#1: Course Overview

Sankha Narayan Guria

EECS 700: Introduction to Program Synthesis

Instructor

Sankha Narayan Guria

- Assistant Professor @ EECS
- Teaching this class
- Research: Program synthesis, program analysis, type systems

Why take this class?

- Software is an amazing idea
  - One of the core drivers of computer science
- Software is not just something humans write
  - Intended to be read and manipulated by a machine
- Running code: Compilers or Interpreters
  - Interpreter = run a programming language to compute the result
  - Compiler = translator from one programming language to the other
- But running code is not the only possibility …

Three related ideas

- Program Analysis
  - Prove facts about program behavior
  - Grew out of optimizing compilers
  - Most popular use today: static bug detection
- Program Verification
  - How to argue that a program is correct?
  - State of the art: machine checked proofs of correctness
- Program Synthesis
  - Writing code is hard!
    - Good for employment of software engineers, but maybe bad overall
  - Develop ways to search for code satisfying a specification
  - Key difference from machine learning: resulting program should always work, not just probabilistically.

Logistics

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

But you already knew that!

- Office Hours:
  - Wed: 2:00 - 3:00pm Eaton 2034

- Course Website:
  - https://sankhs.com/eecs700/
  - Communications through Canvas

Objectives

1. Understand what program synthesis can do and how

- Lectures
- Read and discuss research papers

2. Use existing synthesis tools

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

- Project

Evaluation

- **Class Participation**
    - Ask/answer questions in class
    - Participate in discussions on Canvas
- **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 Canvas
    - 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

