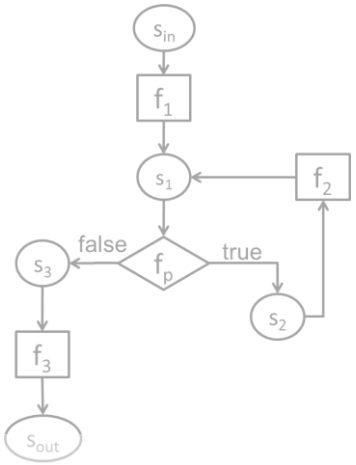
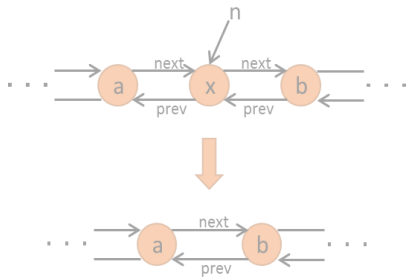
$$\exists c \forall in\ Q(c, in)$$

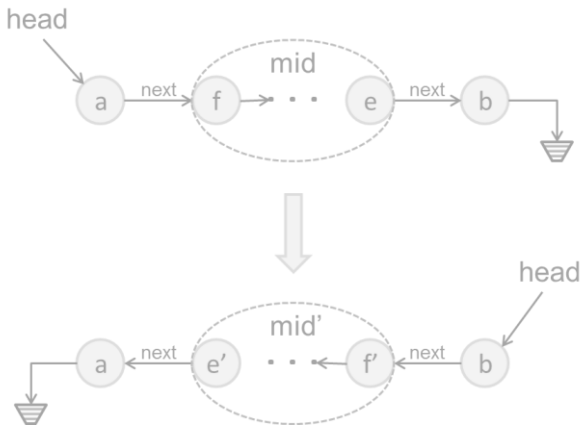
```
/* Average of x and y without using x+y (avoid overflow)*/
int avg(int x, int y){
  int t = expr({x/2, y/2, x%2, y%2, 2 }, {PLUS, DIV});
  assert t == (x+y)/2;
  return t;
}
```

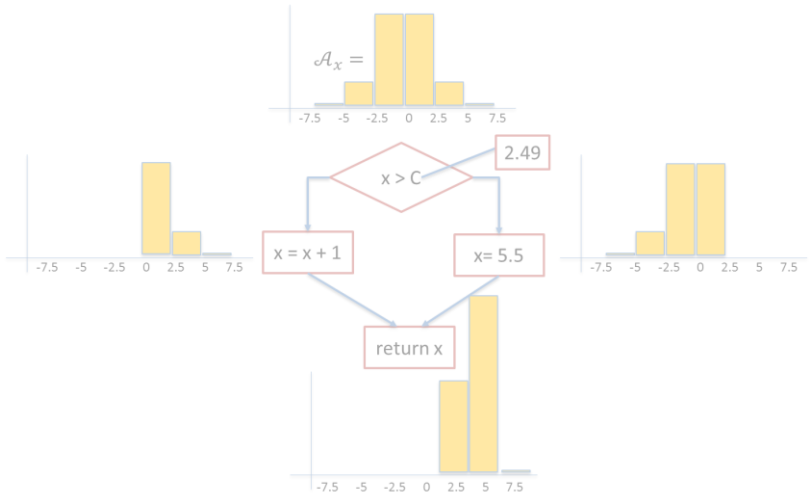





```
{
  s  = n.succ;
  p = n.pred;
  p.succ = s;
  s.pred = p;
}
```

Program Synthesis





$$\varphi(p)$$

$$Sk[c](in)$$

Lecture 1
Course Overview and Introduction to Synthesis

Nadia Polikarpova

Instructor

Nadia Polikarpova

- Assistant Professor
- Member of the ProgSys group since 2017
- Before that: postdoc at MIT with Armando Solar-Lezama
- Before that: PhD at ETH Zurich
- Research areas: program synthesis and program verification

Logistics

Lecture

- When: Tue/Thu 3:30-4:50
- Where: CSE 2154

Office Hours

- When: Fri 4:00-5:00
- Where: my office (CSE 3102)

Course Website

- https://github.com/nadia-polikarpova/cse291-program-synthesis
- To ask questions: use the issue tracker (you'll need a github account)

