Lecture 5
Representation-based Search

This week

Topics:

- Representation-based search
- Stochastic search

Paper: Rishabh Singh: BlinkFill: Semisupervised Programming By Example for Syntactic String Transformations. VLDB’16

The problem statement

Behavioral constraints = examples

```
[1,4,7,2,0,6,9,2,5]  →  [1,2,4,7,0]
[0] →  [0]
[5,1] →  [1,5,0]
```

Search strategy?

Enumerative
Representation-based
Stochastic
Constraint-based

Structural constraints = grammar

```
L ::= sort(L)  |  L[N..N]
    |  L + L  |  [N]  |  x
N ::= find(L,N)  |  0
```

Representation-based search

Idea:

1. build a graph that represents the search space
2. search in that graph (or not)

Tradeoff: easy to build vs easy to search

Representations

Version Space Algebra (VSA)

Finite Tree Automaton (FTA)

Type Transition Net (TTN)

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Version Space Algebra

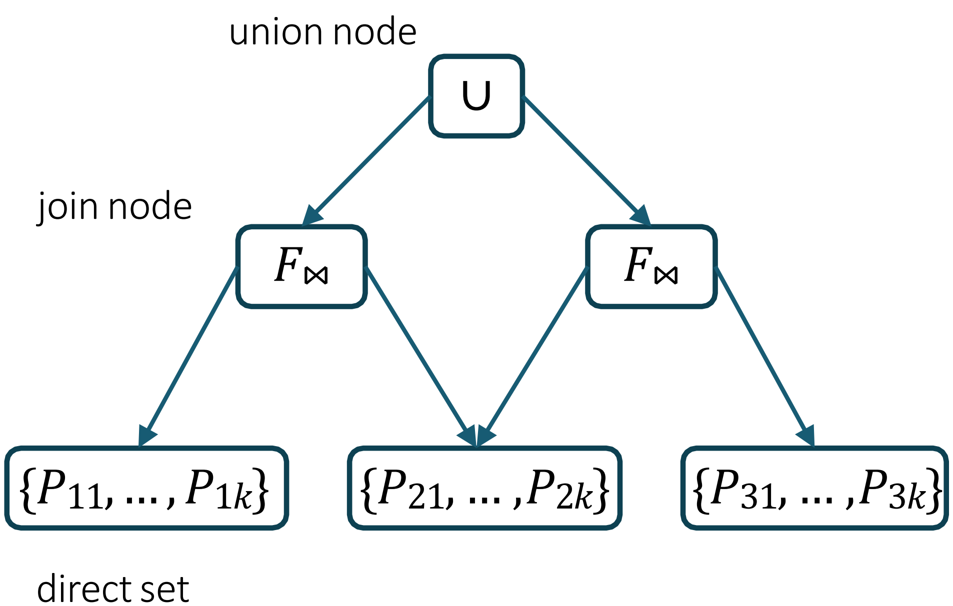
Idea: build a data structure that succinctly represents the set of programs consistent with a spec

- called a version space

Operations on version spaces:

- `learn <i, o>` $\rightarrow$ `VS`
- $VS_1 \cap VS_2 \rightarrow$ `VS`
- `pick VS` $\rightarrow$ `program`

Version Space Algebra



Volume of a VSA
(the number of nodes) $V(VSA)$

Size of a VSA
(the number of programs) $|VSA|$

$$V(VSA) = O(\log|VSA|)$$

Version Space Algebra: history

Mitchell: *Generalization as search*. AI 1982

Lau, Domingos, Weld. *Version space algebra and its application to programming by example*. ICML 2000

Gulwani: *Automating string processing in spreadsheets using input-output examples.* POPL 2011.

