# #1: Course Overview

**Sankha Narayan Guria**

EECS 700: Introduction to Program Synthesis

# Instructor

## Sankha Narayan Guria

- Assistant Professor starting this Fall
- Previously: PhD @ University of Maryland
- Research Areas: Program synthesis and program analysis

# Logistics

- Lectures:
  - Mon Wed Fri: 3:00 - 3:50pm LEEP2 G411

But you already knew that!

- Office Hours:
  - Wed: 4:00 - 5:00pm Eaton 2034
- Course Website:
  - https://sankhs.com/eecs700/
  - Communications through Canvas and Discord

# Objectives

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

- **Class Participation**
  - Ask/answer questions in class
  - Participate in discussions on Discord
- **Paper Reviews**
  - 9 papers, 5% each
- **Final Project**
  - Team formed by deadline: 5%
  - 1 page project proposal: 15%
  - Project presentation: 15%
  - Final report: 15%

# Paper Reviews

- Due on Thursday, by end of day
  - First review is due next week!
- Will be posted on website a week before due date
- Reviews submitted via Canvas
  - Link on website
- Website has details of review guidelines
- Discussion:
  - Before review is due: discuss on Discord
  - After review is due: discuss in class (Friday)

# Project

- **Kinds of projects:**
  - Re-implement techniques 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