Goals and activities

1. Understand what program synthesis can do and how

2. Use existing synthesis tools

3. Contribute to synthesis techniques and tools towards a publication in an academic conference

lectures
read and discuss research papers

project

Evaluation

2 credits

Class Participation: 5%

- answer questions in class
- answer your peers' questions on the issue tracker

Paper reviews: 45%

- 9 papers, 5% each

Final Project: 50%

- Team formed by deadline: 5%
- 1-page project proposal: 15%
- Project presentation: 15%
- Final report: 15%

4 credits

Papers reviews

Due on Wed of weeks 2-10, by the end of the day

- First review due next week

Posted on the syllabus page at least a week before due date

Reviews submitted through EasyChair: see wiki

- You will get an email invitation to join the “Program Committee” for CSE291-2020
- Create an EasyChair account **using the email from the invitation** (@uscd instead of @eng!)
- Login as PC Member, not Author
- You will be able to see reviews by others once you submit your own

Review content: see wiki

Project

Kinds of projects:

- re-implement a technique from a paper
- apply existing synthesis framework to a new domain
- extend/improve existing synthesis algorithm or tool
- develop a new synthesis algorithm or tool
- ...

Judged in terms of

- quality of execution
- originality
- scope

Project

Team forming

Teams of 2/3

Pick a project:

- List of suggested projects on the wiki (but feel free to propose your own)
- Talk to me!

Proposal

One page: explain what you plan to do and give some evidence that you've started to work on it

Presentation

During the exam week

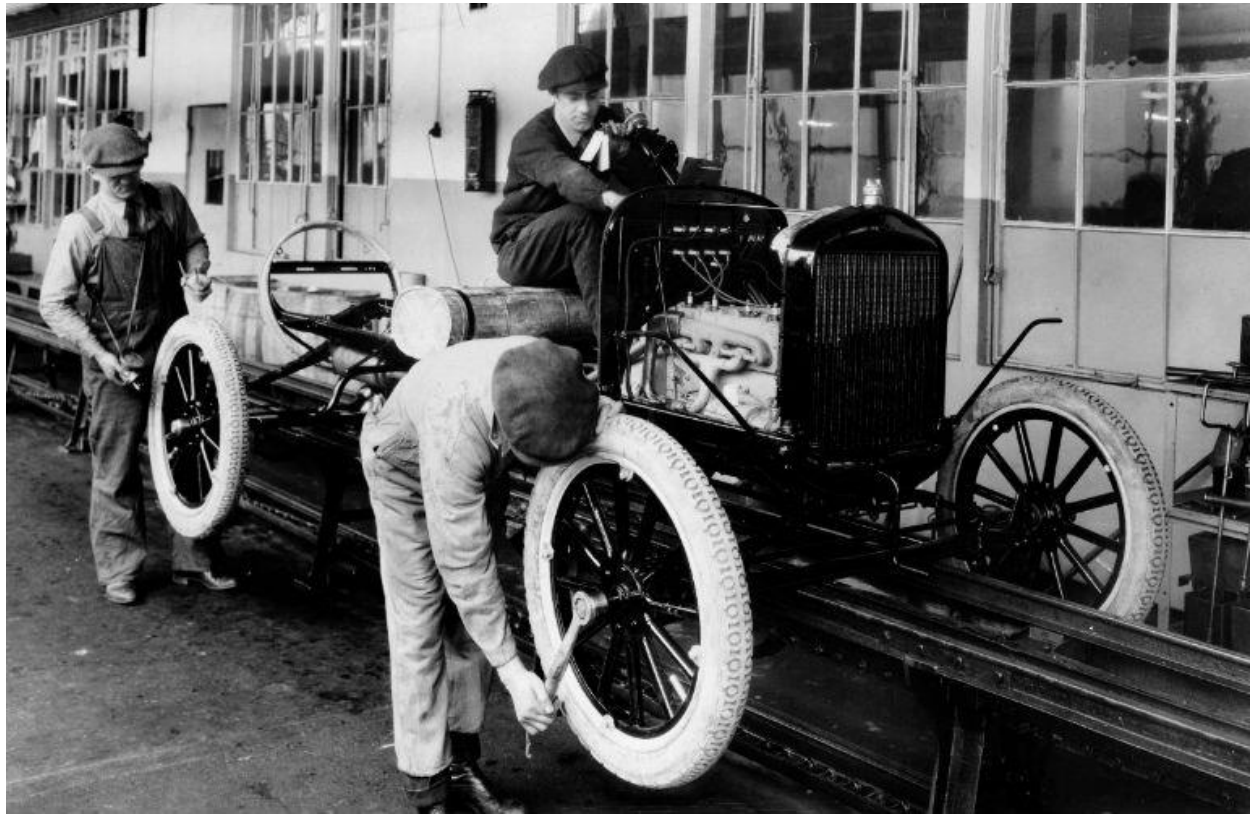
- ~5-10 min per project

Report

3-8 pages, structured like a research paper

And now the good stuff

The goal: automate programming



What is program synthesis?

