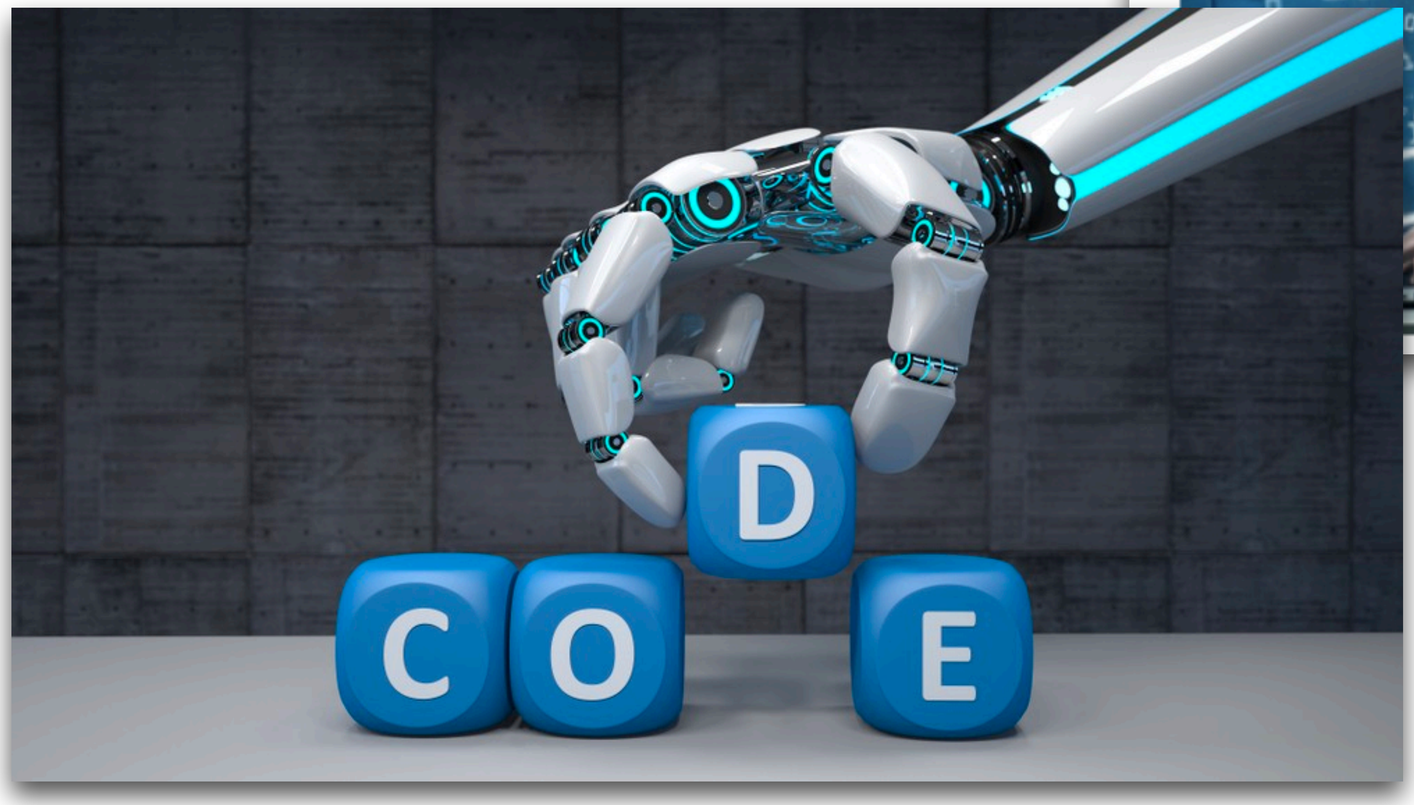
Program Synthesis (Part I)



July 8, 2019

Program Synthesis Moves a Step Closer to Reality

George Leopold

As data scientists and software developers sort through the plethora of tools and APIs ranging from Python to Apache Spark, automation schemes are emerging to help programmers navigate those tools and the accompanying

Apr 16 **Wed**	Program Synthesis (Part 1) [overview]	
Apr 21 **Mon**	Program Synthesis (Part 2) [overview]	
Apr 24 **Thu**	—	Exam #2 Due (you pick a 2-hour window within this 24-hour day)
Apr 25 **Fri**	—	HW 6b (Contribution) Due All Course Materials Due (cannot be accepted later than this, please plan accordingly)

Agenda

- A gentle introduction to program synthesis
  - Mostly using examples/demos/figures
  - But also some formalisms/algorithms (Part 1 and Part 2)
- Goals
  - Get exposed to “program synthesis”
  - Appreciate this research topic
  - Learn a little bit about how synthesis works

Example 1

What are we doing here?