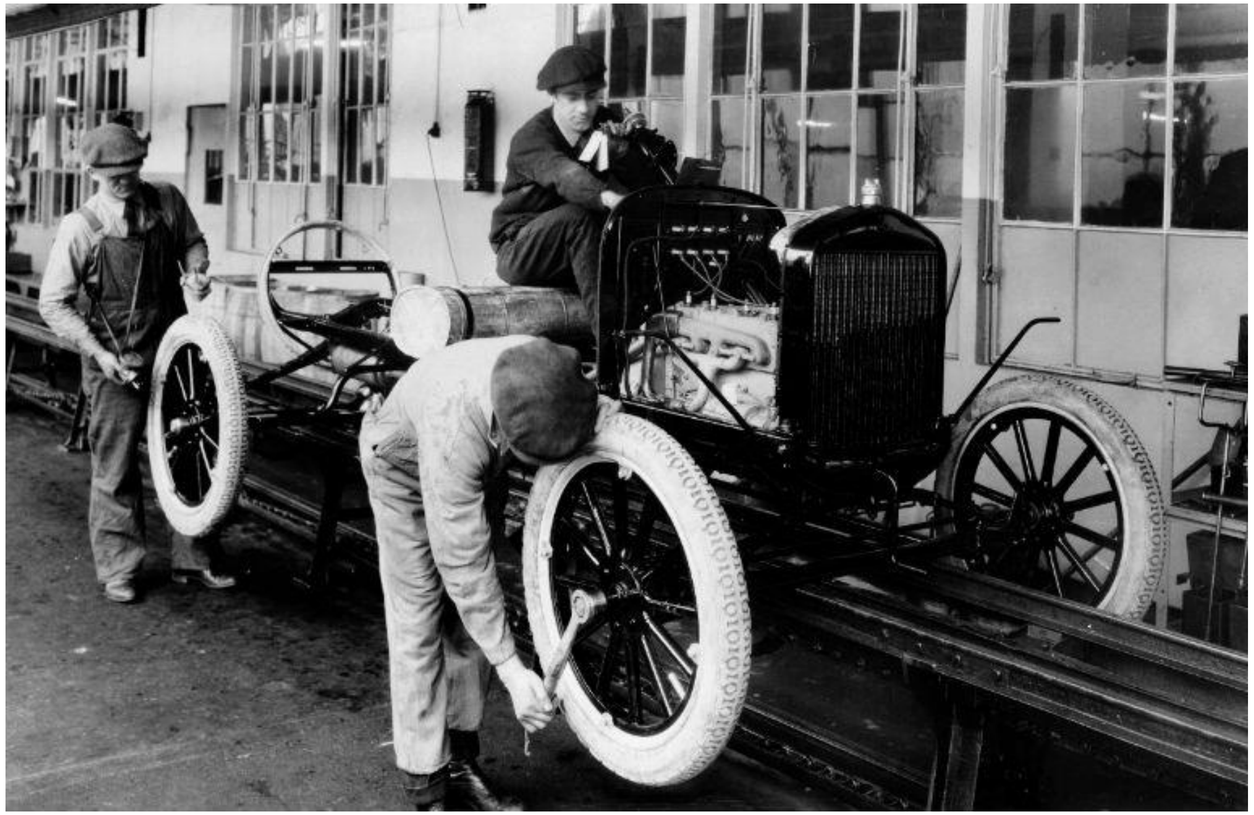
Project

- Team forming
- Proposal
- Presentation
- Report

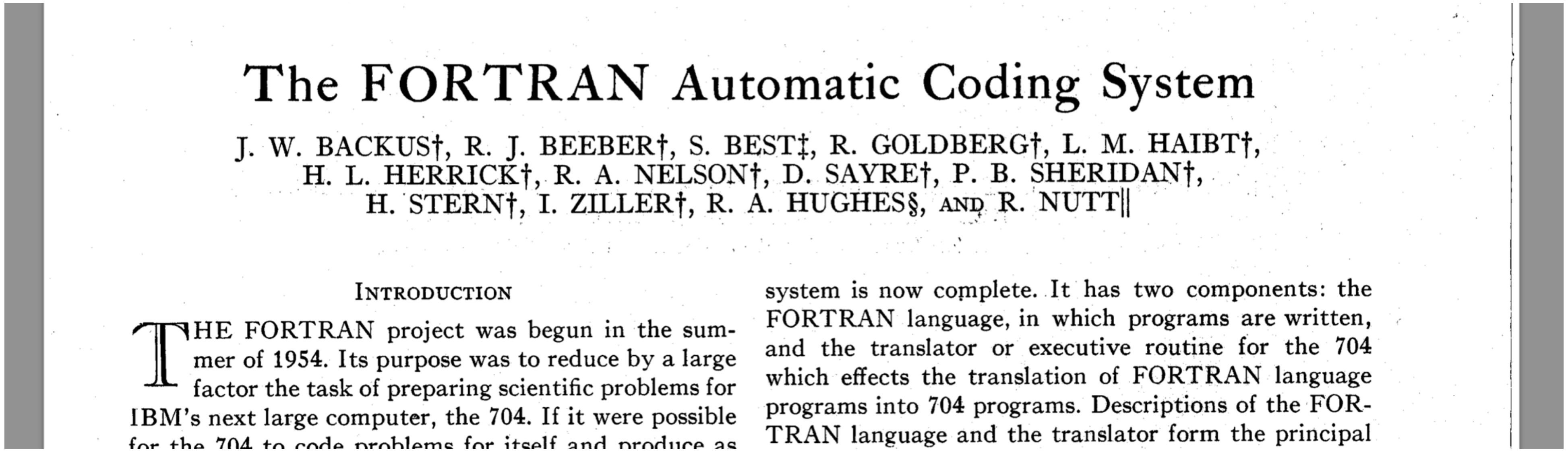
- Teams of 2-3
- Pick a project:
  - List of suggested projects on website
  - Please talk to me!
- One page: explain what you plan to do and give some evidence that you've started to work on it
- Presentations in last few classes
  - ~10-15 min per project
- 5-8 pages, structured like a research paper

