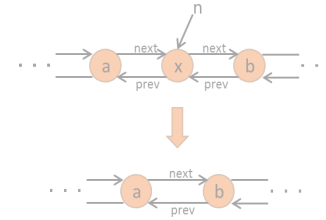
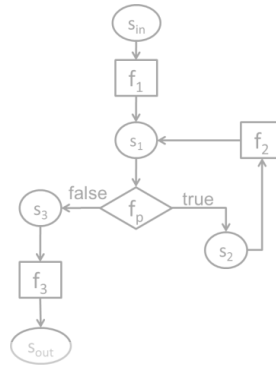


$$\exists c \forall in \ Q(c, in)$$

```

/* Average of x and y without using x+y (avoid overflow)*/
int avg(int x, int y){
  int t = expr({x/2, y/2, x%2, y%2, 2 }, {PLUS, DIV});
  assert t == (x+y)/2;
  return t;
}

```

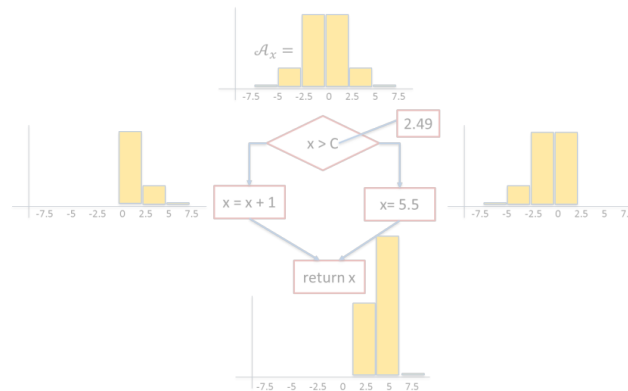
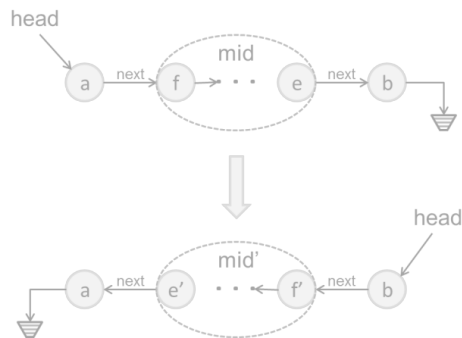


```

{
  s = n.succ;
  p = n.pred;
  p.succ = s;
  s.pred = p;
}

```

Program Synthesis



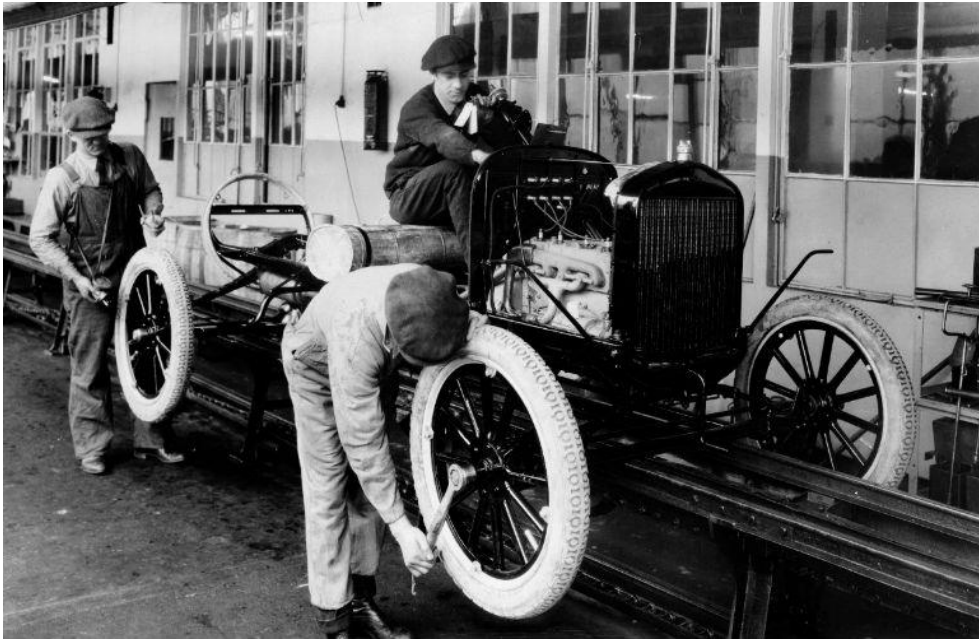
$$\varphi(p)$$

$$Sk[c](in)$$

Lecture 1

Introduction to Synthesis

The goal: automate programming



Modern program synthesis: FlashFill

[Gulwani 2011]