- BlinkFill, FlashExtract, FlashRelate, …
- generalized in the PROSE framework

FlashFill

[Gulwani '11]

Simplified grammar:

`E ::= F	concat(F, E)`	"Trace" expression
`F ::= cstr(S)	sub(P, P)`	Atomic expression
`P ::= cpos(K)	pos(R, R)`	Position expression
$R ::= (T_1, \ldots, T_n)$	Regular expression
`T ::= C	C+`	Token expression

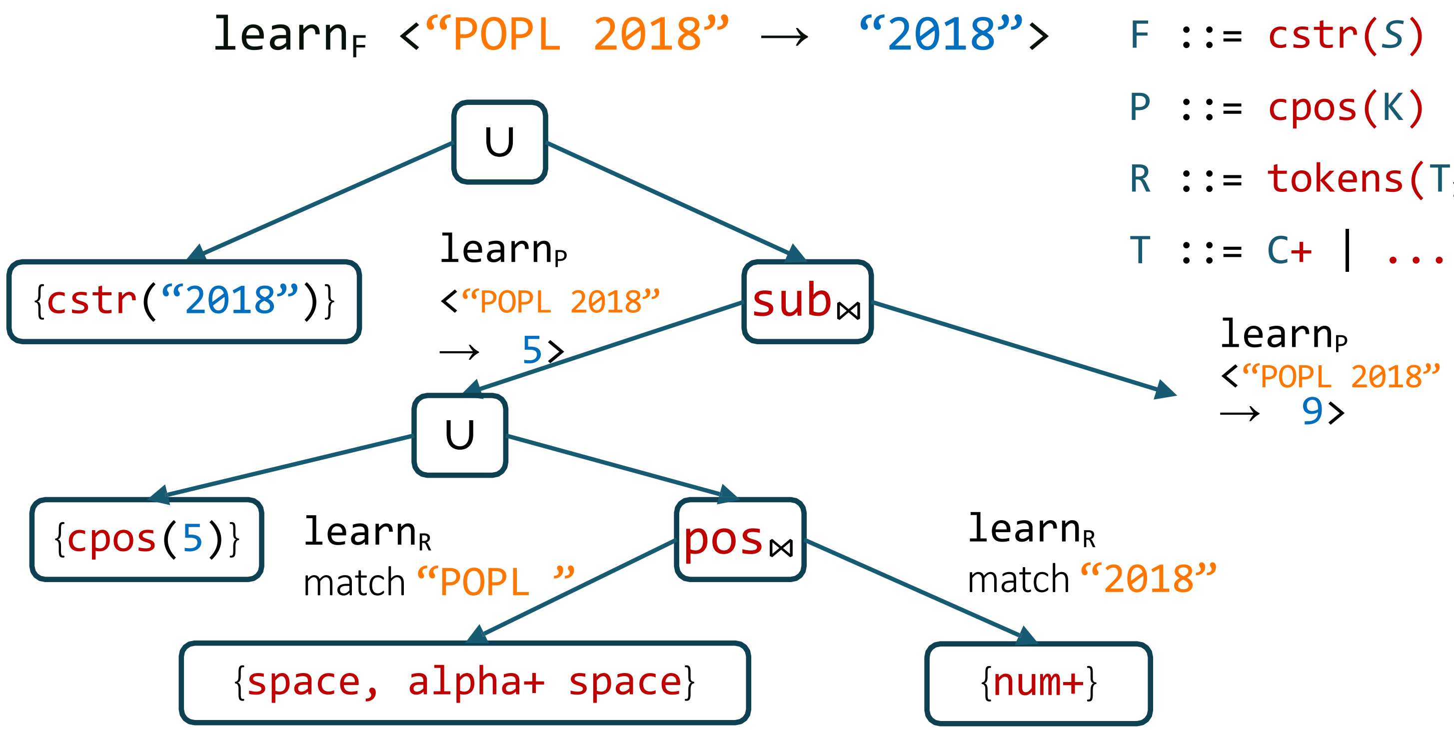
FlashFill: example

“Hello POPL 2020” ⟶ “POPL’2020”
“Goodbye PLDI 2019” ⟶ “PLDI’2019”

```
E ::= F | concat(F, E)
F ::= cstr(S) | sub(P, P)
P ::= cpos(K) | pos(R, R)
R ::= (T1, ..., Tn)
T ::= C | C+
```

```
concat(
  sub(pos(ws, C), pos(C, (ws, d))),
  concat(cstr(“’”),
    sub(pos(ws, d), pos(d, $))))
```