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
```

```
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;
    }
  }
}
```

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

"Any sufficiently advanced compiler is indistinguishable from a synthesizer"

?

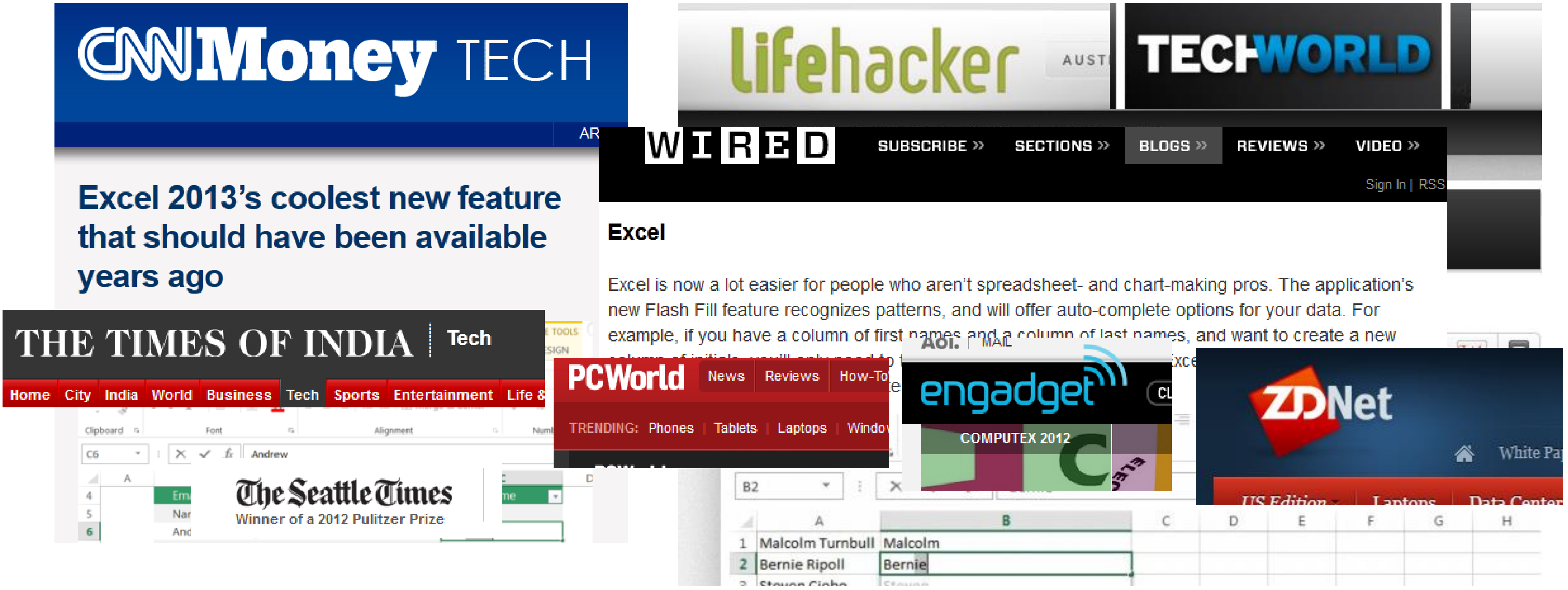
Assembly

C

Haskell

modern program synthesis

Modern program synthesis: FlashFill



Excel 2013's coolest new feature that should have been available years ago

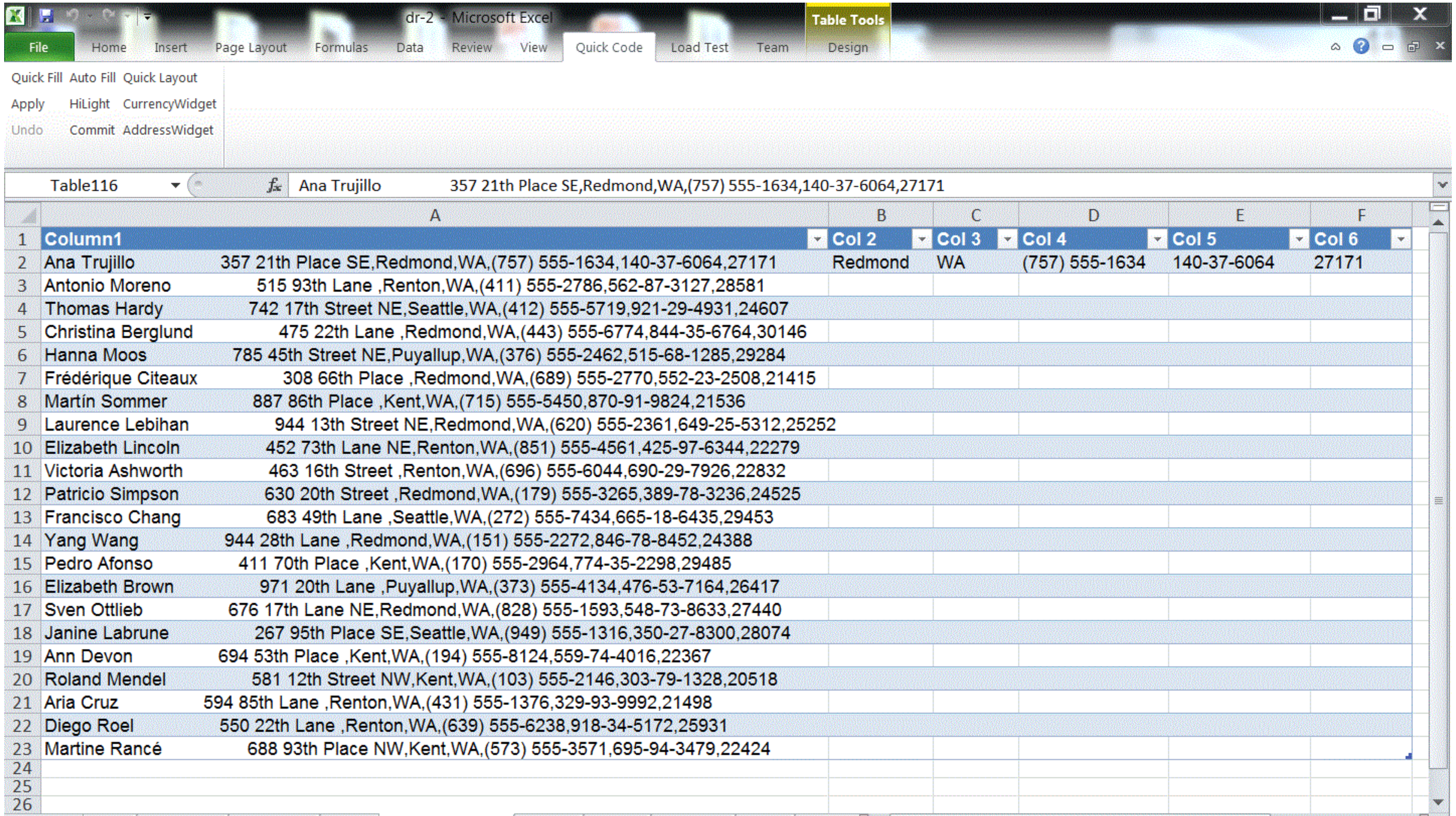
Excel

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

	A	B	C	D	E	F	G	H
1	Malcolm Turnbull	Malcolm						
2	Bernie Ripoll	Bernie						