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Filling in Initials for Names

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How would you do it?

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- Filling in Initials for Names

How would you do it?

- Idea 1: manually
- Idea 2: write an Excel formula?
- Idea 3: hire someone to do it for you?
- Idea 4: StackOverflow?
- Idea 5: ChatGPT?

Example 1

What are we doing here?

- Filling in Initials for Names

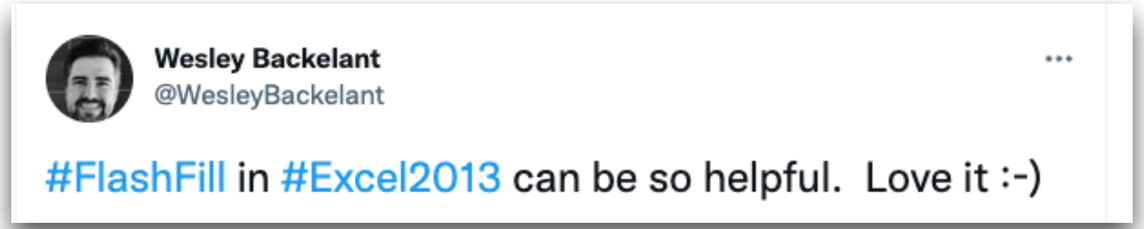
How would you do it?

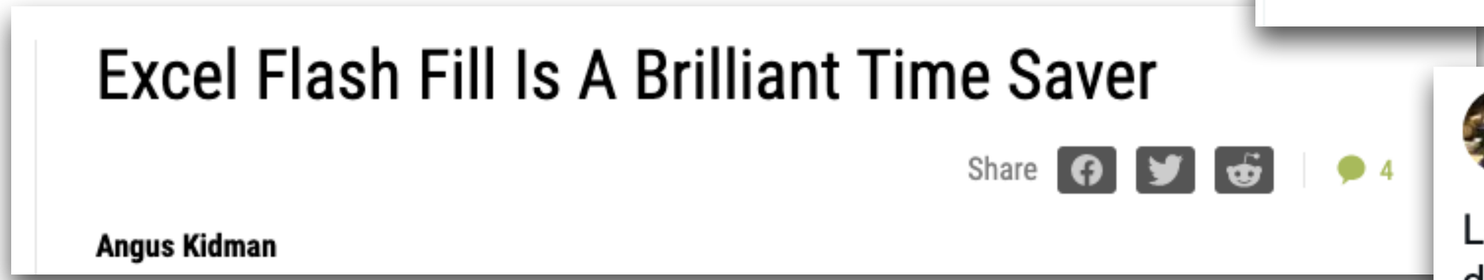
- Idea 1: manually
- Idea 2: write an Excel formula?
- Idea 3: hire someone to do it for you?
- Idea 4: StackOverflow?
- Idea 5: ChatGPT?

What are some problems with each idea?

FlashFill

- No (very little) manual work
- No need to write Excel macros
- Highly automated
- People love it





FlashFill Demo

Watch video demo..

 https://www.youtube.com/watch?v=LbK-FfCEBOw&t=20s

What’s FlashFill?

- FlashFill is *an Excel feature that automatically transforms strings using examples*.

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What does a desired program do in this case?

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- FlashFill is *an Excel feature that automatically transforms strings using examples*.

What does a desired program do in this case?

FlashFill synthesizes a program:

(1) Take the first char. of first name

(2) Concatenate it with space

(3) Concatenate it with the first char. of last name

Guess What FlashFill Would Do?