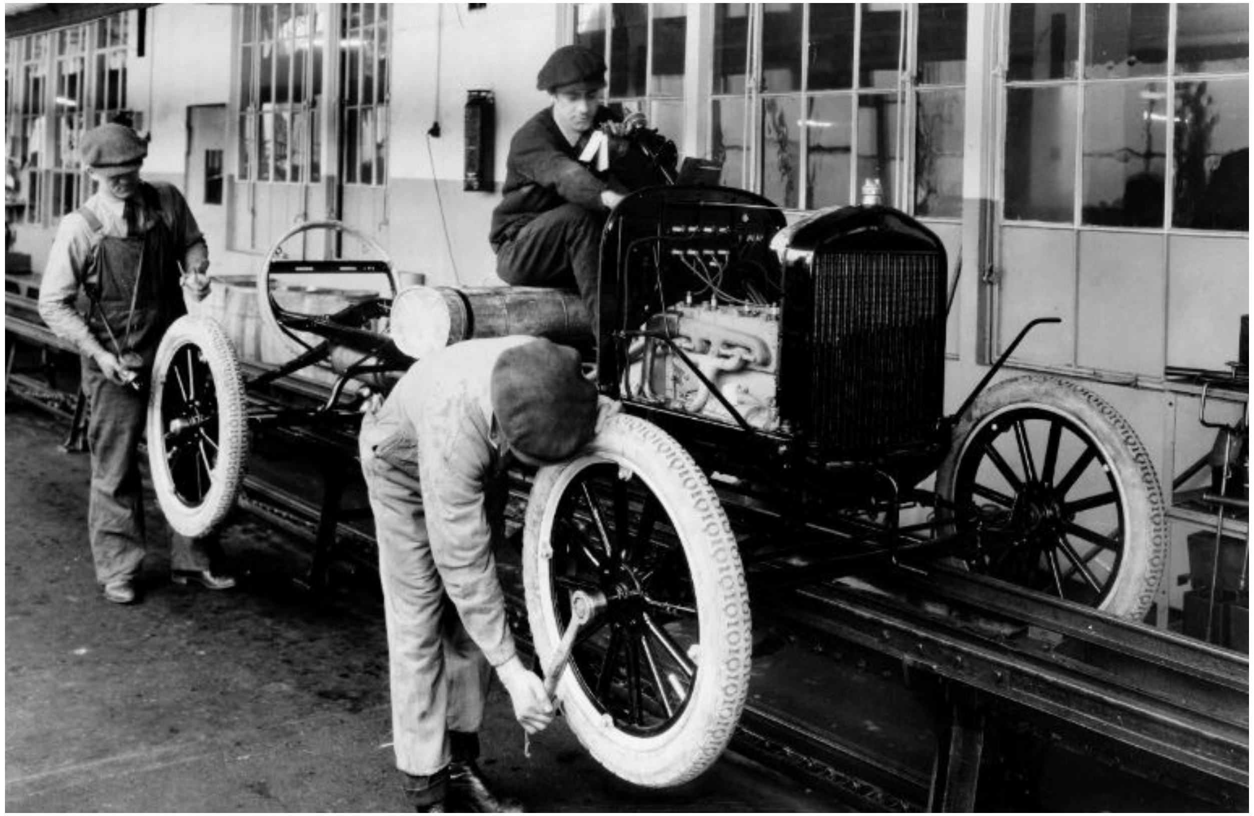
# Project

- Team forming
- Proposal
- Presentation
- Report

- Teams of 2-3
- Pick a project:
  - List of suggested projects coming soon on website
  - Please talk to me!
- One page: explain what you plan to do and give some evidence that you've started to work on it
- Presentations in last few classes
  - ~10-15 min per project
- 3-8 pages, structured like a research paper

# Now to 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

```
append:
    push ebp
    mov ebp, esp
    push eax
    push ebx
    push len
    call malloc
    mov ebx, [ebp + 12]
    mov [eax + info], ebx
    mov dword [eax + next], 0
    mov ebx, [ebp + 8]
    cmp dword [ebx], 0
    je null_pointer
    mov ebx, [ebx]

next_element:
    cmp dword [ebx + next], 0
    je found_last
    mov ebx, [ebx + next]
    jmp next_element

found_last:
    push eax
    push addMes
    call puts
    add esp, 4
    pop eax
    mov [ebx + next], eax

go_out:
    pop ebx
    pop eax
    mov esp, ebp
    pop ebp
    ret 8

null_pointer:
    push eax
    push nullMes
    call puts
    add esp, 4
    pop eax
    mov [ebx], eax
    jmp go_out
```

Assembly

```
void insert(node *xs, int x) {
  node *new;
  node *temp;
  node *prev;

  new = (node *)malloc(sizeof(node));
  if(new == NULL) {
    printf("Insufficient memory.");
    return;
  }
  new->val = x;
  new->next = NULL;
  if (xs == NULL) {
    xs = new;
  } else if(x < xs->val) {
    new->next = xs;
    xs = new;
  } else {
    prev = xs;
    temp = xs->next;
    while(temp != NULL && x > temp->val) {
      prev = temp;
      temp = temp->next;
    }
    if(temp == NULL) {
      prev->next = new;
    } else {
      new->next = temp;
      prev->next = new;
    }
  }
}
```

C

“Any sufficiently advanced compiler is indistinguishable from a synthesizer”

```
insert x []       = [x]
insert x (y:ys)
  | x ≤ y         = x:y:ys
  | otherwise     = y:(insert x ys)
```