3	Steven Ciobo	Steven						

[Gulwani 2011]

FlashFill: a feature of Excel 2013



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

	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					
4	Thomas Hardy 742 17th Street NE,Seattle,WA,(412) 555-5719,921-29-4931,24607					
5	Christina Berglund 475 22th Lane ,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					
7	Frédérique Citeaux 308 66th Place ,Redmond,WA,(689) 555-2770,552-23-2508,21415					
8	Martín Sommer 887 86th Place ,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					
10	Elizabeth Lincoln 452 73th Lane NE,Renton,WA,(851) 555-4561,425-97-6344,22279					
11	Victoria Ashworth 463 16th Street ,Renton,WA,(696) 555-6044,690-29-7926,22832					
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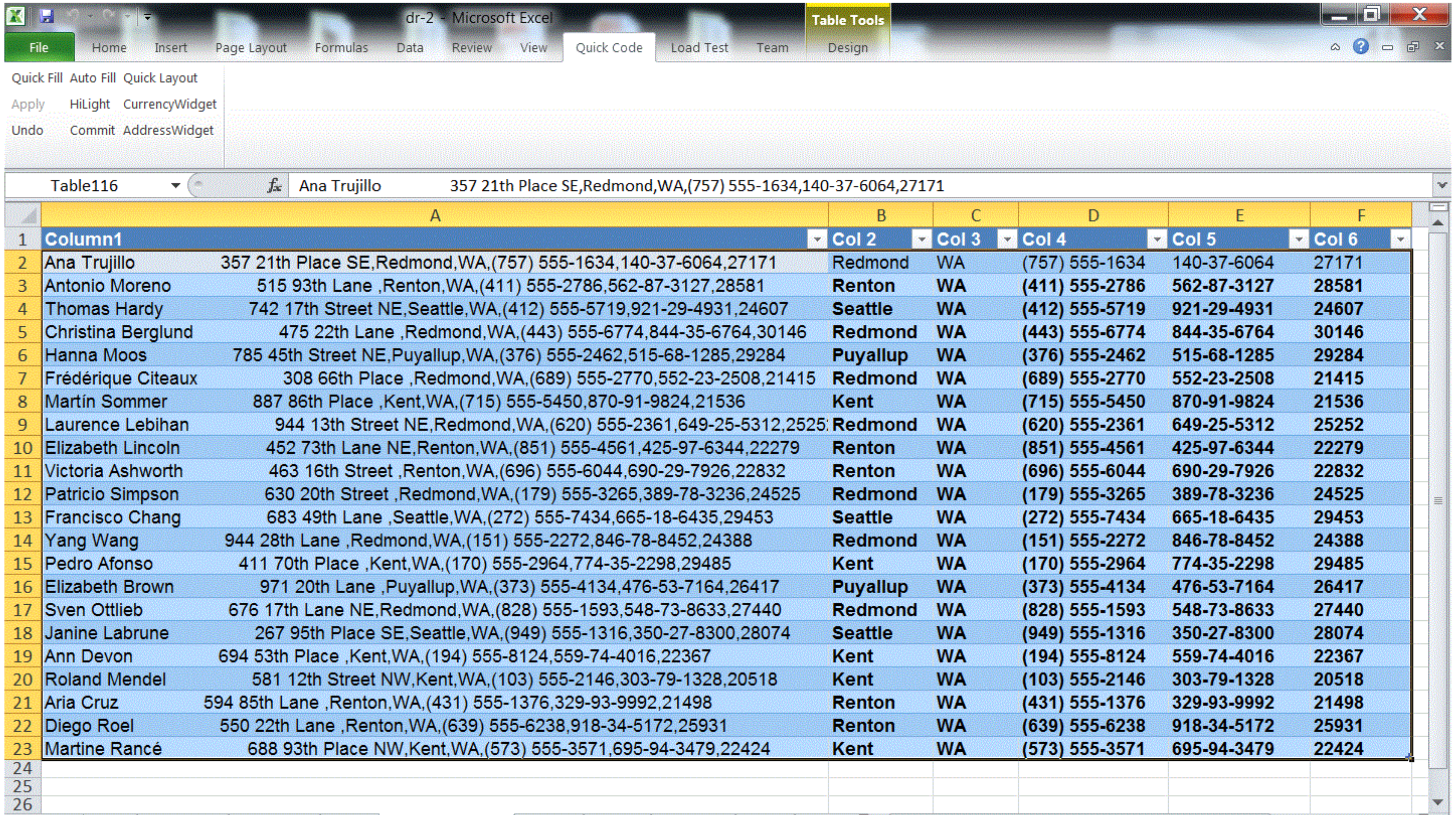
13	Francisco Chang 683 49th Lane ,Seattle,WA,(272) 555-7434,665-18-6435,29453					
14	Yang Wang 944 28th Lane ,Redmond,WA,(151) 555-2272,846-78-8452,24388					
15	Pedro Afonso 411 70th Place ,Kent,WA,(170) 555-2964,774-35-2298,29485					
16	Elizabeth Brown 971 20th Lane ,Puyallup,WA,(373) 555-4134,476-53-7164,26417					
17	Sven Ottlieb 676 17th Lane NE,Redmond,WA,(828) 555-1593,548-73-8633,27440					
18	Janine Labrune 267 95th Place SE,Seattle,WA,(949) 555-1316,350-27-8300,28074					