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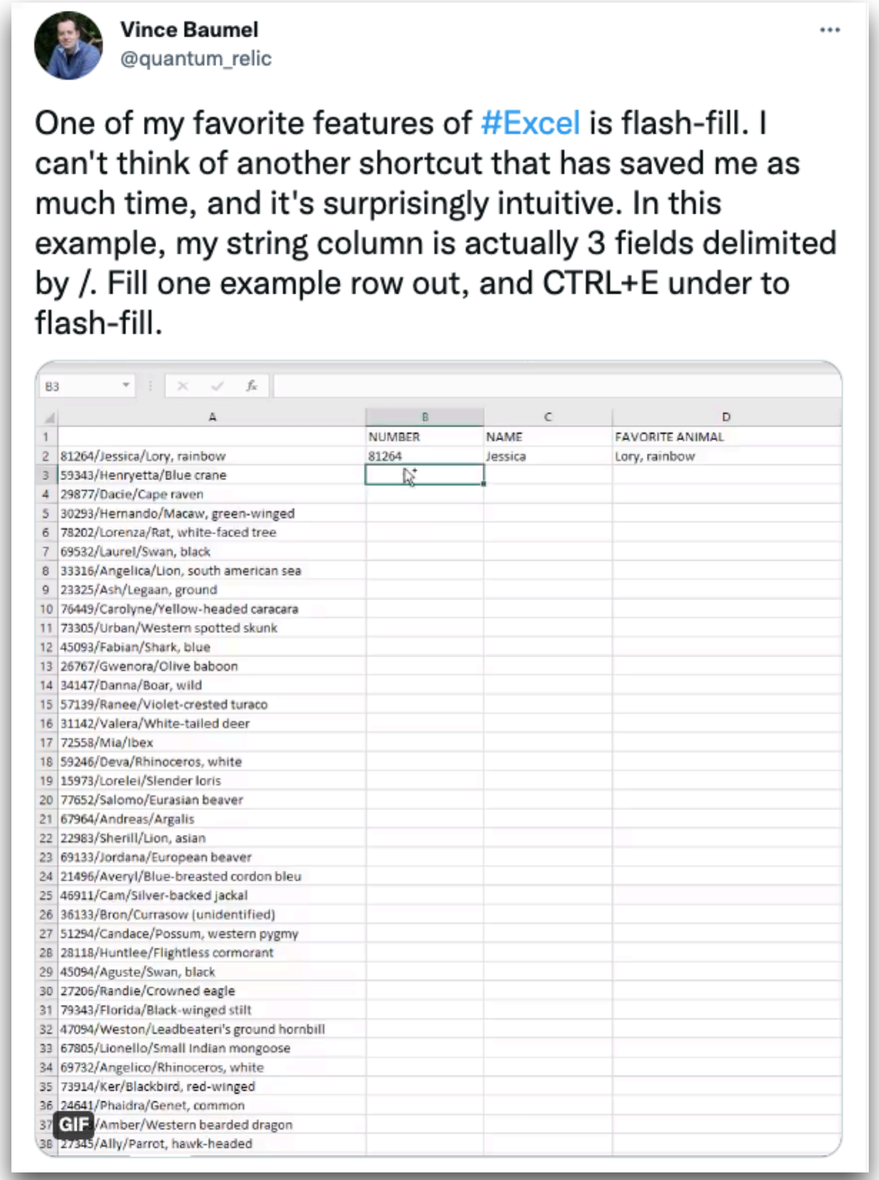
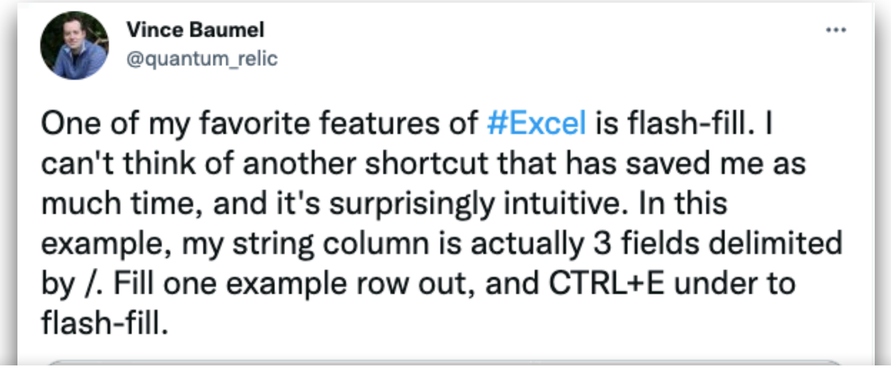


What (kind of) program do you think FlashFill would synthesize?

(next)

https://twitter.com/i/status/1462868647815397377

Guess What FlashFill Would Do?