Learning atomic expressions



$$F ::= \mathtt{cstr}(S) \mid \mathtt{sub}(P_1, P_2)$$

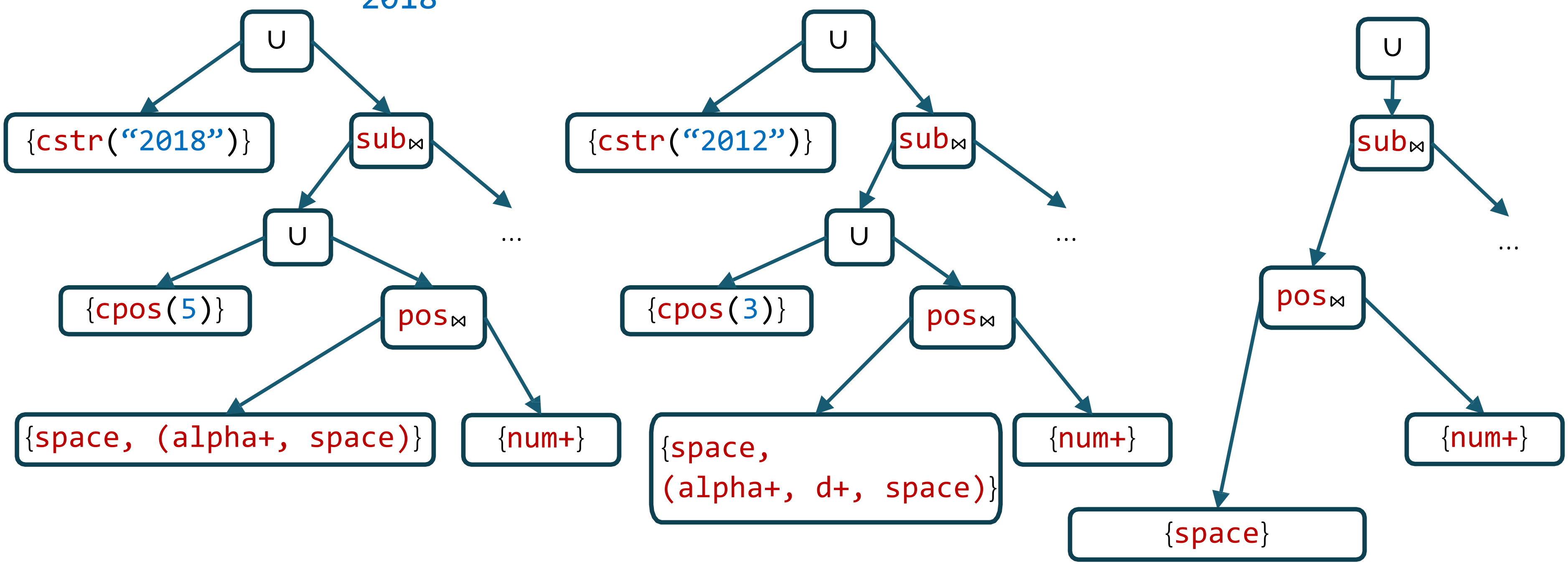
$$P ::= \mathtt{cpos}(K) \mid \mathtt{pos}(R_1, R_2)$$

$$R ::= \mathtt{tokens}(T_1, \ldots, T_n)$$

$$T ::= C+ \mid \ldots$$

Intersection

“POPL 2018” → “2018”   “F1 2012” → “2012”