Haskell

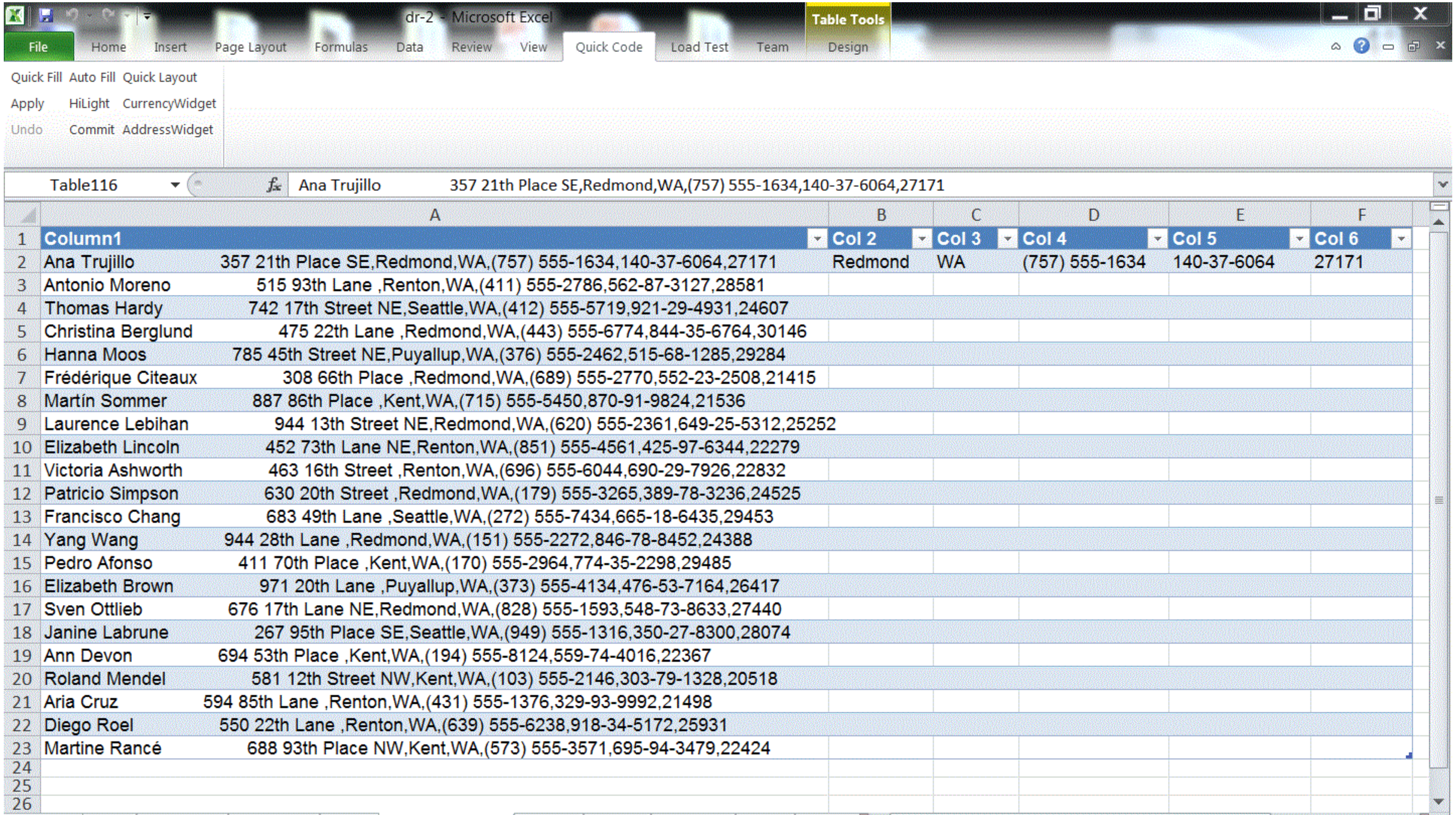
?

modern program synthesis

# Modern program synthesis: FlashFill


[Gulwani 2011]