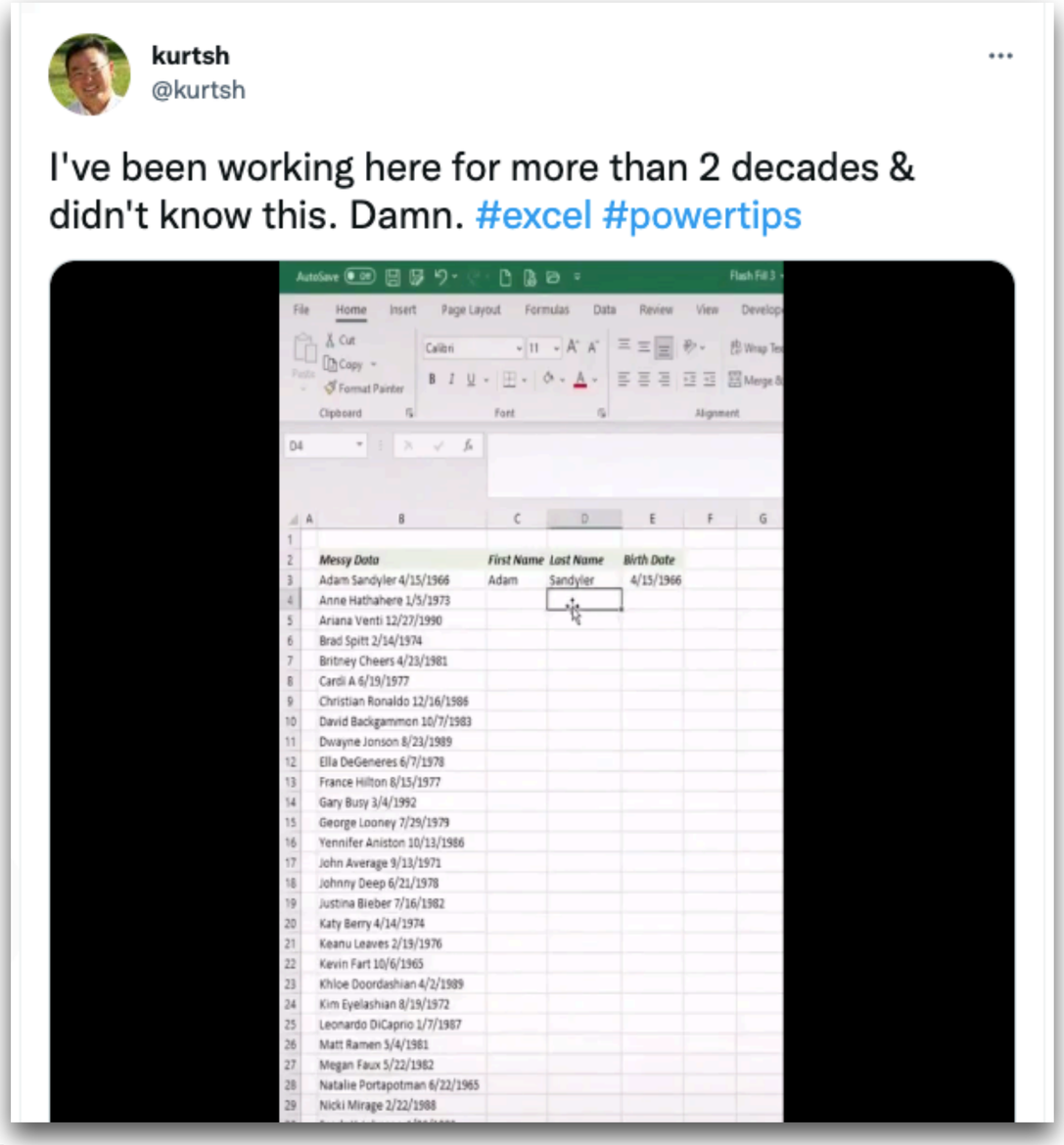
What (kind of) program do you think FlashFill would synthesize?

B3

	A	B	C	D
1		NUMBER	NAME	FAVORITE ANIMAL
2	81264/Jessica/Lory, rainbow	81264	Jessica	Lory, rainbow
3	59343/Henryetta/Blue crane			
4	29877/Dacie/Cape raven			
5	30293/Hernando/Macaw, green-winged			
6	78202/Lorenza/Rat, white-faced tree			
7	69532/Laurel/Swan, black			
8	33316/Angelica/Lion, south american sea			

https://twitter.com/i/status/1462868647815397377

Guess What FlashFill Would Do?