19	Ann Devon 694 53th Place ,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					
21	Aria Cruz 594 85th Lane ,Renton,WA,(431) 555-1376,329-93-9992,21498					
22	Diego Roel 550 22th Lane ,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					

FlashFill: a feature of Excel 2013



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24						
25						
26						

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*

sorted list

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

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

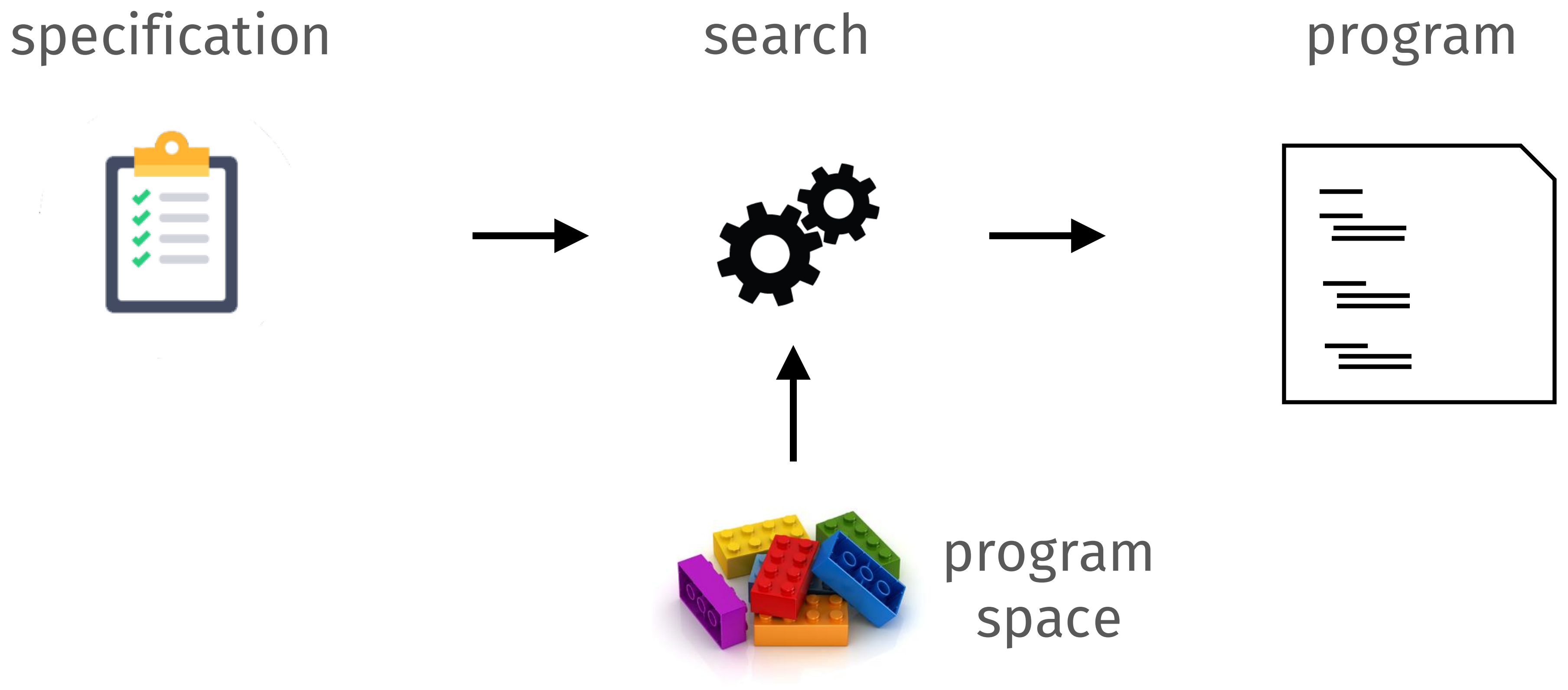
```
// find all images
// and add a green border around them
// and add class “githubCopilot” to them
function go() {