# FlashFill: a feature of Excel 2013




| | 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 | | | | | |
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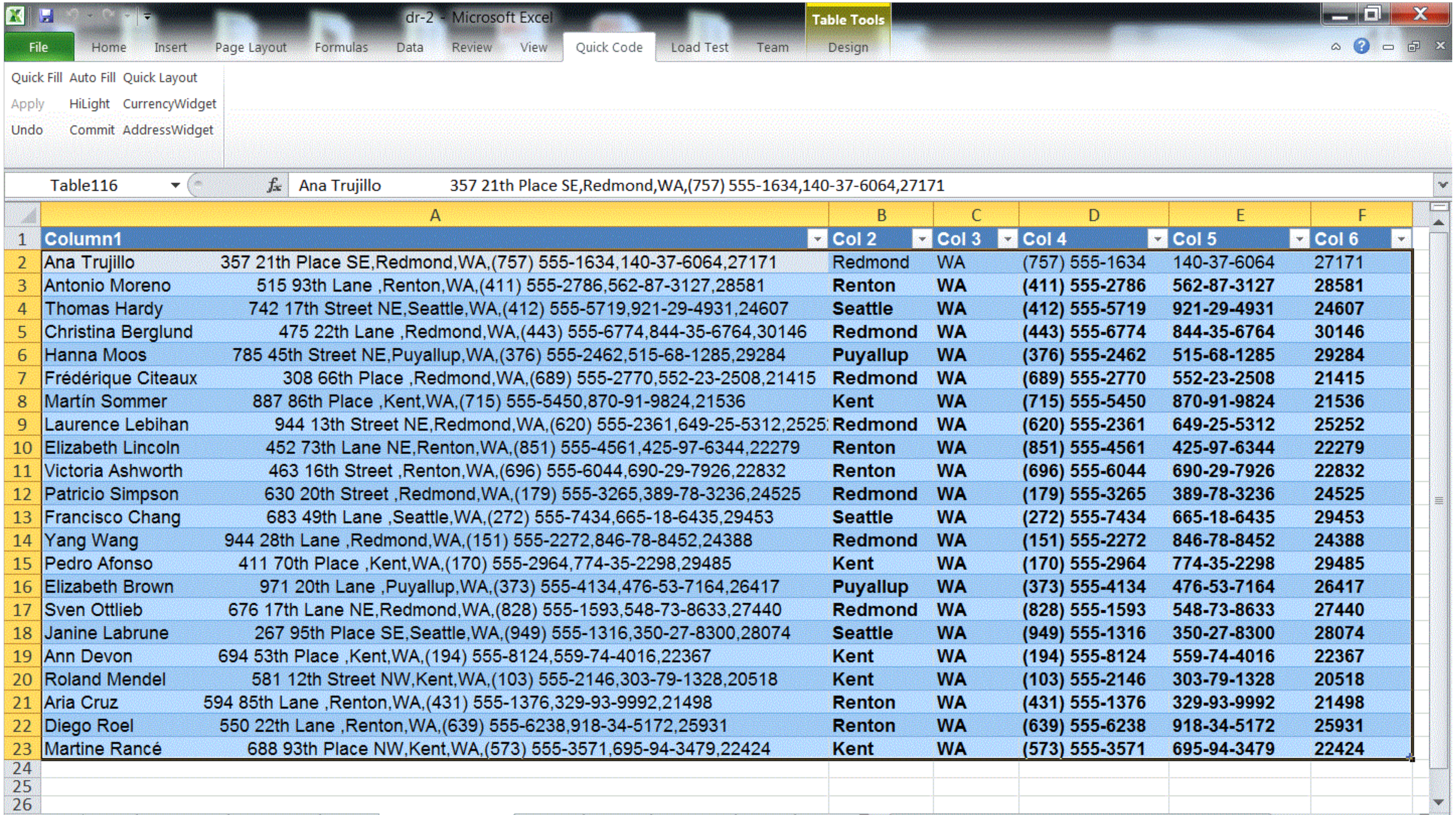
# FlashFill: a feature of Excel 2013

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# Modern program synthesis: Sketch

- **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

[Solar-Lezama 2013]