The collage features several overlapping elements:

- CNNMoney TECH**: A blue header with the CNNMoney logo and the word "TECH".
- Lifehacker**: A green and white header with the word "Lifehacker" and a small "AUST" button.
- TECHWORLD**: A black header with the word "TECHWORLD" in blue and white.
- WIRED**: A black header with the word "WIRED" in white, followed by navigation links: "SUBSCRIBE >>", "SECTIONS >>", "BLOGS >>", "REVIEWS >>", and "VIDEO >>".
- Excel**: A section titled "Excel" with a paragraph: "Excel is now a lot easier for people who aren't spreadsheet- and chart-making pros. The application's new Flash Fill feature recognizes patterns, and will offer auto-complete options for your data. For example, if you have a column of first names and a column of last names, and want to create a new..."
- THE TIMES OF INDIA Tech**: A red header with the text "THE TIMES OF INDIA" and "Tech". Below it is a navigation bar with links: "Home", "City", "India", "World", "Business", "Tech", "Sports", "Entertainment", and "Life & Style".
- PCWorld**: A red header with the word "PCWorld" and navigation links: "News", "Reviews", and "How-To". Below it is a "TRENDING" section with links: "Phones", "Tablets", "Laptops", and "Windows".
- engadget**: A blue and green header with the word "engadget" and a "COMPUTEX 2012" banner.
- ZDNet**: A red and blue header with the word "ZDNet" and a "White Paper" link.
- The Seattle Times**: A newspaper clipping with the headline "The Seattle Times Winner of a 2012 Pulitzer Prize".
- Excel Spreadsheet**: A screenshot of an Excel spreadsheet showing a table with names. The first column contains "Malcolm", "Bernie", and "Steven". The second column contains "Turnbull", "Ripoll", and "Gibbs". The third column contains "Malcolm", "Bernie", and "Steven".

FlashFill: a feature of Excel 2013

[Gulwani 2011]

Table116

Column1	Col 2	Col 3	Col 4	Col 5	Col 6
Ana Trujillo	357 21th Place SE,Redmond,WA,(757) 555-1634,140-37-6064,27171	Redmond	WA	(757) 555-1634	140-37-6064 27171
Antonio Moreno	515 93th Lane ,Renton,WA,(411) 555-2786,562-87-3127,28581				
Thomas Hardy	742 17th Street NE,Seattle,WA,(412) 555-5719,921-29-4931,24607				
Christina Berglund	475 22th Lane ,Redmond,WA,(443) 555-6774,844-35-6764,30146				
Hanna Moos	785 45th Street NE,Puyallup,WA,(376) 555-2462,515-68-1285,29284				
Frédérique Citeaux	308 66th Place ,Redmond,WA,(689) 555-2770,552-23-2508,21415				
Martin Sommer	887 86th Place ,Kent,WA,(715) 555-5450,870-91-9824,21536				
Laurence Leblhan	944 13th Street NE,Redmond,WA,(620) 555-2361,649-25-5312,25252				
Elizabeth Lincoln	452 73th Lane NE,Renton,WA,(851) 555-4561,425-97-6344,22279				
Victoria Ashworth	463 16th Street ,Renton,WA,(696) 555-6044,690-29-7926,22832				
Patricio Simpson	630 20th Street ,Redmond,WA,(179) 555-3265,389-78-3236,24525				
Francisco Chang	683 49th Lane ,Seattle,WA,(272) 555-7434,665-18-6435,29453				
Yang Wang	944 28th Lane ,Redmond,WA,(151) 555-2272,846-78-8452,24388				
Pedro Afonso	411 70th Place ,Kent,WA,(170) 555-2964,774-35-2298,29485				
Elizabeth Brown	971 20th Lane ,Puyallup,WA,(373) 555-4134,476-53-7164,26417				
Sven Ottlieb	676 17th Lane NE,Redmond,WA,(828) 555-1593,548-73-8633,27440				
Janine Labrune	267 95th Place SE,Seattle,WA,(949) 555-1316,350-27-8300,28074				
Ann Devon	694 53th Place ,Kent,WA,(194) 555-8124,559-74-4016,22367				
Roland Mendel	581 12th Street NW,Kent,WA,(103) 555-2146,303-79-1328,20518				
Aria Cruz	594 85th Lane ,Renton,WA,(431) 555-1376,329-93-9992,21498				
Diego Roel	550 22th Lane ,Renton,WA,(639) 555-6238,918-34-5172,25931				
Martine Rancé	688 93th Place NW,Kent,WA,(573) 555-3571,695-94-3479,22424				