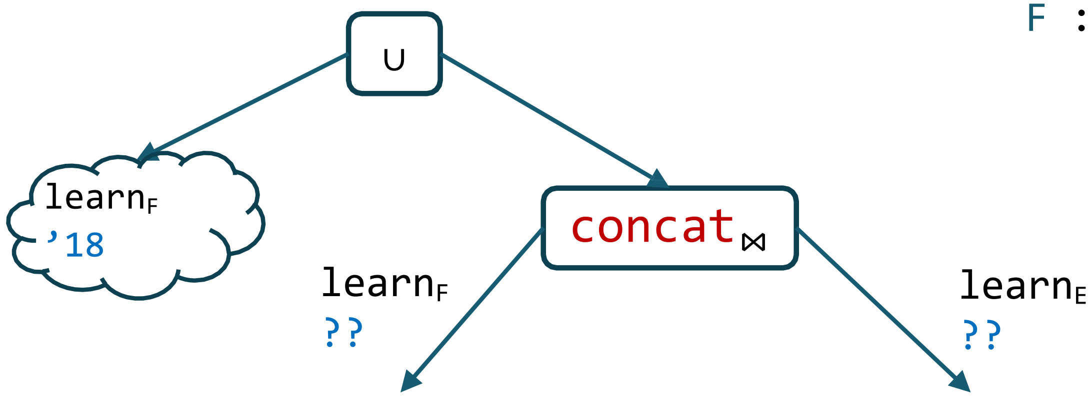


Learning trace expressions

learn$_E$ <“POPL 2018” ⟶ “’18”>

E ::= F | concat(F, E)

F ::= ...