# 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);
}
```

```
 ~0010 0101         0010 0101 + 1
= 1101 1010       = 0010 0110

               &
          0000 0010
```

# Modern program synthesis: Synquid

- **Problem:** intersection of sets represented as 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!

[Polikarpova et al. 2016]

# 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: 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: GitHub Copilot

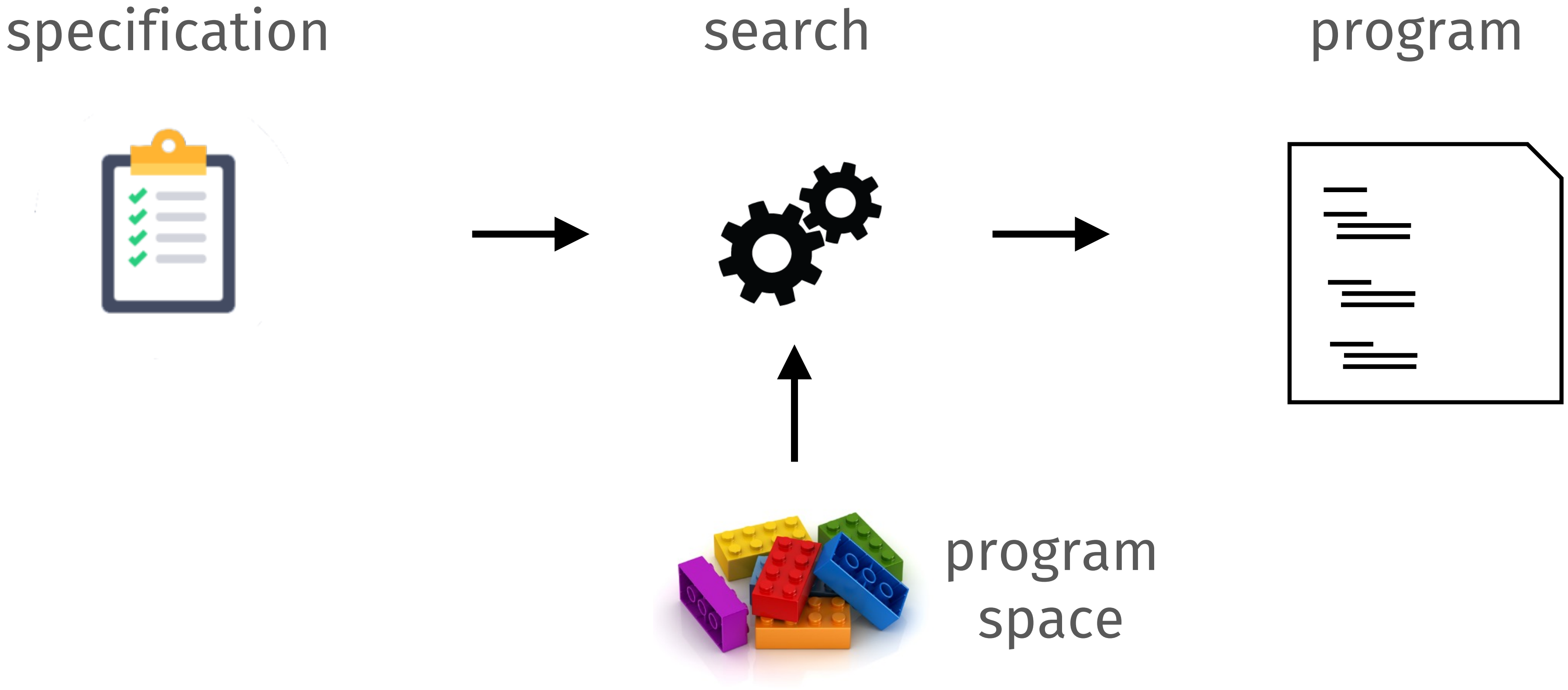
```
// find all images
// and add a green border around them
// and add class “githubCopilot” to them
function go() {