Ready Average: 27171 Count: 27 Sum: 27171 106%

FlashFill: a feature of Excel 2013

dr-2 - Microsoft Excel

File Home Insert Page Layout Formulas Data Review View Quick Code Load Test Team Design

Quick Fill Auto Fill Quick Layout
Apply HiLight CurrencyWidget
Undo Commit AddressWidget

Table116 Ana Trujillo 357 21th Place SE,Redmond,WA,(757) 555-1634,140-37-6064,27171

	A	B	C	D	E	F
1	Column1	Col 2	Col 3	Col 4	Col 5	Col 6
2	Ana Trujillo 357 21th Place SE,Redmond,WA,(757) 555-1634,140-37-6064,27171	Redmond	WA	(757) 555-1634	140-37-6064	27171
3	Antonio Moreno 515 93th Lane ,Renton,WA,(411) 555-2786,562-87-3127,28581	Renton	WA	(411) 555-2786	562-87-3127	28581
4	Thomas Hardy 742 17th Street NE,Seattle,WA,(412) 555-5719,921-29-4931,24607	Seattle	WA	(412) 555-5719	921-29-4931	24607
5	Christina Berglund 475 22th Lane ,Redmond,WA,(443) 555-6774,844-35-6764,30146	Redmond	WA	(443) 555-6774	844-35-6764	30146
6	Hanna Moos 785 45th Street NE,Puyallup,WA,(376) 555-2462,515-68-1285,29284	Puyallup	WA	(376) 555-2462	515-68-1285	29284
7	Frédérique Citeaux 308 66th Place ,Redmond,WA,(689) 555-2770,552-23-2508,21415	Redmond	WA	(689) 555-2770	552-23-2508	21415
8	Martin Sommer 887 86th Place ,Kent,WA,(715) 555-5450,870-91-9824,21536	Kent	WA	(715) 555-5450	870-91-9824	21536
9	Laurence Lebihan 944 13th Street NE,Redmond,WA,(620) 555-2361,649-25-5312,25252	Redmond	WA	(620) 555-2361	649-25-5312	25252
10	Elizabeth Lincoln 452 73th Lane NE,Renton,WA,(851) 555-4561,425-97-6344,22279	Renton	WA	(851) 555-4561	425-97-6344	22279
11	Victoria Ashworth 463 16th Street ,Renton,WA,(696) 555-6044,690-29-7926,22832	Renton	WA	(696) 555-6044	690-29-7926	22832
12	Patricio Simpson 630 20th Street ,Redmond,WA,(179) 555-3265,389-78-3236,24525	Redmond	WA	(179) 555-3265	389-78-3236	24525
13	Francisco Chang 683 49th Lane ,Seattle,WA,(272) 555-7434,665-18-6435,29453	Seattle	WA	(272) 555-7434	665-18-6435	29453
14	Yang Wang 944 28th Lane ,Redmond,WA,(151) 555-2272,846-78-8452,24388	Redmond	WA	(151) 555-2272	846-78-8452	24388
15	Pedro Afonso 411 70th Place ,Kent,WA,(170) 555-2964,774-35-2298,29485	Kent	WA	(170) 555-2964	774-35-2298	29485
16	Elizabeth Brown 971 20th Lane ,Puyallup,WA,(373) 555-4134,476-53-7164,26417	Puyallup	WA	(373) 555-4134	476-53-7164	26417
17	Sven Ottlieb 676 17th Lane NE,Redmond,WA,(828) 555-1593,548-73-8633,27440	Redmond	WA	(828) 555-1593	548-73-8633	27440
18	Janine Labrune 267 95th Place SE,Seattle,WA,(949) 555-1316,350-27-8300,28074	Seattle	WA	(949) 555-1316	350-27-8300	28074
19	Ann Devon 694 53th Place ,Kent,WA,(194) 555-8124,559-74-4016,22367	Kent	WA	(194) 555-8124	559-74-4016	22367
20	Roland Mendel 581 12th Street NW,Kent,WA,(103) 555-2146,303-79-1328,20518	Kent	WA	(103) 555-2146	303-79-1328	20518
21	Aria Cruz 594 85th Lane ,Renton,WA,(431) 555-1376,329-93-9992,21498	Renton	WA	(431) 555-1376	329-93-9992	21498
22	Diego Roel 550 22th Lane ,Renton,WA,(639) 555-6238,918-34-5172,25931	Renton	WA	(639) 555-6238	918-34-5172	25931
23	Martine Rancé 688 93th Place NW,Kent,WA,(573) 555-3571,695-94-3479,22424	Kent	WA	(573) 555-3571	695-94-3479	22424
24						
25						
26						