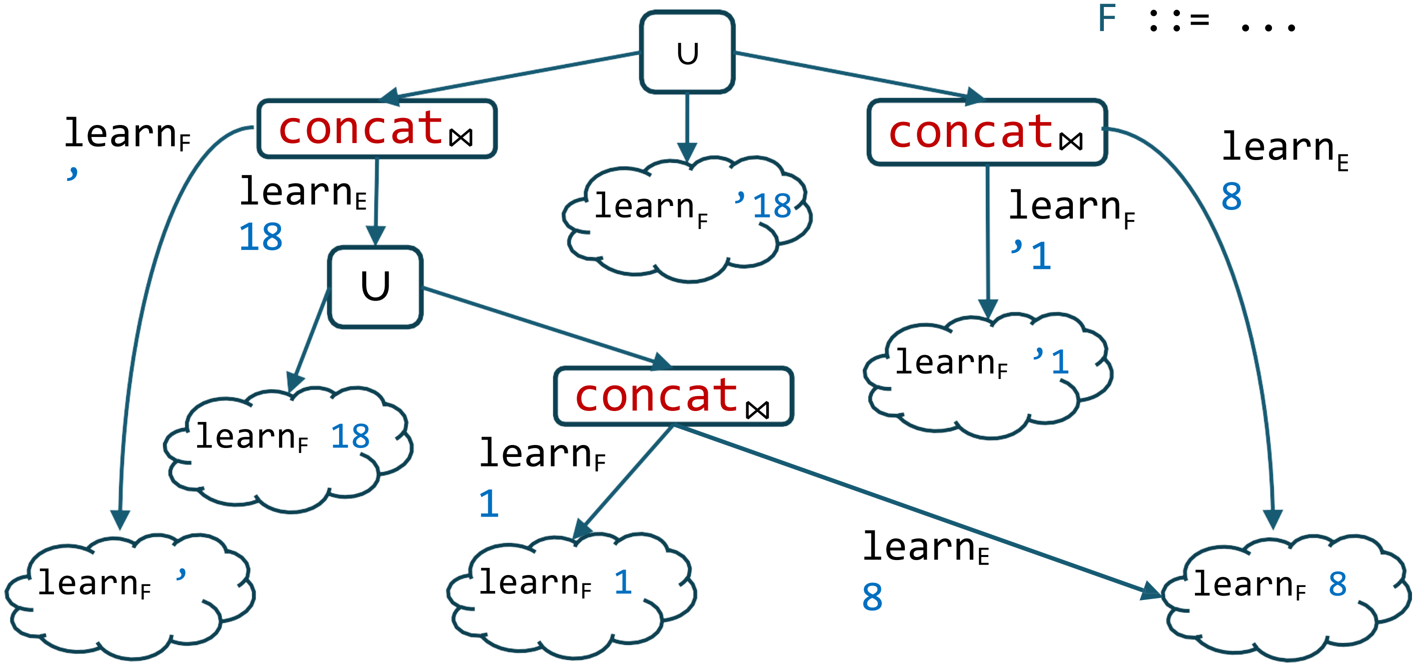


Learning trace expressions

learn$_E$ <"POPL 2018" $\longrightarrow$ "'18">

E ::= F | concat(F, E)

F ::= ...



Discussion

Why could we build a finite representation of all expressions?

- Could we do it for this language?

```
E ::= F + F
F ::= K | x
```

$K \in \mathbb{Z}$ + is integer addition

- What about this language?

```
E ::= F | F + E
F ::= K | x
```

$K \in [0,9]$ + is addition mod 10

Discussion

Why could we build a *compact* representation of all expressions?

- Could we do this for this language?

```
E.::= F & F
F.::= K | x
```

K is a 32-bit word, **&** is bit-and

VSA: DSL restrictions

Every recursive rule generates a strictly smaller subproblem

```
E ::= F | concat(F, E)
```

PROSE

[Polozov, Gulwani '15]

Ranking function

```
r :: Program -> Int
```

Grammar

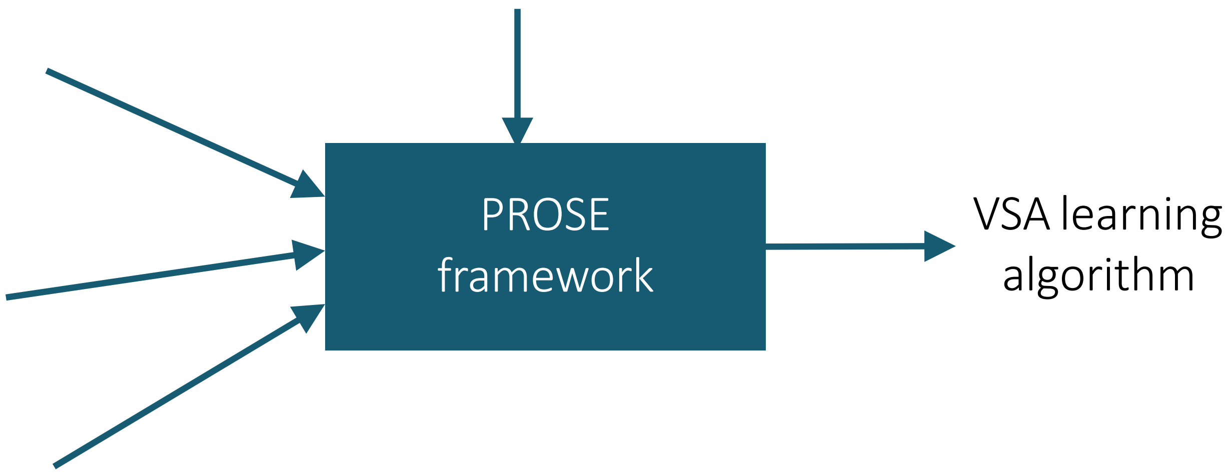
```
A ::= f(B, C) | ...
B ::= g(D, E) | ...
```

Semantics

```
f :: (B, C) -> A
f (b, c) = ...
```

Inverse semantics

```
f⁻¹ :: A -> {(B, C)}
f⁻¹ a = ...
```



https://microsoft.github.io/prose/

Representations

Version Space Algebra (VSA)

Finite Tree Automaton (FTA)

Type Transition Net (TTN)

