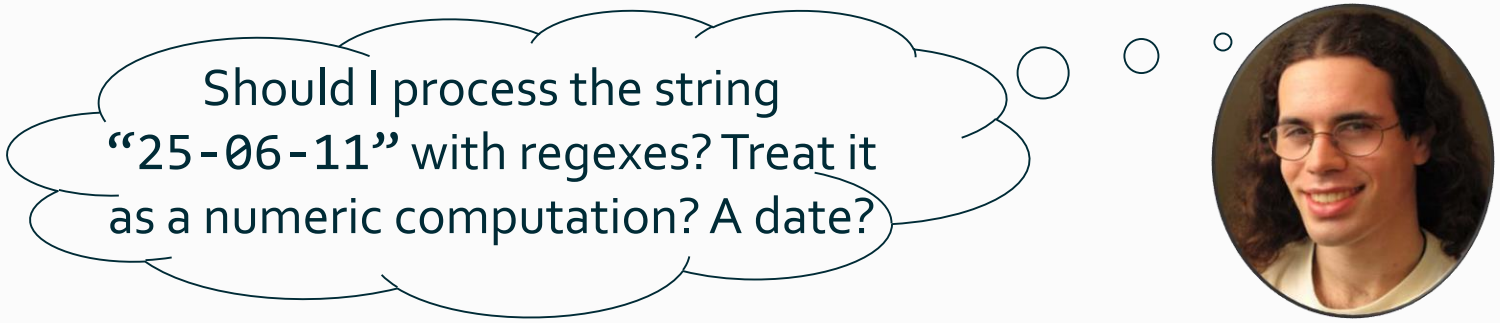
# Performance-minded engineering

- Parallelization of learning matters
  - *E.g.:* multi-user log file processing in Azure Log Analytics
- Performance of program execution matters
  - *E.g.:* "Big Data" on an end-user's machine
  - Smallest ≠ fastest!
  - **(1)** Synthesize many correct programs, then **(2)** optimize for the fast ones

Robustness-based ranking

Performance-based ranking

# Development




- DSL design: ≈ 10 months → ≈ 2 weeks
  - This is not a bottleneck!*
- Ranking: bulk of the effort
  - Designing a score for an operator $F$ is 2-3x longer than designing $F$ (incl. synthesis!)
  - *E.g.:* rock-paper-scissors among string processing operators

* Once you learn the skill…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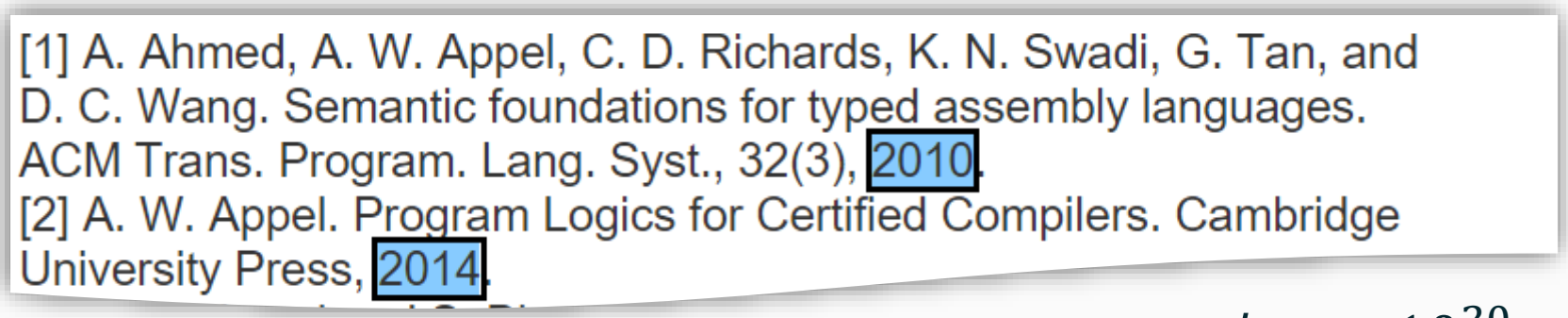


**From:** *…and up to* $10^{20}$ *more candidates*

all lines ending with "Number ∘ Dot"
"Space ∘ Number ∘ Dot"

starting with "Word ∘ Space ∘ CamelCase"

**Extract:**

the first "Number" before a "Dot"
the last "Number" before a "Dot"
the last "Number" before a "Dot ∘ LineBreak"
the last "Number"
text between the last "Space" and the last "Dot"
the first "Comma ∘ Space" and the last "Dot ∘ LineBreak"

# Anecdotes

- FlashFill was not accepted to Excel until it solved the most common scenarios from 1 example

| Adam Smith | Adam |
|---|---|
| Alice Williams | Alic |

- Some users still don't know you can give 2!

# Ambiguity resolution

**Option 1:** machine-learned robustness-based ranking [CAV 15]

- Idioms/patterns from test data can influence search & ranking
- *E.g.:* bucketing