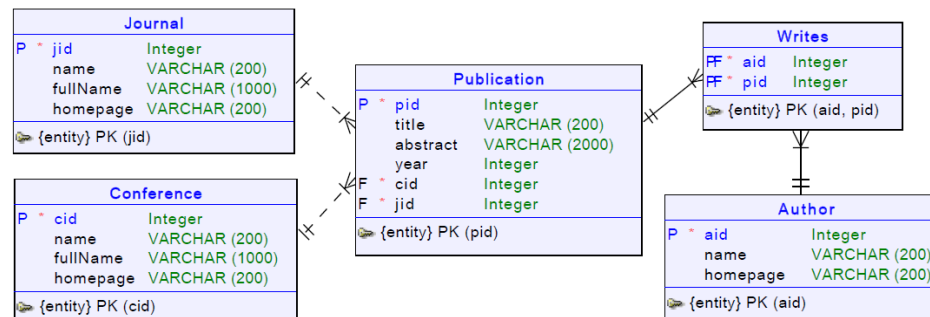
ssn / FixTrunc2 / FixTrunc3 / bigbets CustomerData Dates2 / Layout / Currency / Dates / Abbrevial

Ready Average: 27171 Count: 132 Sum: 27171 106%

Modern program synthesis: SQLizer

[Yaghmazadeh et al. 2017]

Problem: “Find the number of papers in OOPSLA 2010”



Output:

```
SELECT count(Publication.pid)
FROM Publication JOIN Conference ON Publication.cid = Conference.cid
WHERE Conference.name = "OOPSLA" AND Publication.year = 2010
```

Modern program synthesis: Sketch

[Solar-Lezama 2013]

Problem: isolate the least significant zero bit in a word

- example: 0010 0101 → 0000 0010

Easy to implement with a loop

```
int W = 32;
bit[W] isolate0 (bit[W] x) {      // W: word size
    bit[W] ret = 0;
    for (int i = 0; i < W; i++)
        if (!x[i]) { ret[i] = 1; return ret; }
}
```

Can this be done more efficiently with bit manipulation?