The FORTRAN Automatic Coding System

J. W. BACKUS†, R. J. BEEBER†, S. BEST‡, R. GOLDBERG†, L. M. HAIBT†,
H. L. HERRICK†, R. A. NELSON†, D. SAYRE†, P. B. SHERIDAN†,
H. STERN†, I. ZILLER†, R. A. HUGHES§, AND R. NUTT‖

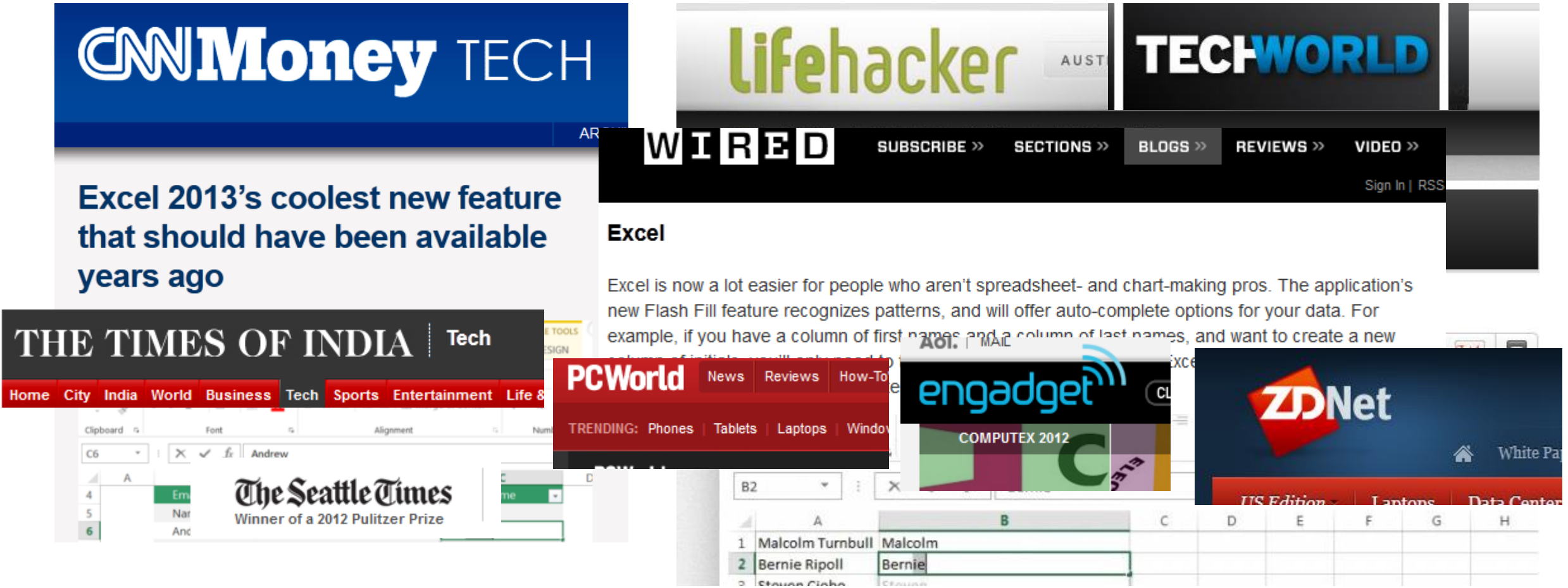
INTRODUCTION

THE FORTRAN project was begun in the summer of 1954. Its purpose was to reduce by a large factor the task of preparing scientific problems for IBM's next large computer, the 704. If it were possible for the 704 to code problems for itself and produce as

system is now complete. It has two components: the FORTRAN language, in which programs are written, and the translator or executive routine for the 704 which effects the translation of FORTRAN language programs into 704 programs. Descriptions of the FORTRAN language and the translator form the principal