 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’;
   }
 }
```

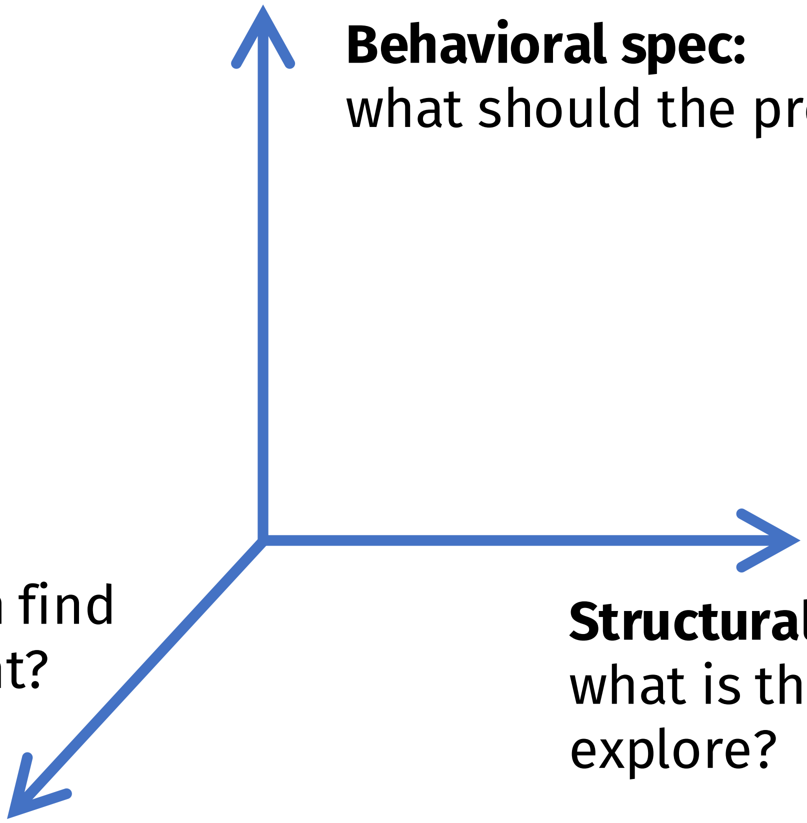
input

output

What is program synthesis?



Dimensions in program synthesis



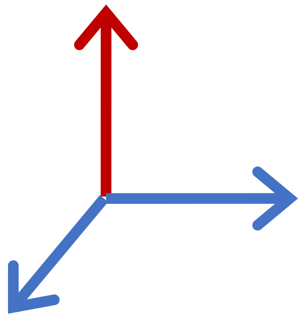
Behavioral spec:
what should the program should do?

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

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

[Gulwani 2010]

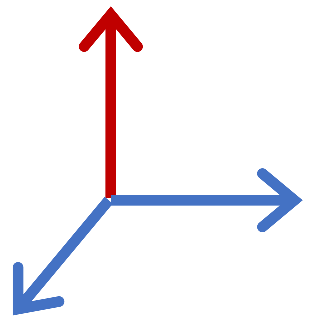
Behavioral spec



- 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?

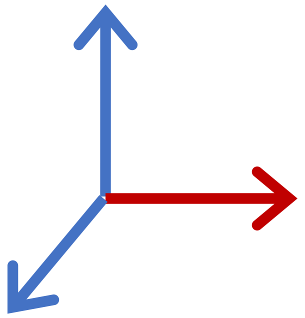
- **Q:** What did the behavioral spec look like in FlashFill / Sketch / Synquid / Copilot?

Behavioral spec: examples



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

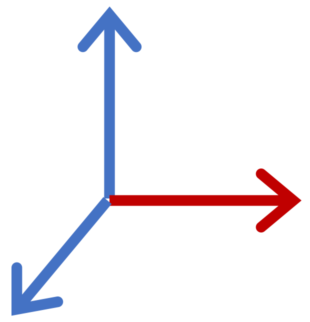
Structural spec



- 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?

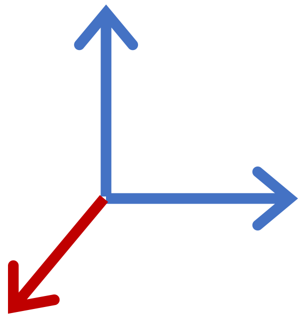
- **Q:** What did the structural spec look like in FlashFill / Sketch / Synquid / Copilot?

Structural spec: examples



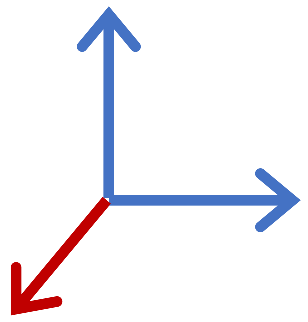
- Built-in DSL
- User-defined DSL (grammar)
- User-provided components
- Languages with synthesis constructs
  - e.g. generators in Sketch
- Learned language model

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