Example

Grammar

```
N ::= id(V) | N + T | N * T
T ::= 2 | 3
V ::= x
```

Spec

$1 \rightarrow 9$

Finite Tree Automata

$\langle A, \mathbb{Z} \rangle$

$A \in \{N, T, V\}$

$\{\langle N, 9 \rangle\}$

states

final states

$$\mathcal{A} = \langle Q, F, Q_f, \Delta \rangle$$

alphabet

transitions

`id`, `+`, `*`

$f(q_1, \dots, q_n) \to q$

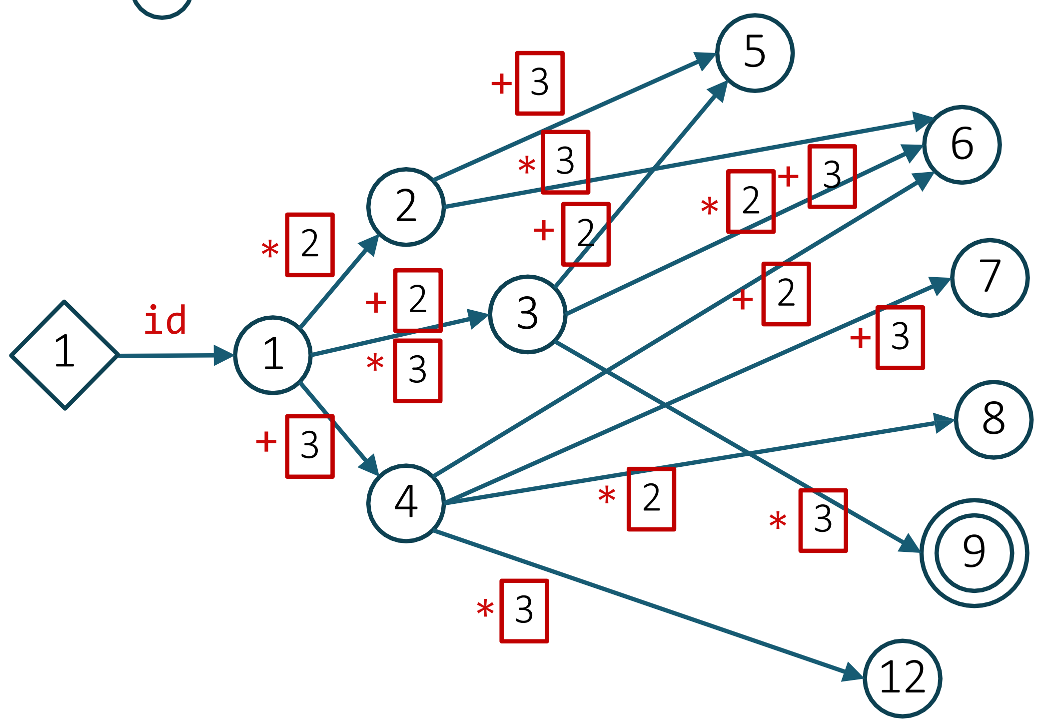
```
+(<N,1>,<T,2>) → <N,3>
...
```

Finite Tree Automata

[Wang, Dillig, Singh OOPSLA'17]

```
N ::= id(V) | N + T | N * T
T ::= 2 | 3
V ::= x
```

1 → 9



Abstract FTA

Challenge: FTA still has too many states

Idea:

- instead of one state = one value
- we can do one state = set of values (= abstract value)

Abstract FTA

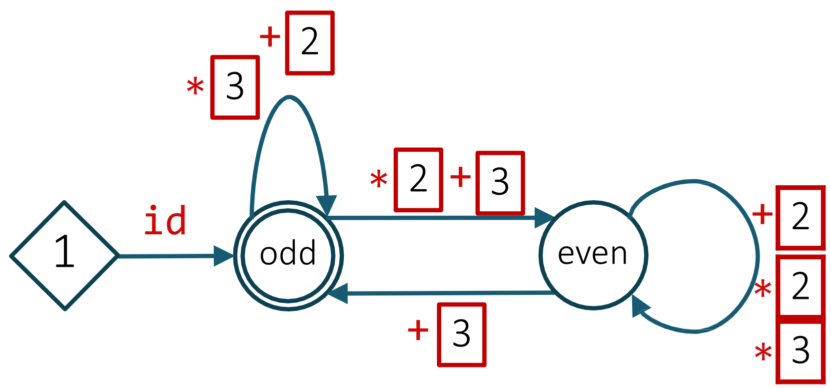
[Wang, Dillig, Singh POPL'18]