- Trick: adding 1 to a string of ones turns the next zero to a 1
- i.e. 000111 + 1 = 001000

Sketch: space of possible implementations

```
/**
 * Generate the set of all bit-vector expressions
 * involving +, &, xor and bitwise negation (~).
 */

generator bit[W] gen(bit[W] x){
    if(??) return x;
    if(??) return ??;
    if(??) return ~gen(x);
    if(??){
        return { | gen(x) (+ | & | ^) gen(x) | };
    }
}
```

Sketch: synthesis goal

```
generator bit[W] gen(bit[W] x, int depth){
    assert depth > 0;
    if(??) return x;
    if(??) return ??;
    if(??) return ~gen(x, depth-1);
    if(??){
        return { | gen(x, depth-1) (+ | & | ^) gen(x, depth-1) | };
    }
}

bit[W] isolate0fast (bit[W] x) implements isolate0 {
    return gen(x, 3);
}
```

Sketch: output

```
bit[W] isolate0fast (bit[W] x) {  
    return (~x) & (x + 1);  
}
```

Modern program synthesis: Synquid

[Polikarpova et al. 2016]

Problem: intersection of strictly sorted lists

- example: intersect [4, 8, 15, 16, 23, 42] [8, 16, 32, 64] → [8, 16]

Also: we want a guarantee that it's correct on all inputs!

Synquid: synthesis goal and components

Step 1: define synthesis goal as a *type*

`intersect :: xs:List a → ys:List a → List a`

sorted list

the set of elements

Step 2: define a set of components

- Which primitive operations is our function likely to use?
- Here: {**Nil**, **Cons**, **<**}

Synquid: synthesis goal and components

Example: Synquid

specification

```
intersect :: xs:SList a →  
  ys:SList a →  
  {v:SList a | elems v = elems xs ∩  
                      elems ys}
```



program

```
intersection = \xs . \ys .  
  match xs with  
  Nil -> xs  
  Cons x xt ->  
    match ys with  
    Nil -> ys  
    Cons y yt ->  
      if x < y  
      then intersection xt ys  
      else  
        if y < x  
        then intersection xs yt  
        else Cons x (intersection xt yt)
```

Synquid: output

	xs	ys	result
intersection = \xs . \ys . match xs with Nil -> xs Cons x xt -> match ys with Nil -> ys Cons y yt -> if x < y then intersection xt ys else if y < x then intersection xs yt else Cons x (intersection xt yt)	[4, 8, 15, 16, 23, 42]	[8, 16, 32, 64]	
	[8, 15, 16, 23, 42]	[8, 16, 32, 64]	[8]
	[15, 16, 23, 42]	[16, 32, 64]	
	[16, 23, 42]	[16, 32, 64]	[8, 16]
	[23, 42]	[32, 64]	
	[42]	[32, 64]	
	[42]	[64]	
	[]	[64]	

What is program synthesis?

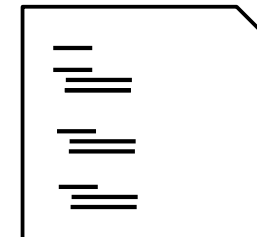
specification



search



program



program
space



What is program synthesis?

Automatic programming?

- but I still have to tell the computer what I want...

level of
abstraction



???

Python, Haskell, ...