 var images = document.getElementByTagName(‘img’);
 for (var i = 0; i < images.length; i++) {
   if (images[i].className.indexOf(‘githubCopilot’) == -1) {
     images[i].className += ‘ githubCopilot’;
     images[i].style.border = ‘1px solid green’;
   }
 }
```

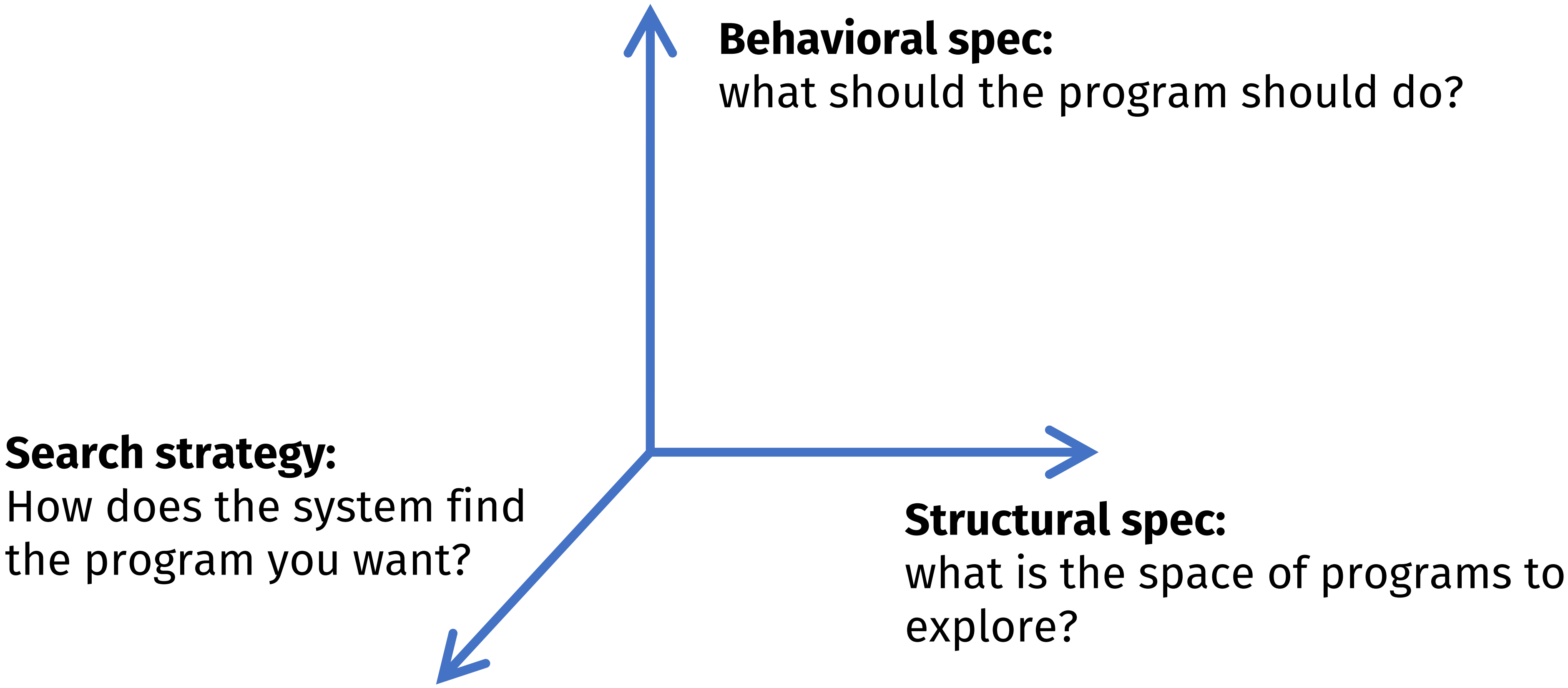
input

output

# What is program synthesis?

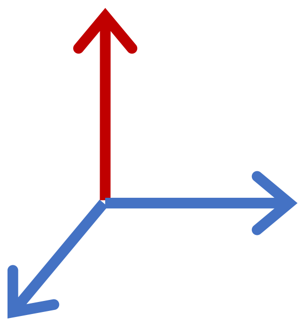


# Dimensions in program synthesis




[Gulwani 2010]

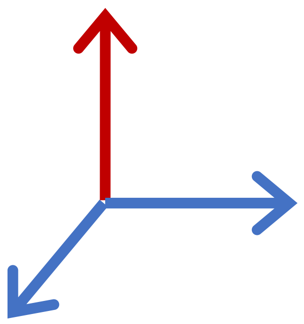
# Behavioral spec



- 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?

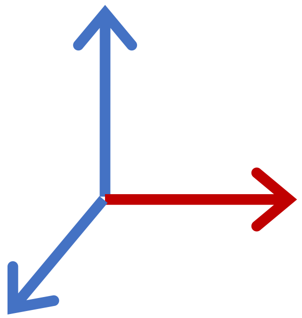
- **Q:** What did the behavioral spec look like in FlashFill / Sketch / Synquid / Copilot?

# Behavioral spec: examples



- Input/output examples
- Reference implementation
- Formal specifications (pre/post conditions, types, …)
- Natural language
- Context

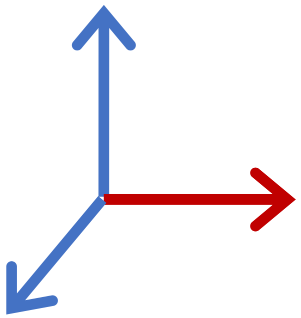
# Structural spec



- 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?

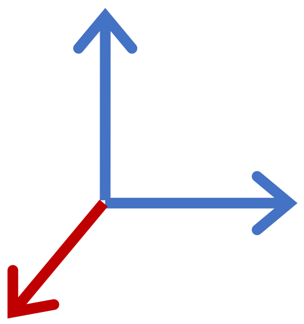
- **Q:** What did the structural spec look like in FlashFill / Sketch / Synquid / Copilot?

# Structural spec: examples



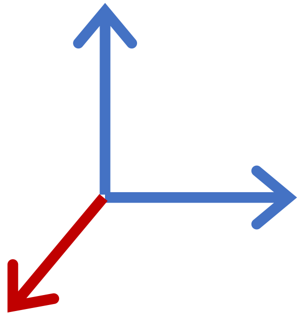
- Built-in DSL
- User-defined DSL (grammar)
- User-provided components
- Languages with synthesis constructs
  - e.g. generators in Sketch
- Learned language model

# 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