N ::= id(V) | N + T | N * T

T ::= 2 | 3

V ::= x

1 → 9



In the paper:

- different abstractions
- refining the abstractions to eliminate spurious paths

Representations

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Type-Transitions Nets

Context: Component-based synthesis

- given a library of components
- and a query: type + examples?
- synthesize composition of components

Idea: Build a compact graph of the search space using

- types as nodes
- components as transitions

TTN: History

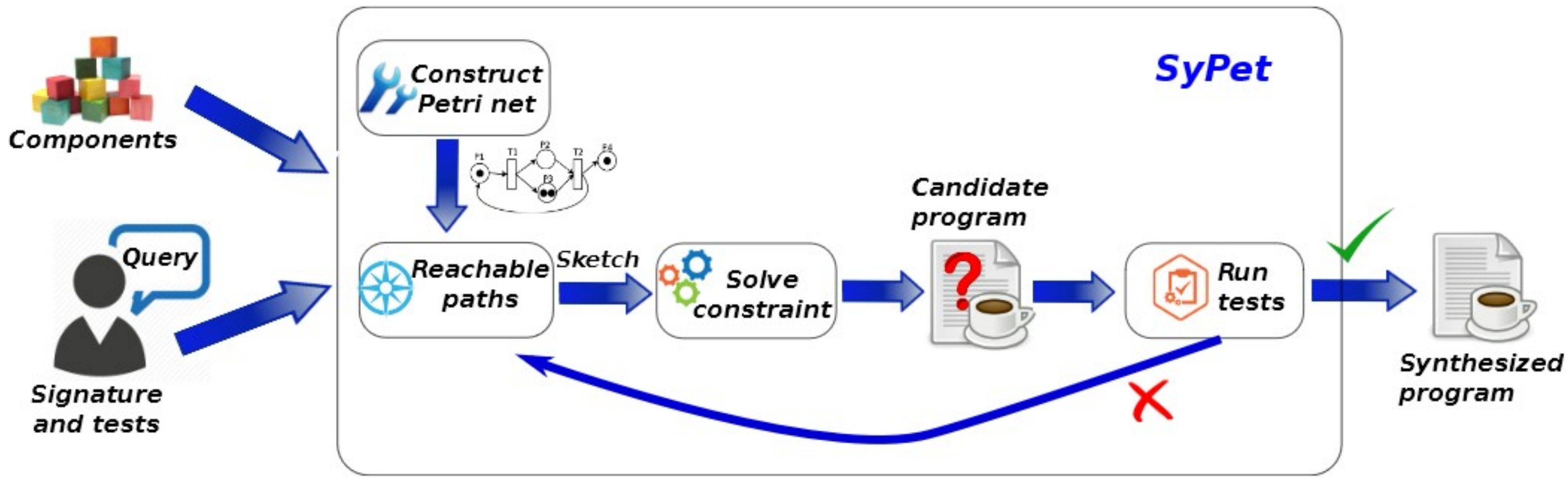
Mandelin, Xu, Bodik, Kimelman: *Jungloid mining: helping to navigate the API jungle.* PLDI'05

Gvero, Kuncak, Kuraj, Piskac: *Complete completion using types and weights.* PLDI'13

Feng, Martins, Wang, Dillig, Reps: *Component-based synthesis for complex APIs.* POPL'17

Guo, James, Justo, Zhou, Wang, Jhala, Polikarpova: *Synthesis by type-Guided Abstraction Refinement.* POPL'20