| | |
|---|---|
| 100 | 76-100 |
| 51 | 51-75 |
| 86 | |

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```
x ⇒ Concat(Round(x, Down, 25), Const("-"), Round(x, Up, 25))
```

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**Option 2:** interactive clarification


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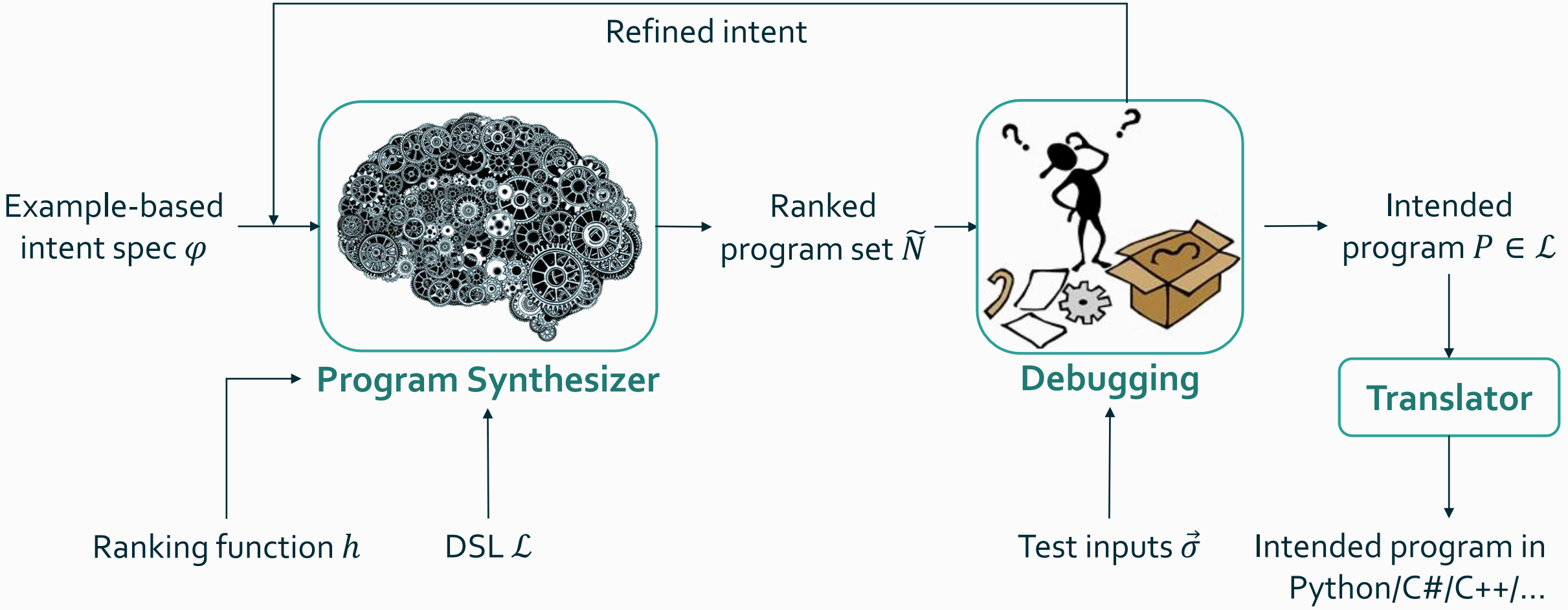
# PBE Architecture



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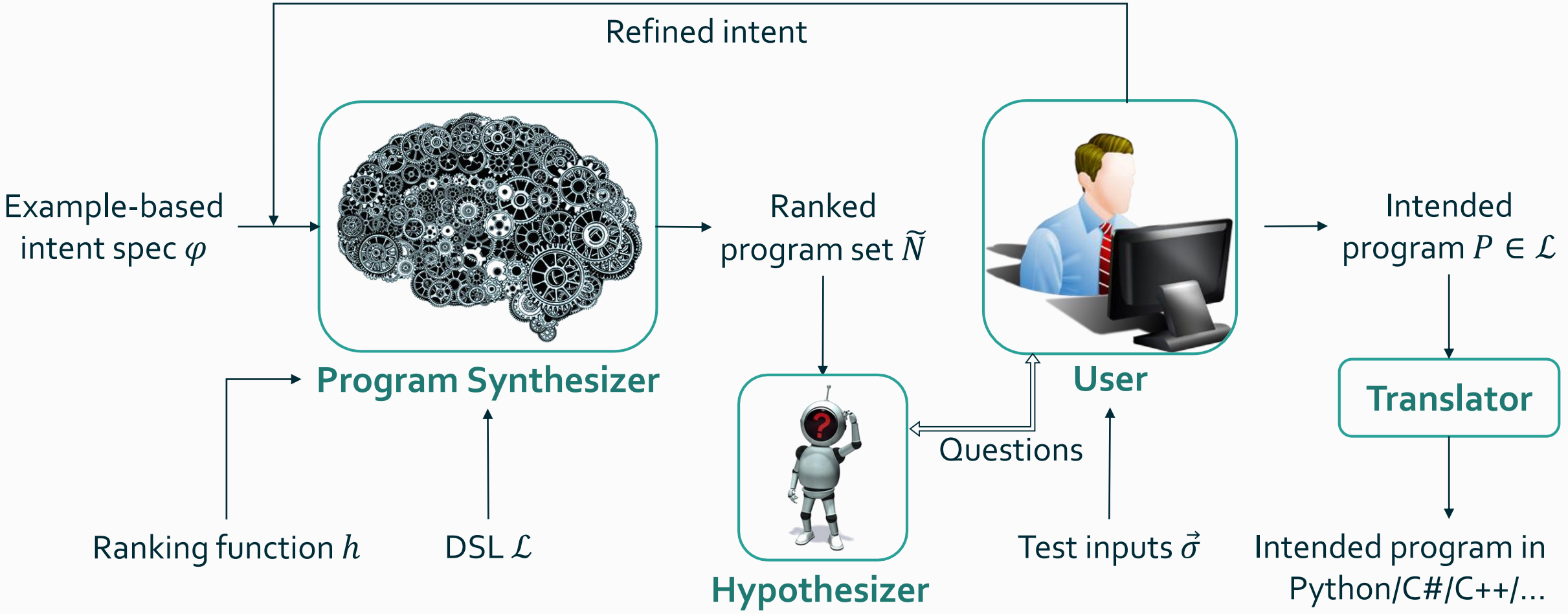

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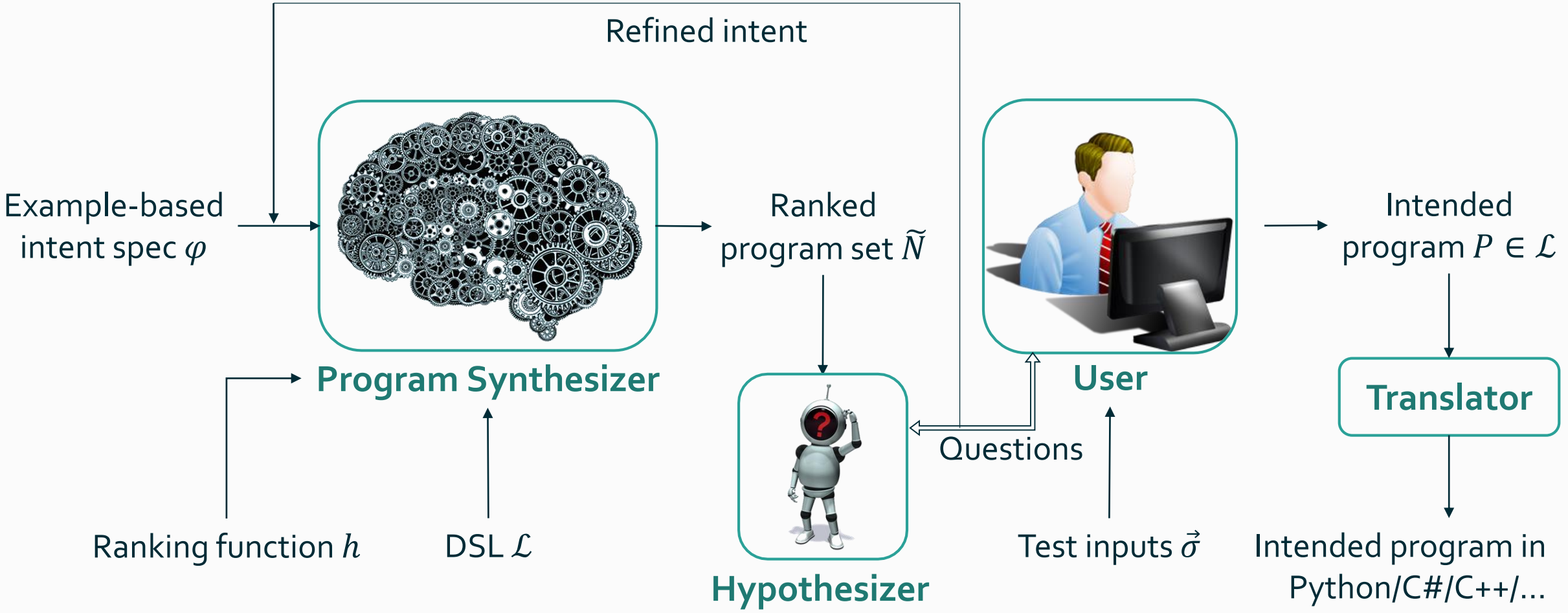


# Hypothesizer

**Given a program set $\widetilde{N}$, find program constraints *("hypotheses")* $\varphi$ that best disambiguate among programs in $\widetilde{N}$, and present them to the user as multiple-choice questions.**

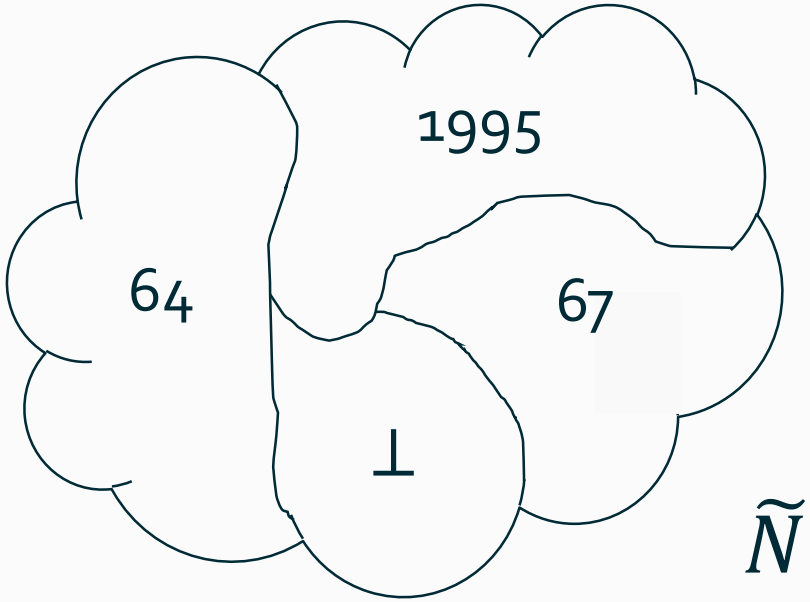