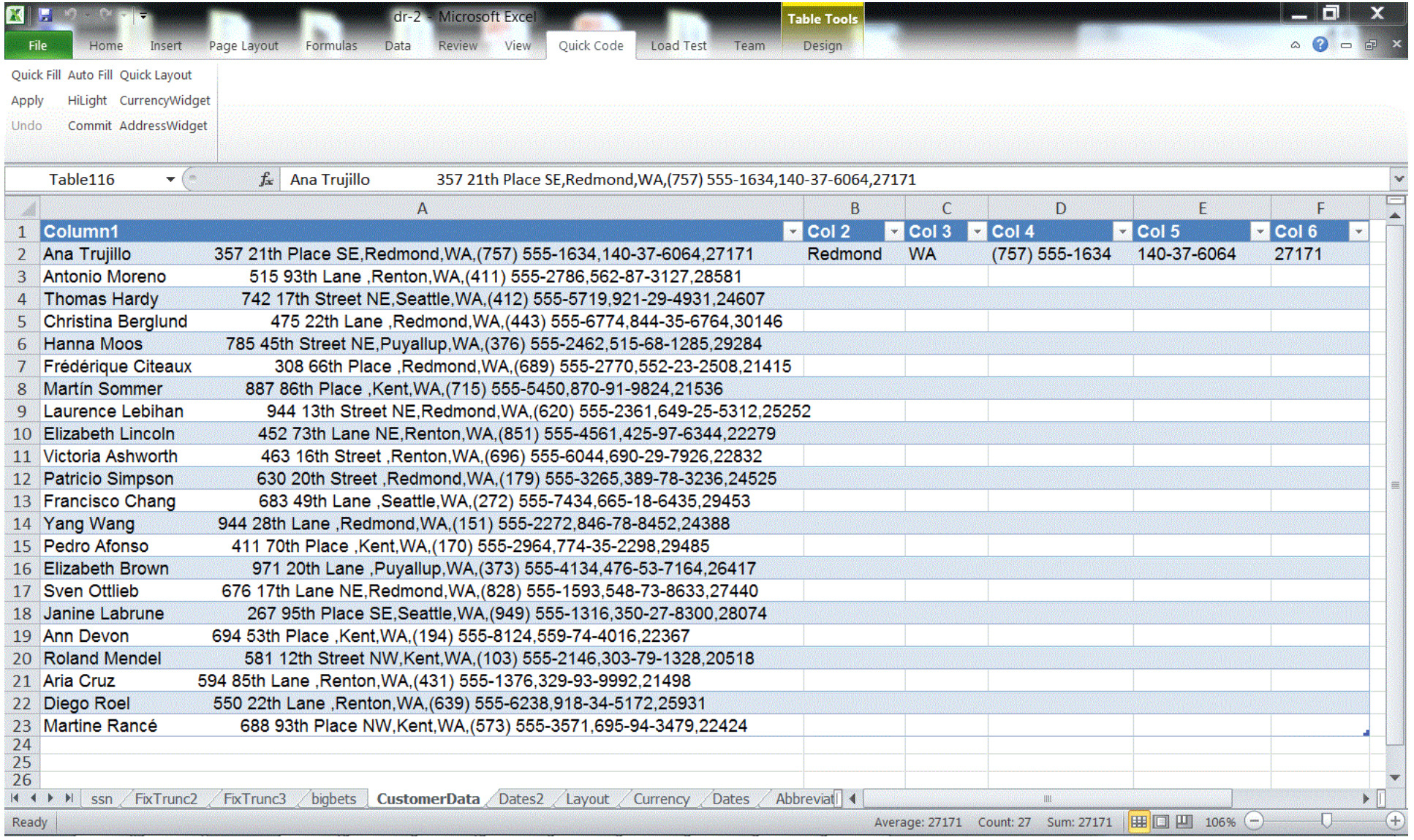
Modern program synthesis: FlashFill

[Gulwani 2011]



FlashFill: a feature of Excel 2013

[Gulwani 2011]