C

assembly

machine code

Synthesis

=

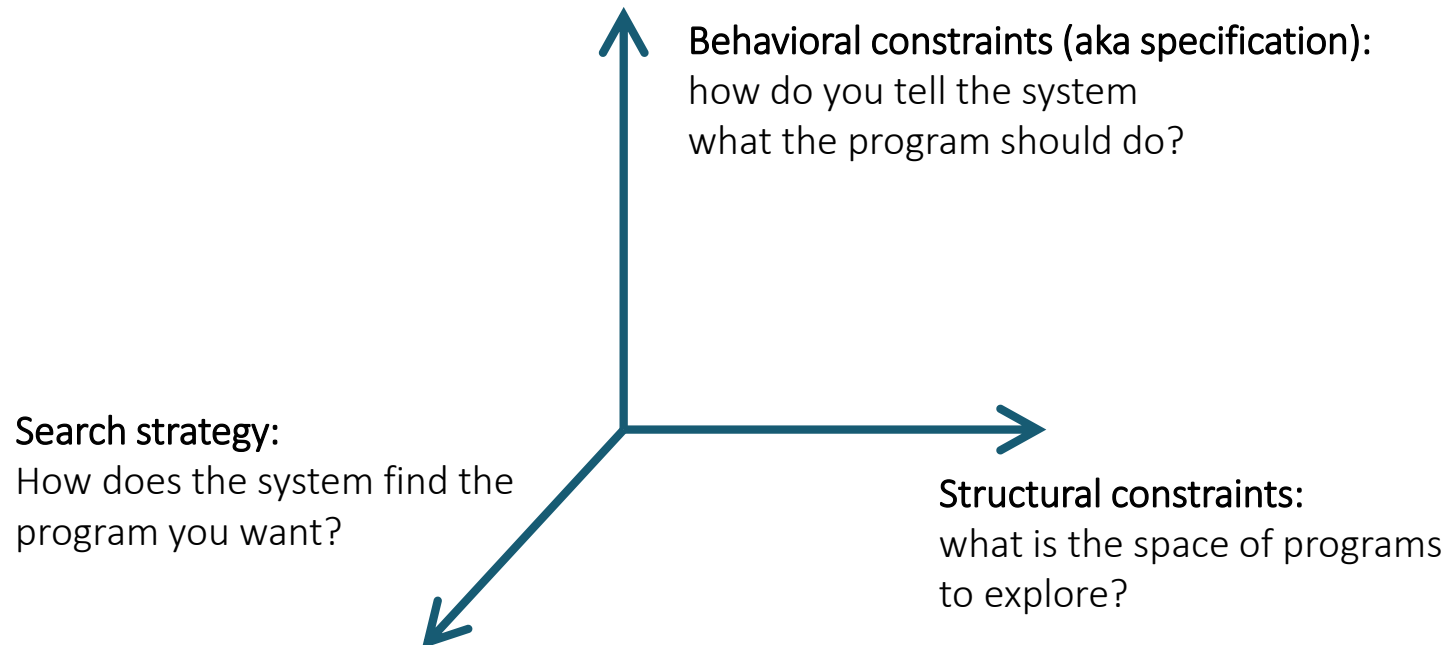
an unusually concise / intuitive
programming language

+

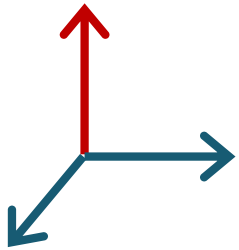
a compiler based on search

Dimensions in program synthesis

[Gulwani 2010]



Behavioral constraints

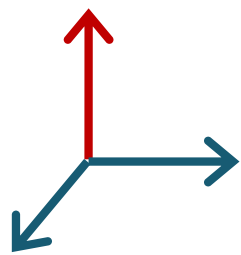


How do you tell the system what the program should do?

- What is the input language / format?
- What is the interaction model?
- What happens when the intent is ambiguous?

Q: What did behavioral constraints look like in FlashFill / Sketch / Synquid / SQLizer?

Behavioral constraints: examples



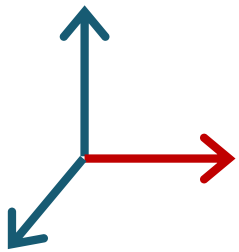
Input/output examples

Equivalent program

Formal specifications (pre/post conditions, types, ...)

Natural language

Structural constraints

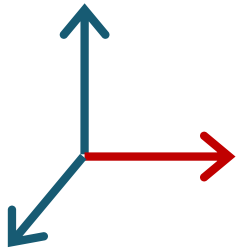


What is the space of programs to explore?

- Large enough to contain interesting programs, yet small enough to exclude garbage and enable efficient search
- Built-in or user defined?
- Can we extract domain knowledge from existing code?

Q: What did structural constraints look like in FlashFill / Sketch / Synquid / SQLizer?