- ✓ Reduces the cognitive load on the user
- ✓ Reduces the number of iterations by choosing the most effective disambiguating questions
- ✓ Increases the user's confidence in the system ("proactive = smart")

# Example

| Missing page numbers, 1993 | 1993 |
|---|---|
| 64-67, 1995 | 64 |
| … … … | |

Which output is correct here?

a. 64
b. 67
c. 1995



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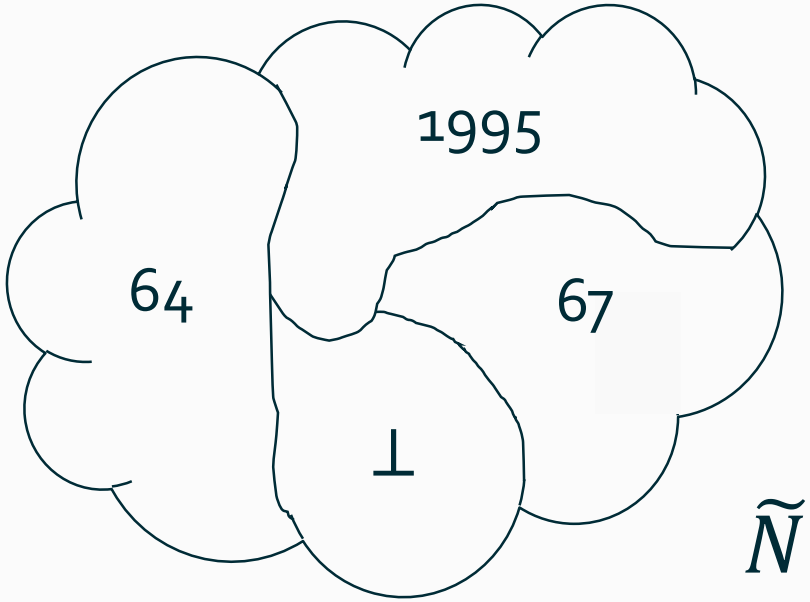
$\varphi_{i+1}$: $P(\sigma_2) =$ "1995"



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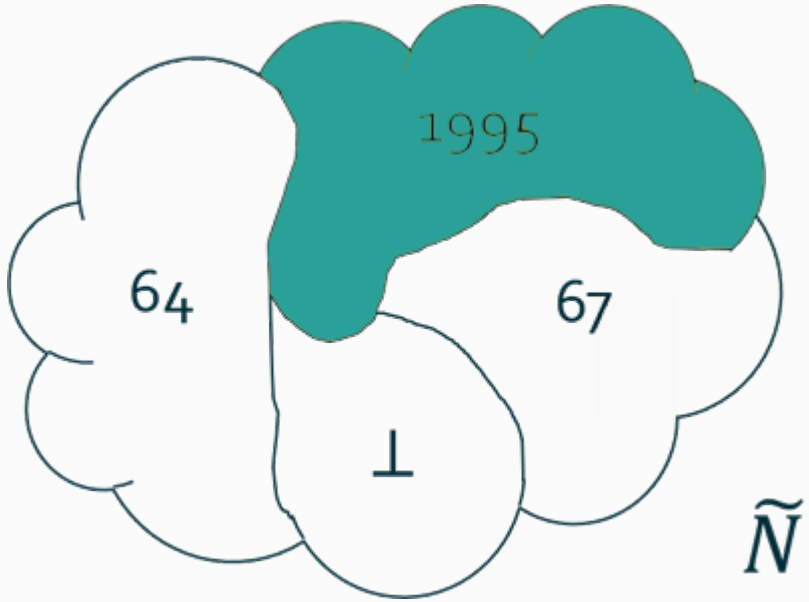
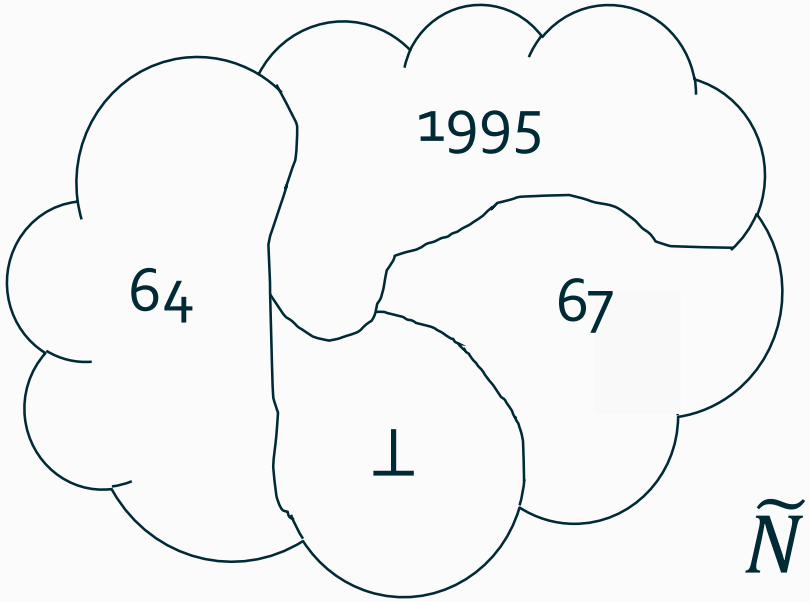