	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
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4	Thomas Hardy 742 17th Street NE,Seattle,WA,(412) 555-5719,921-29-4931,24607					
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6	Hanna Moos 785 45th Street NE,Puyallup,WA,(376) 555-2462,515-68-1285,29284					
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24						
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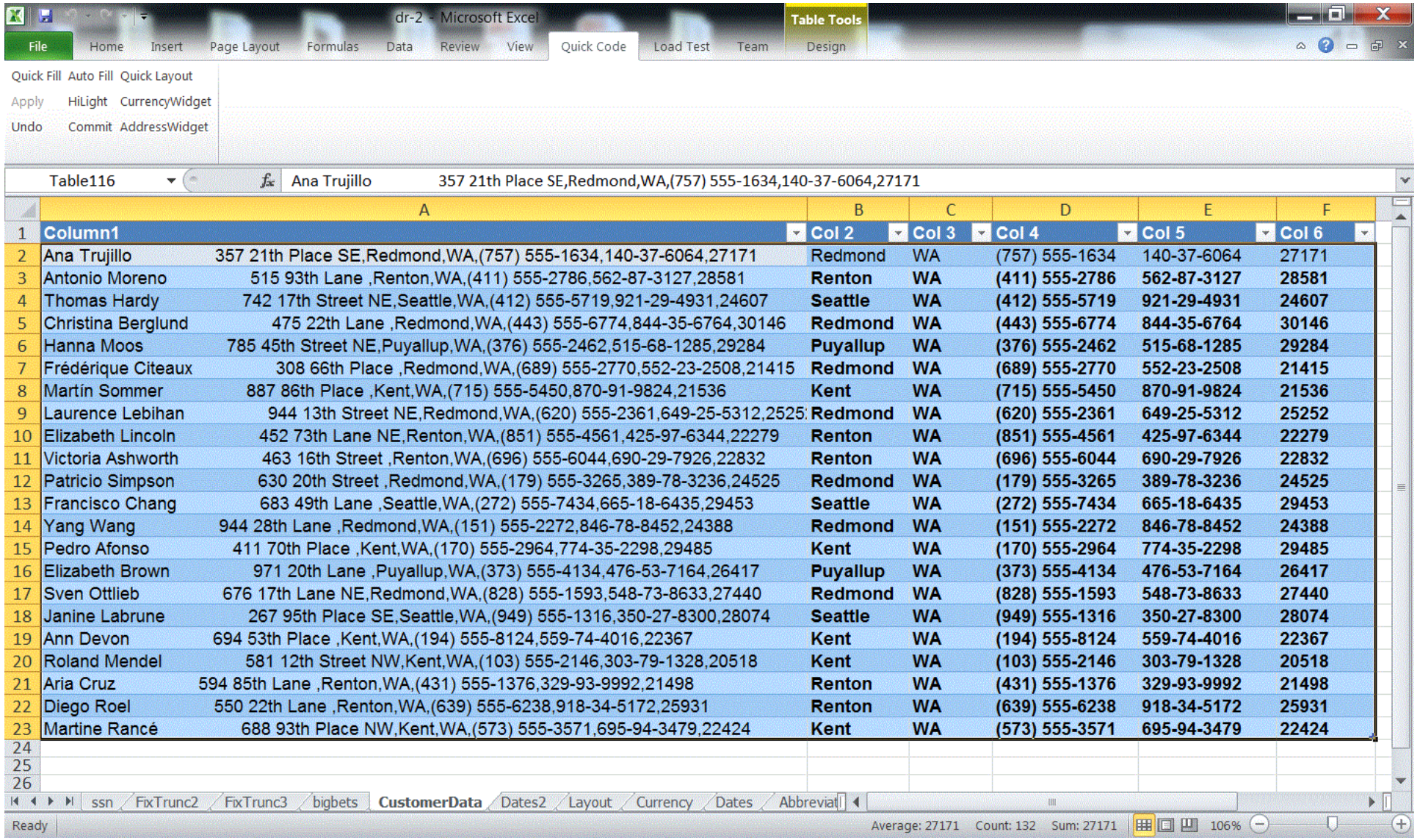
26						

FlashFill: a feature of Excel 2013



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24						
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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]

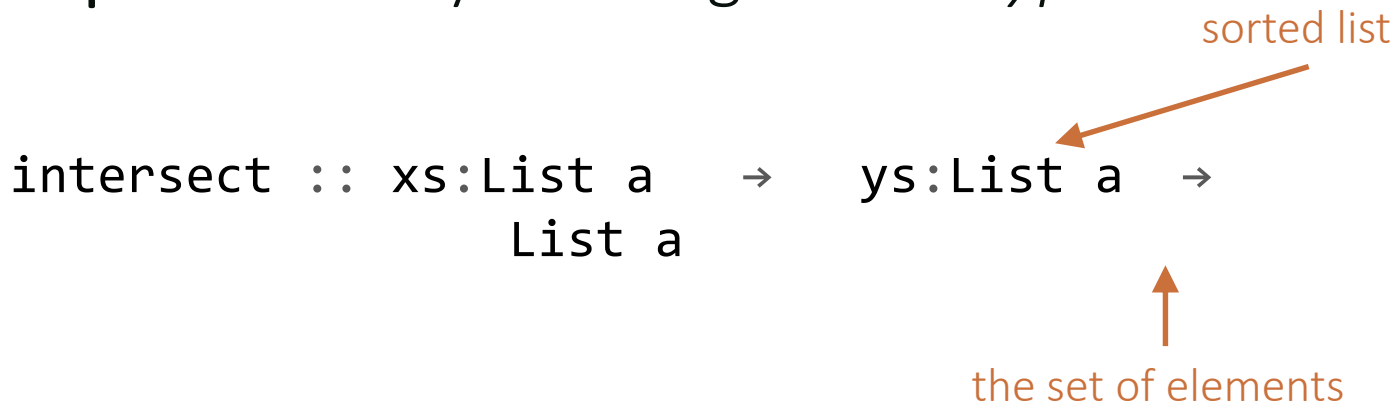
Problem: intersection of strictly sorted lists