SyPet: workflow



SyPet: example

Signature

```
Area rotate(Area obj, Point2D pt, double angle)
{ ?? }
```

Test

```
public void test1() {
  Area a1 = new Area(new Rectangle(0, 0, 10, 2));
  Area a2 = new Area(new Rectangle(-2, 0, 2, 10));
  Point2D p = new Point2D.Double(0, 0);
  assertTrue(a2.equals(rotate(a1, p, Math.PI/2)));
}
```

Components

```
java.awt.geom
```

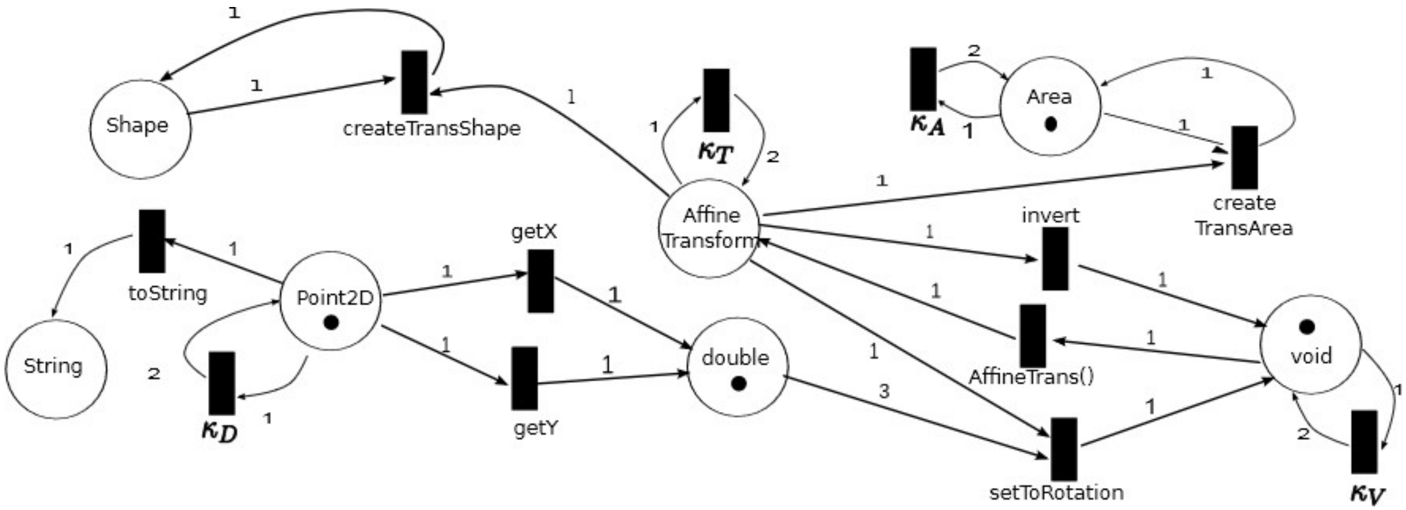
Output

```
Area rotate(Area obj, Point2D pt, double angle) {
  double x = pt.getX();
  double y = pt.getY();
  at.setToRotation(angle, x, y);
  AffineTransform at = new AffineTransform();
  Area obj2 = obj.createTransformedArea(at);
  return obj2;
}
```

Petri Nets

Area createTranArea (AffineTransform at, Area a)
{…}

Library as a Petri Net



Synthesis output:

```
Area rotate(Area obj, Point2D pt, double angle) {
  double x = pt.getX();
  double y = pt.getY();
  at.setToRotation(angle, x, y);
  AffineTransform at = new AffineTransform();
  Area obj2 = obj.createTransformedArea(at);
  return obj2;
}
```

Discussion

Representation-based vs enumerative

- Enumerative unfolds the search space in time, while representation-based stores it in memory
- Benefits / limitations?

FTA ~ bottom-up

- with observational equivalence

VSA ~ top-down

- with top-down propagation

Discussion

Trade-off between work during and after building the representation:

- VSA/FTA: hard to build but easy to find a program
- TTN: easy to build but harder to find a program