# Example – alternative

| Missing page numbers, 1993 | 1993 |
|---|---|
| 64-67, 1995 | 64 |
| … … … | |

Is this part of the input relevant?

a. Yes
b. No
c. Maybe



# Picking the right question

"Distinguishability" = effectiveness for disambiguation

1. An *input* is distinguishing if many top-ranked candidate programs disagree on the intended output on it.
   - Any response will partition the program set well
2. A *question* is distinguishing if the alternative candidate programs corresponding to all potential responses have high ranks.
   - Any response will lead to a good alternative program

Preliminary results: good questions yield just 4-6 iterations until convergence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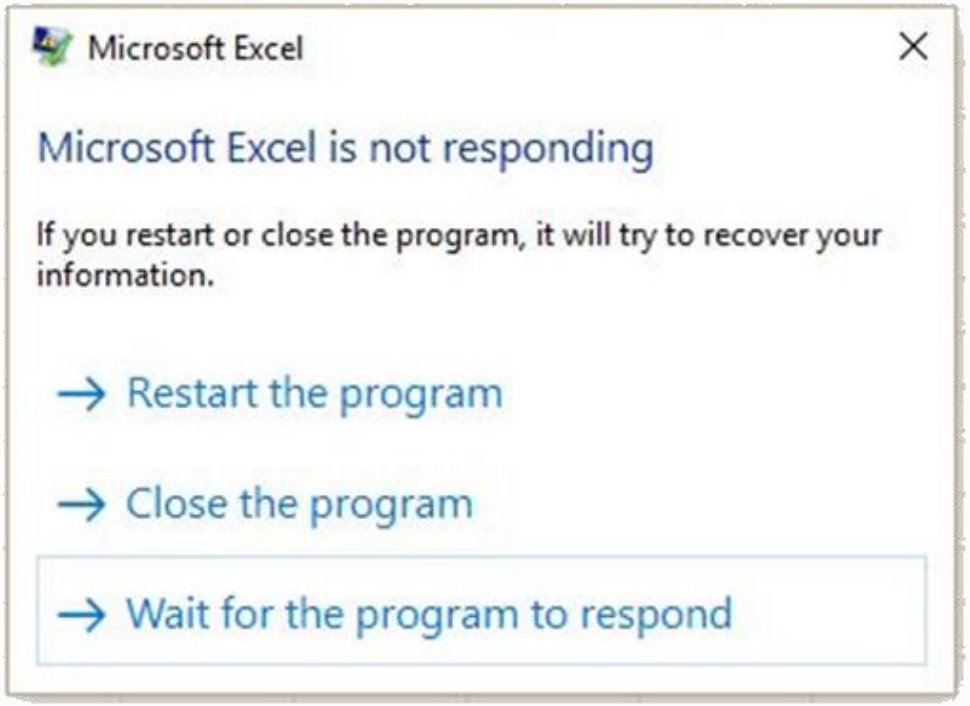