- 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*



Step 2: define a set of components

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

Synquid: output

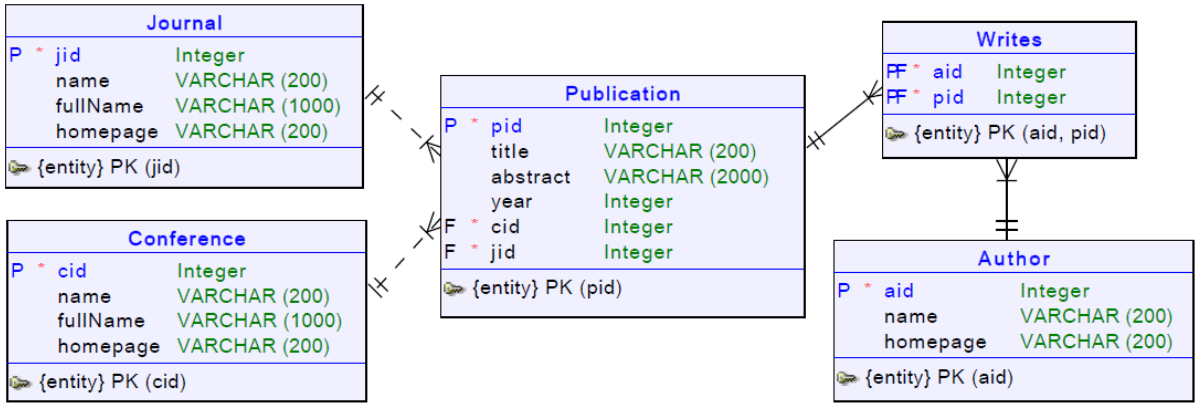
```
intersection = \xs . \ys .
  match xs with
    Nil -> xs
    Cons x xt ->
      match ys with
        Nil -> ys
        Cons y yt ->
          if x < y
          then intersection xt ys
          else
            if y < x
            then intersection xs yt
            else Cons x (intersection xt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

xs	ys	result
[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]	

Modern program synthesis: SQLizer

[Yaghmazadeh et al. 2017]

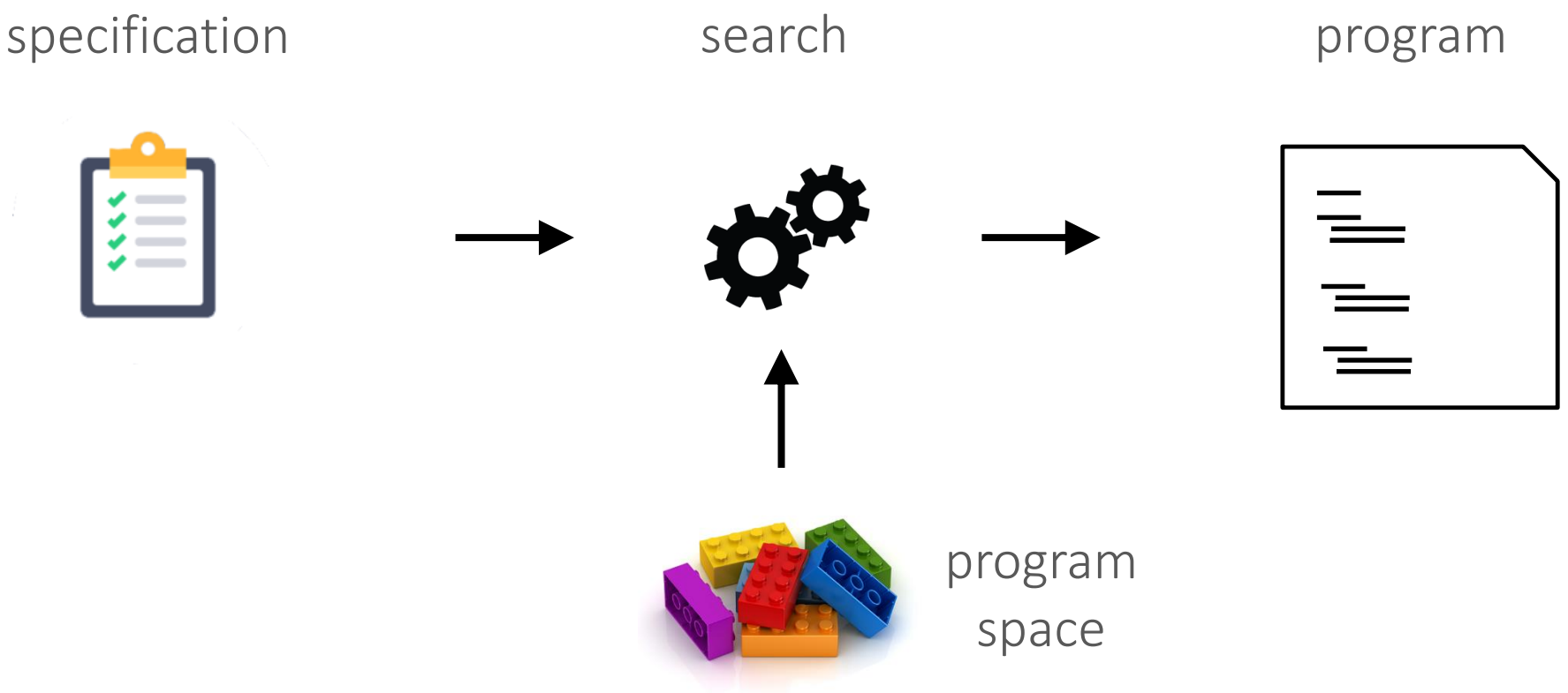
Problem: "Find the number of papers in OOPSLA 2010"



Output:

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

What is program synthesis?



What is program synthesis?

Automatic programming?