Structural constraints: examples



Built-in DSL

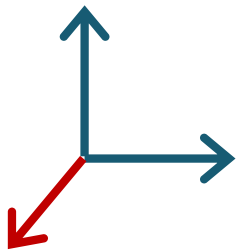
User-defined DSL (grammar)

User-provided components

Languages with synthesis constructs

- e.g. generators in Sketch

Search strategies



Synthesis is search:

- Find a program in the space defined by *structural constraints* that satisfies *behavioral constraints*

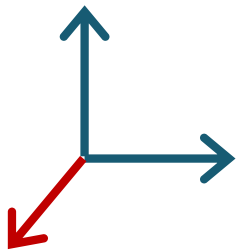
Challenge: the space is astronomically large

- The search algorithm is the heart of a synthesis technique

How does the system find the program you want?

- How does it know it's the program you want?
- How can it leverage structural constraints to guide the search?
- How can it leverage behavioral constraints to guide the search?

Search strategies: examples



Enumerative (explicit) search

- exhaustively enumerate all programs in the language in the order of increasing size

Stochastic search

- random exploration of the search space guided by a fitness function

Representation-based search

- use a data structure to represent a large set of programs

Constraint-based search

- translate to constraints and use a solver

Structure of the Course

Module 1: Searching for Simple Programs

- Easy to decide when a program is correct
- Challenge: search in a large space

Module 2: Searching for Complex Programs

- Deciding when a program is correct can be hard
- Search in a large space is still a problem

Module 3: Applications of Synthesis

- We can search for programs. Now what?

Module 1: Searching for Simple Programs

Example: FlashFill

specification

- 1: "Polikarpova, Nadia" → "Nadia"
- 2: "Van Damme, Jean Claude" → "Jean"

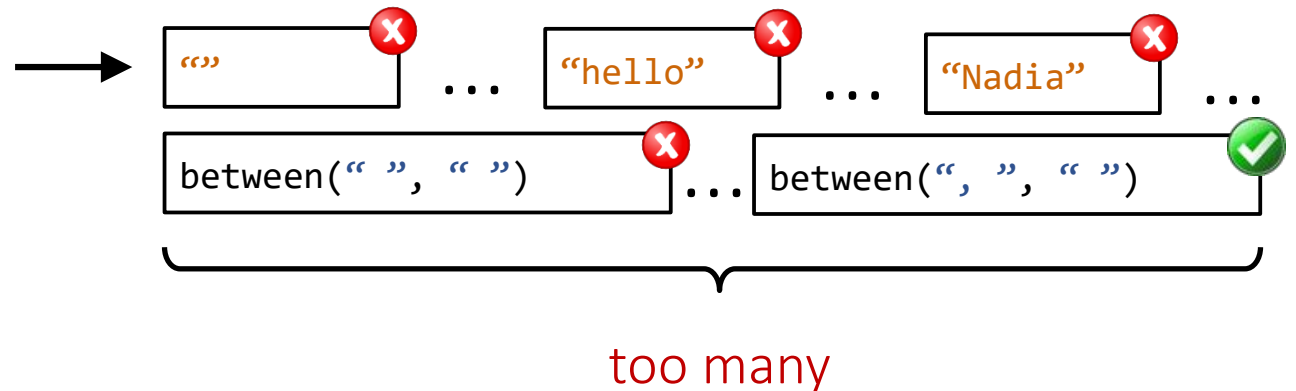
program space

constant string:

"..."

or substring of input:

between("...", "...")



Module 2: Searching for Complex Programs

Example: Synquid

specification

```
intersect :: xs:SList a →  
           ys:SList a →  
           {v:SList a | elems v = elems xs ∩  
                               elems ys}
```



program

```
intersection = \xs . \ys .  
  match xs with  
  Nil -> xs  
  Cons x xt ->  
    match ys with  
    Nil -> ys  
    Cons y yt ->  
      if x < y  
      then intersection xt ys  
      else  
        if y < x  
        then intersection xs yt  
        else Cons x (intersection xt yt)
```

How do we know this program always
produces a sorted list that is the
intersection?

Module 3: Applications of synthesis

Synthesis as a Programming Tool

- How can synthesis help programmers?
- What is the right user interaction model?

Domain-Specific Synthesis

- Super-optimization
- Cryptographic schemes
- SQL Query synthesis
- Graphics kernels

Synthesis as Machine Learning

- Learning interpretable models from few examples