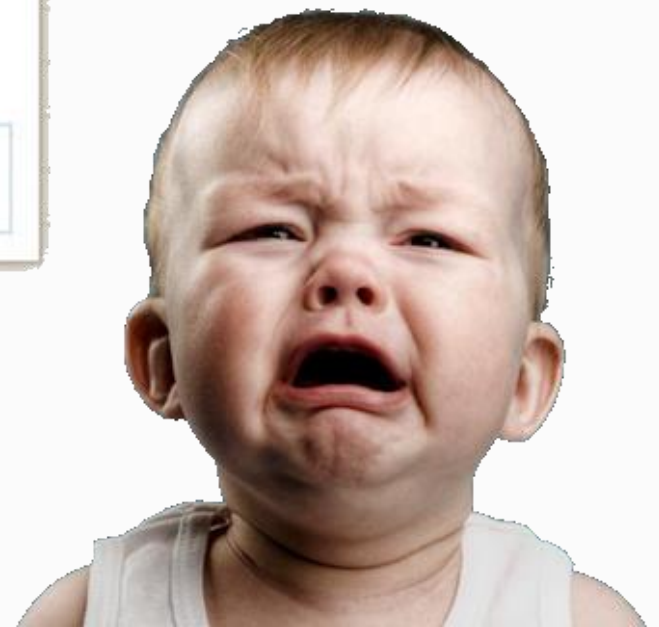
# Big Data


HOW'S THE BIG DATA PROJECT COMING ALONG, HOSKINS?
© D.Fletcher for CloudTweaks.com

# Big Data + Program Synthesis



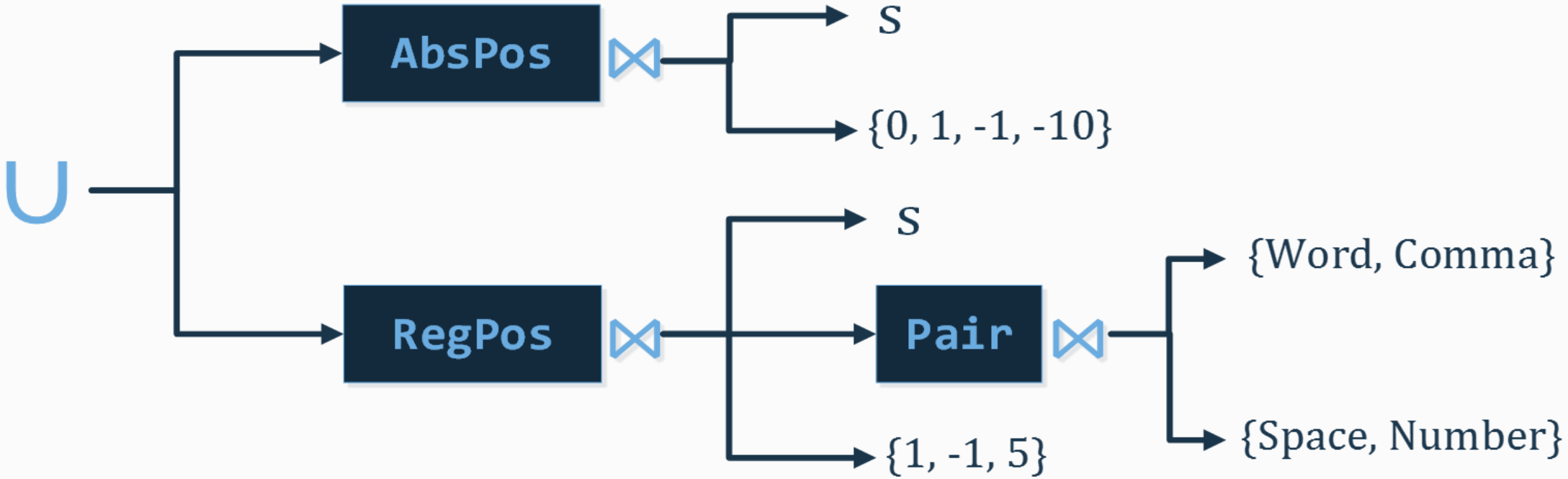
# Problem definition

**Given a program set $\widetilde{N}_i \subset \mathcal{L}$ that satisfies the currently accumulated spec $\varphi_i$, and a new constraint $\psi_{i+1}$, learn a subset $\widetilde{N}_{i+1} \subset \widetilde{N}_i$ of programs that satisfy the new spec $\varphi_{i+1} = \varphi_i \wedge \psi_{i+1}$**

- $\mathcal{L}$ is an industrial DSL (e.g., FlashFill)
- $\left|\widetilde{N}_i\right| \approx 10^{20}$
- Time limit: $\approx 1$ sec

# Background: Version Space Algebra