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

level of abstraction

???

Python, Haskell, ...

C

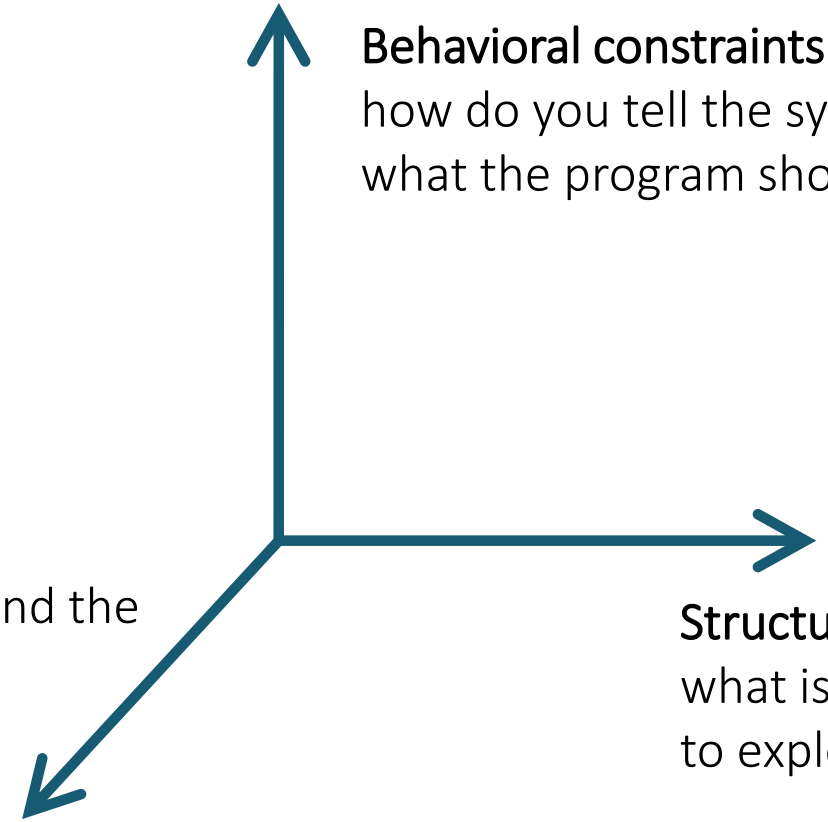
assembly

machine code

Synthesis
=
an unusually concise / intuitive programming language
+
a compiler based on search

Dimensions in program synthesis

[Gulwani 2010]

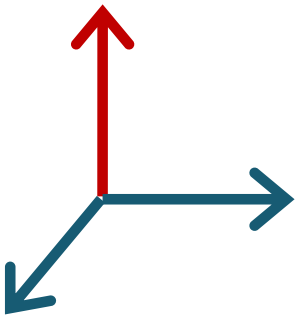


Behavioral constraints (aka specification):
how do you tell the system
what the program should do?

Search strategy:
How does the system find the program you want?

Structural constraints:
what is the space of programs to explore?

Behavioral constraints

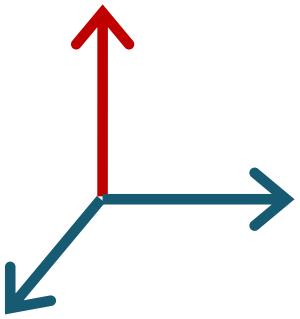


How do you tell the system what the program should do?

- 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



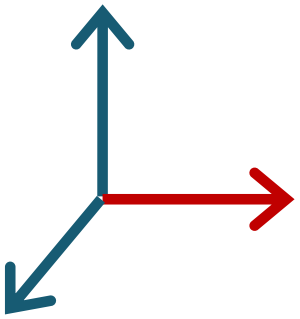
Input/output examples

Equivalent program

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

Natural language

Structural constraints