```
int positionIn[string s] := AbsPos(s, k)
                          | RegPos(s, std.Pair(r, r), k);
```



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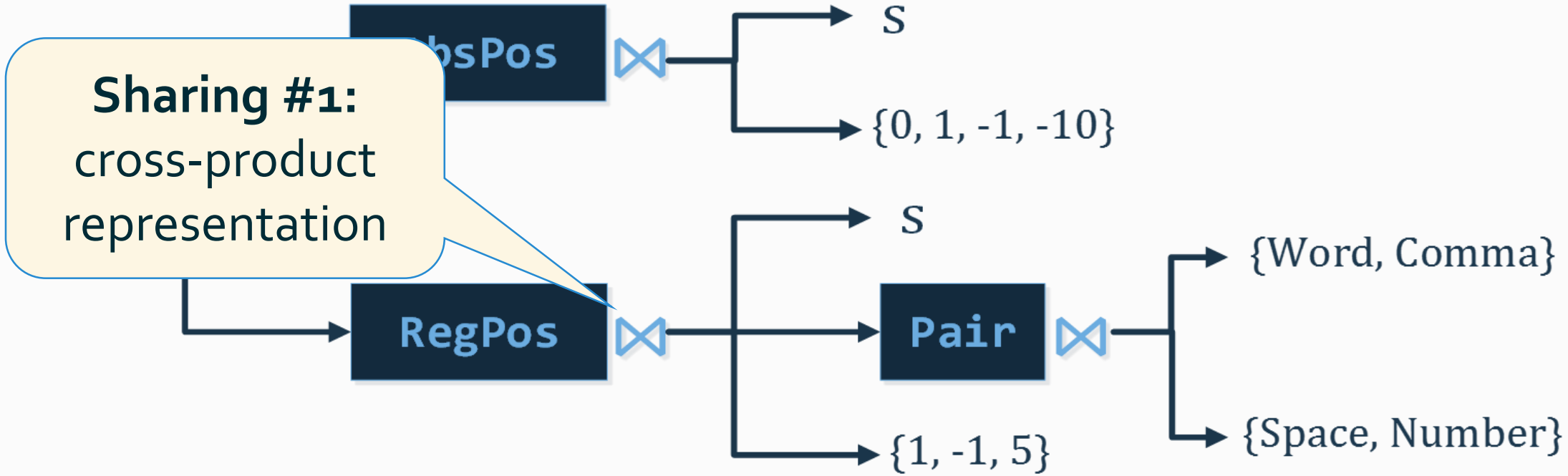

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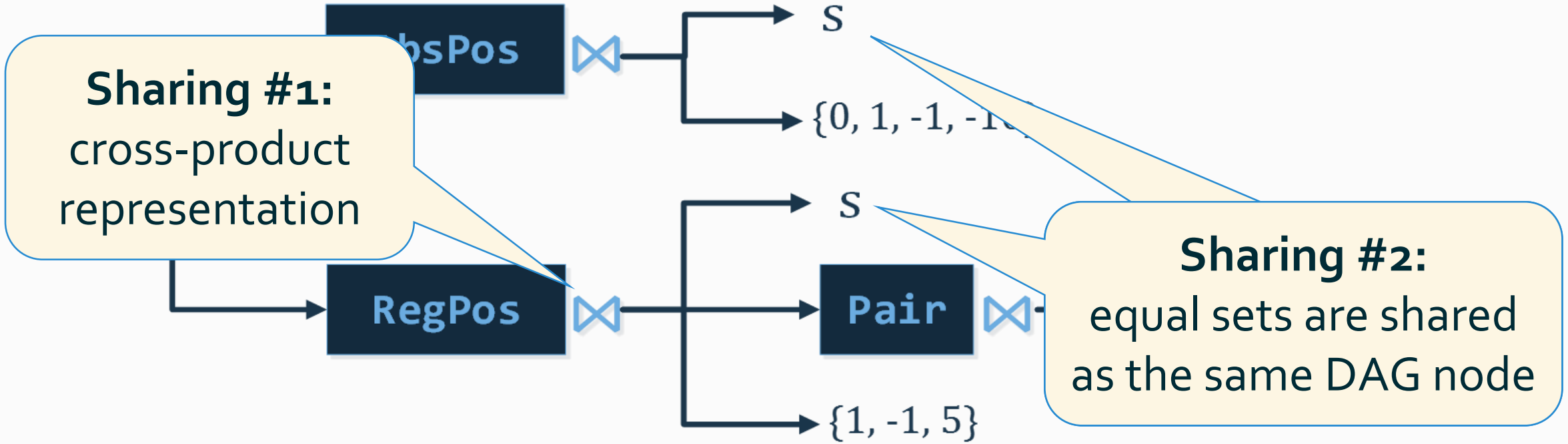
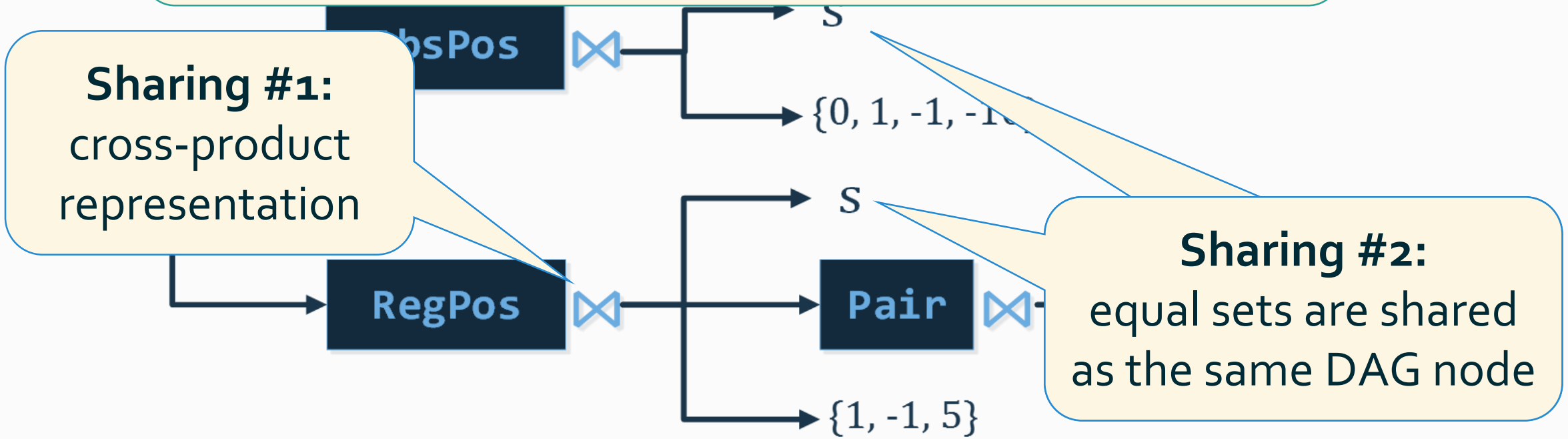


# Background: Version Space Algebra

```
int p                                                    , k);
```

For, e.g., FlashFill, $\text{volume}(\widetilde{N}) \approx 10^5$ when $|\widetilde{N}| \approx 10^{20}$.
Runtime of VSA operations $\propto$ VSA volume.




**Sharing #1:**
cross-product representation

**Sharing #2:**
equal sets are shared as the same DAG node

VSAs and CFGs are two

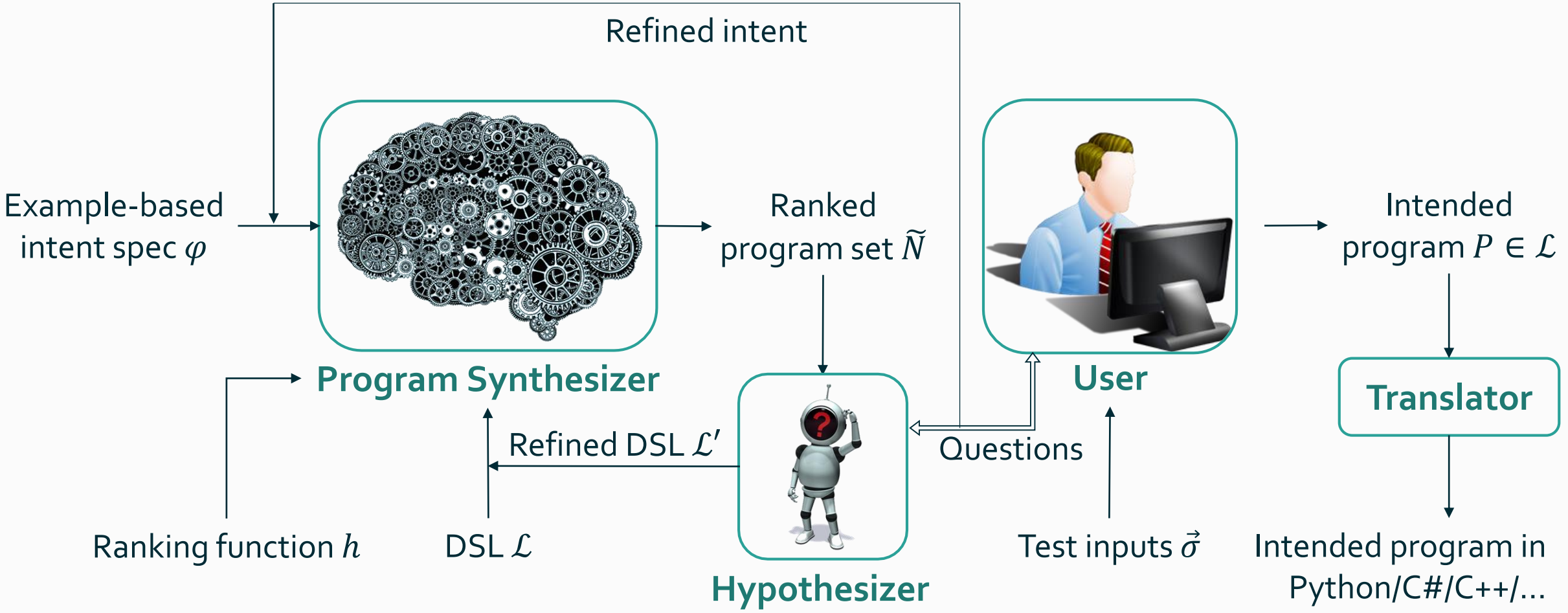
*isomorphic representations* for a *language*

$$\mathrm{Filter}\left(\tilde{N}, \psi\right) \equiv \mathrm{Learn}\left(\mathcal{L}\left(\tilde{N}\right), \psi\right)$$

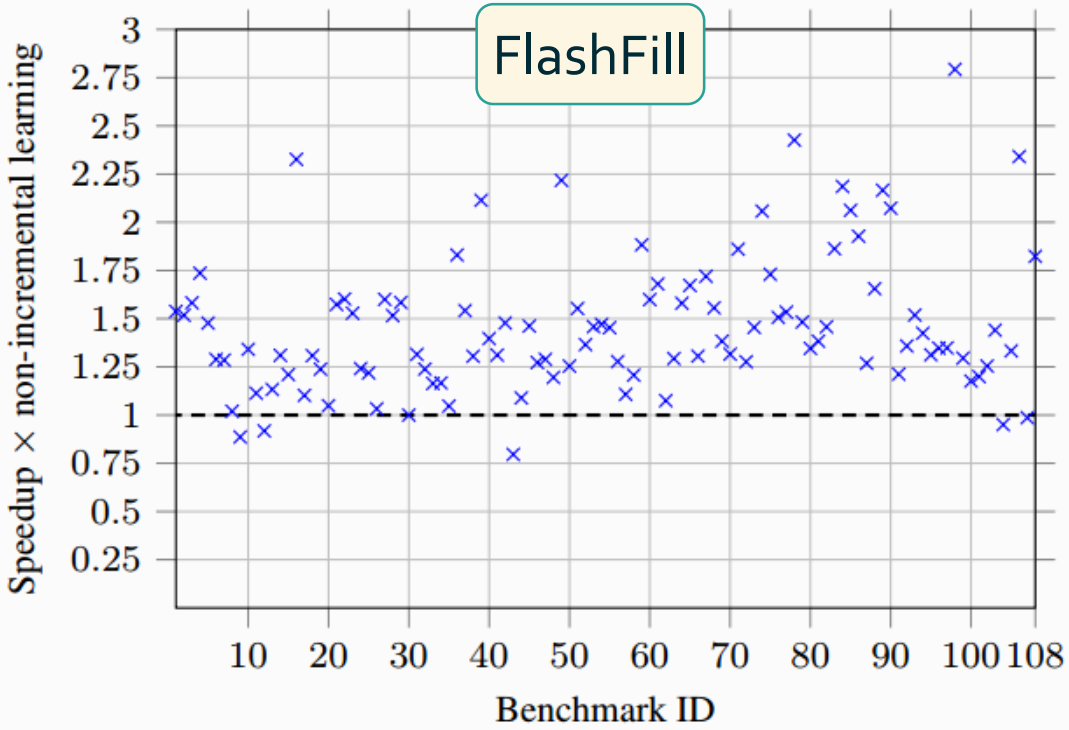
# Incremental Inductive Synthesis

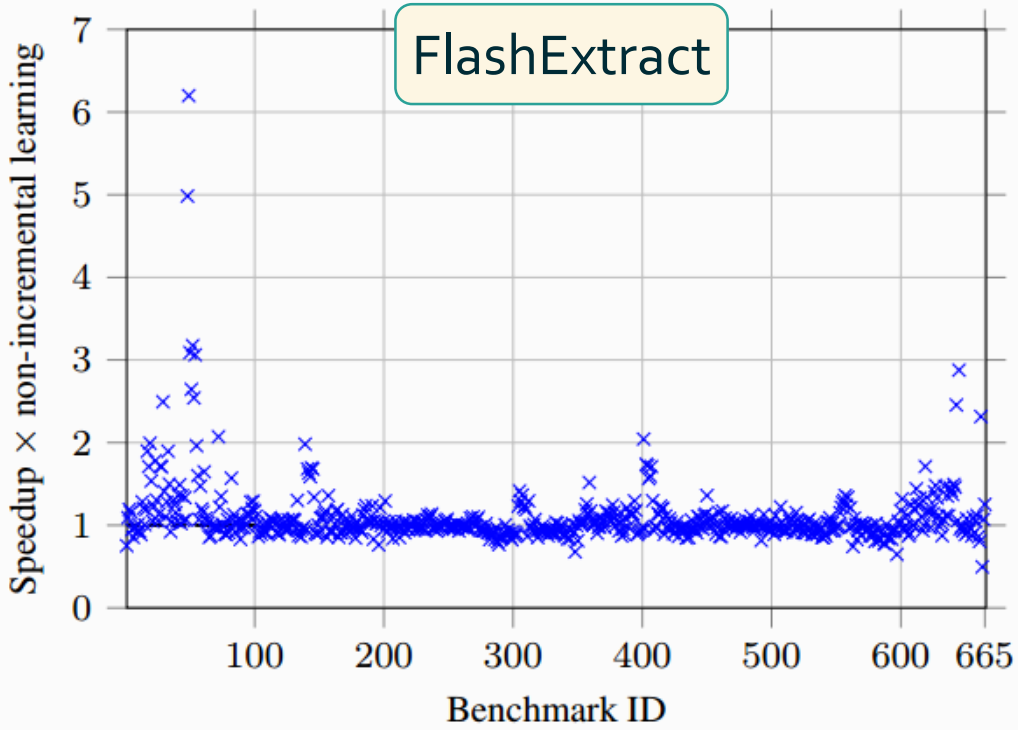
1. Implicitly represent $\widetilde{N}_i$ (already a VSA!) as an isomorphic CFG $\mathcal{L}(\widetilde{N}_i)$.
2. Analyze the *descriptive power* of $\psi_{i+1}$:
   - **Definitive** (*e.g.*, examples, set membership, subsequence constraints):
     Apply regular top-down deductive synthesis on $\mathcal{L}(\widetilde{N}_i)$
   - **Locally refining** (*e.g.*, datatypes, input relevance):
     Re-run backpropagation only on relevant parts of $\mathcal{L}(\widetilde{N}_i)$
   - **Globally refining** (*e.g.*, negative examples):
     Filter $\widetilde{N}_i$ at the top level

# PBE Architecture



# Preliminary results




- Big improvement when VSA fragmentation is limited
- Not the final results; work in progress has orders-of-magnitude improvements

# Lessons & Conclusions

- Robust engineering is the key to PBE deployment
- Ranking ≫ learning (in industrial PBE)
- Interaction models should be first-class citizens in synthesis frameworks
  - Great theoretical results: e.g., OGIS [Jha & Seshia 2015]
  - Also need: HCI evaluations, comparison of query types, worst-case TD optimization
- Proactive ambiguity analysis of current candidate programs
- Incrementality: treat the previous program set as the new search space
  - Requires *full* program set computation (possibly in the background)

Thank you!

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