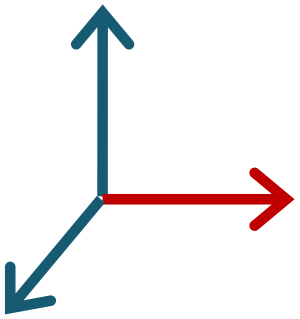


What is the space of programs to explore?

- 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

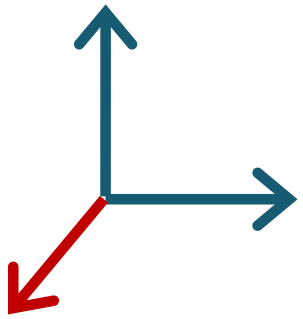
User-defined DSL (grammar)

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*

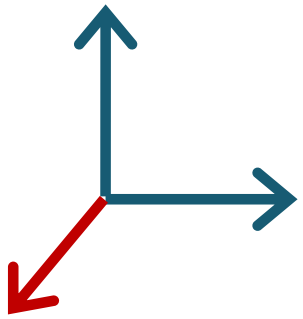
Challenge: the space is astronomically large

- 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”

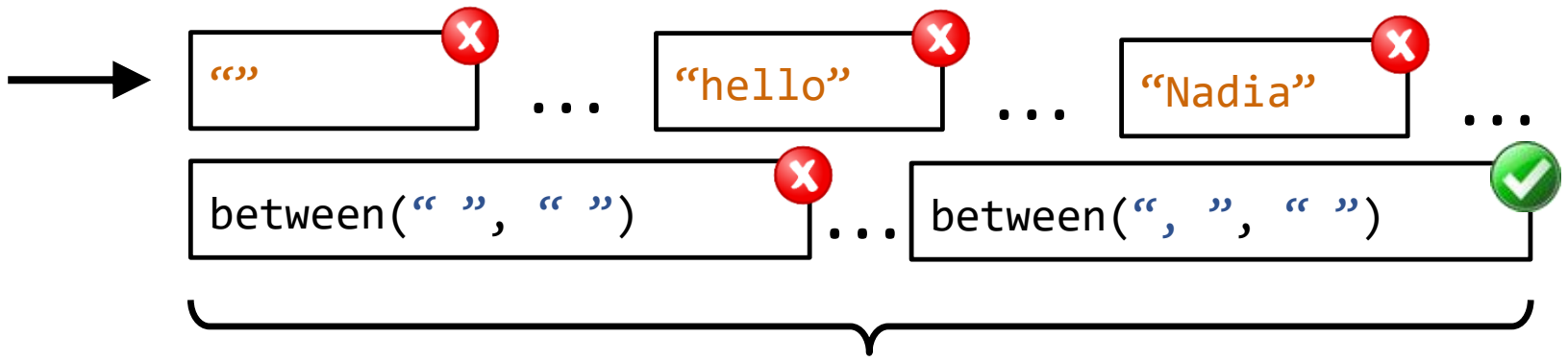
program space

constant string:

“…”

or substring of input:

between(“…”, “…”)



too many

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

Weeks 1-2

Topic: Enumerative synthesis from examples

Paper: Alur, Radhakrishna, Udupa. Scaling Enumerative Program Synthesis via Divide and Conquer

- Review due Wednesday
- Link to PDF on the course wiki
- Submit through EasyChair (check email for invite)

Project:

- Teams due next Friday
- Submit through a Google Sheet (check email for invite and instructions)