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https://twitter.com/kurtsh/status/1462999130960064515?s=20&t=RRDbl1bBg0CTapPZielzhg

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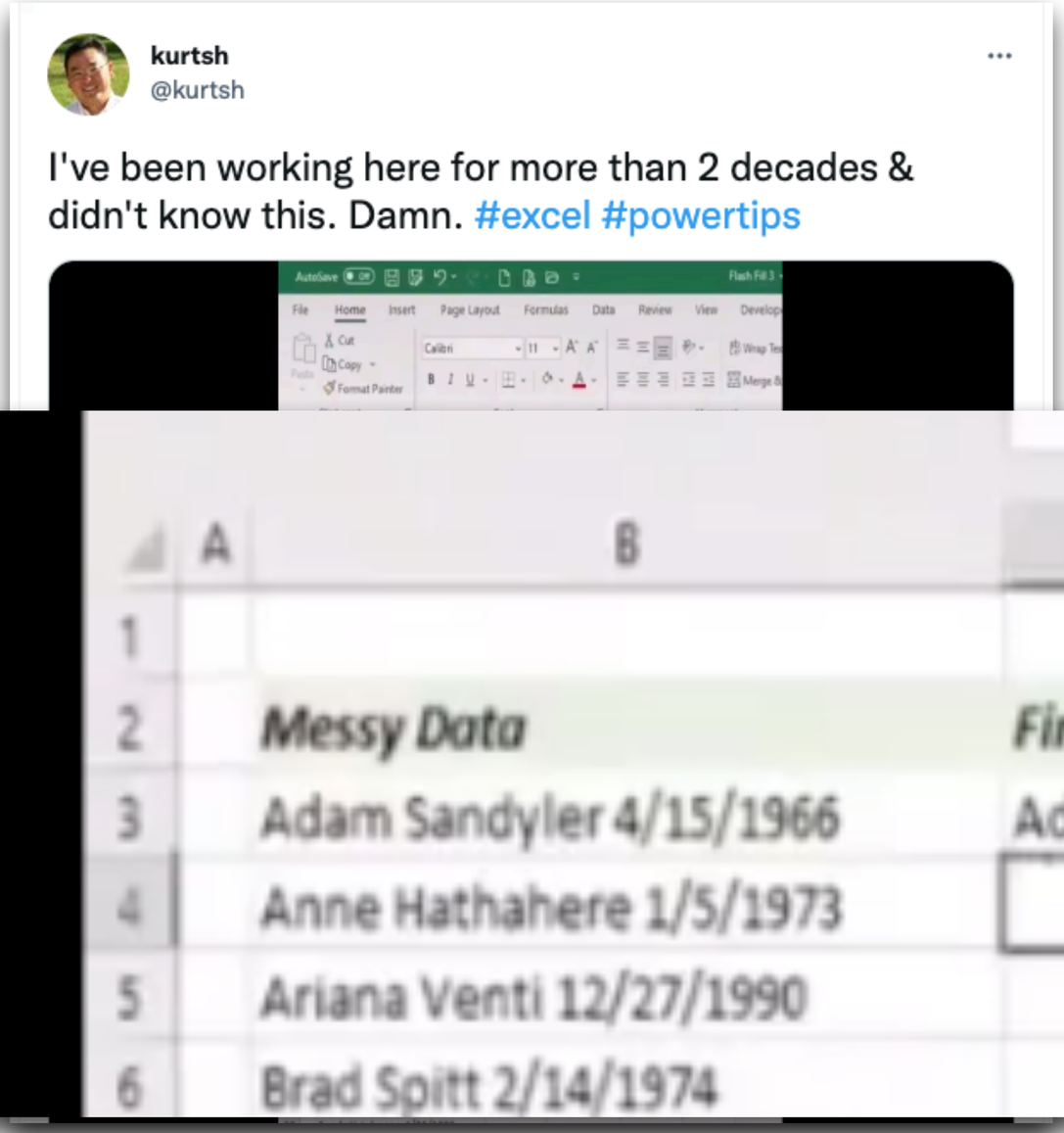
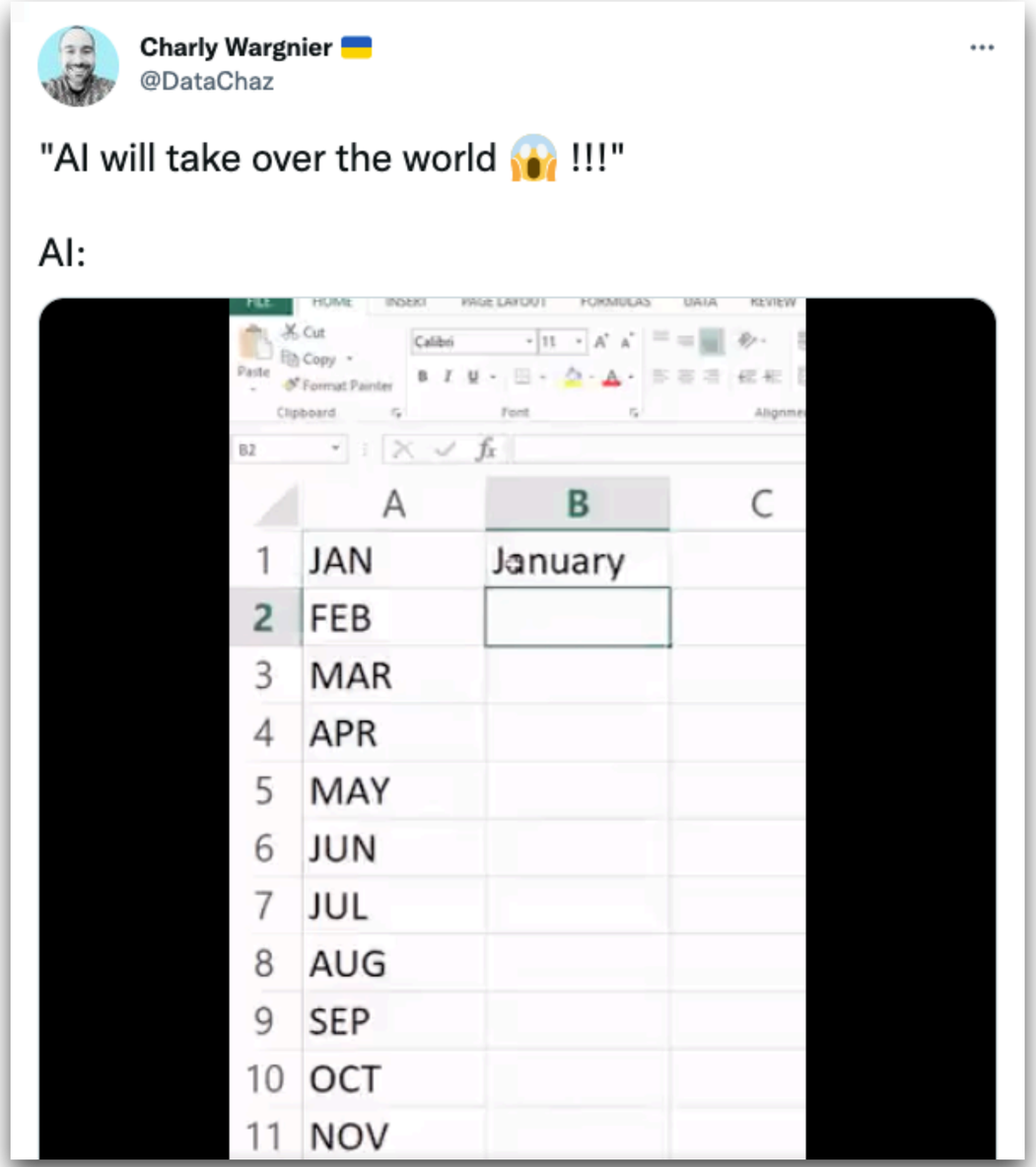


What (kind of) program do you think FlashFill would synthesize?

	A	B	C	D	E	F	G
1							
2		Messy Data	First Name	Last Name	Birth Date		
3		Adam Sandyler 4/15/1966	Adam	Sandyler	4/15/1966		
4		Anne Hathahere 1/5/1973					
5		Ariana Venti 12/27/1990					
6		Brad Spitt 2/14/1974					

https://twitter.com/kurtsh/status/1462999130960064515?s=20&t=RRDbl1bBg0CTapPZielzhg

Guess What FlashFill Would Do?

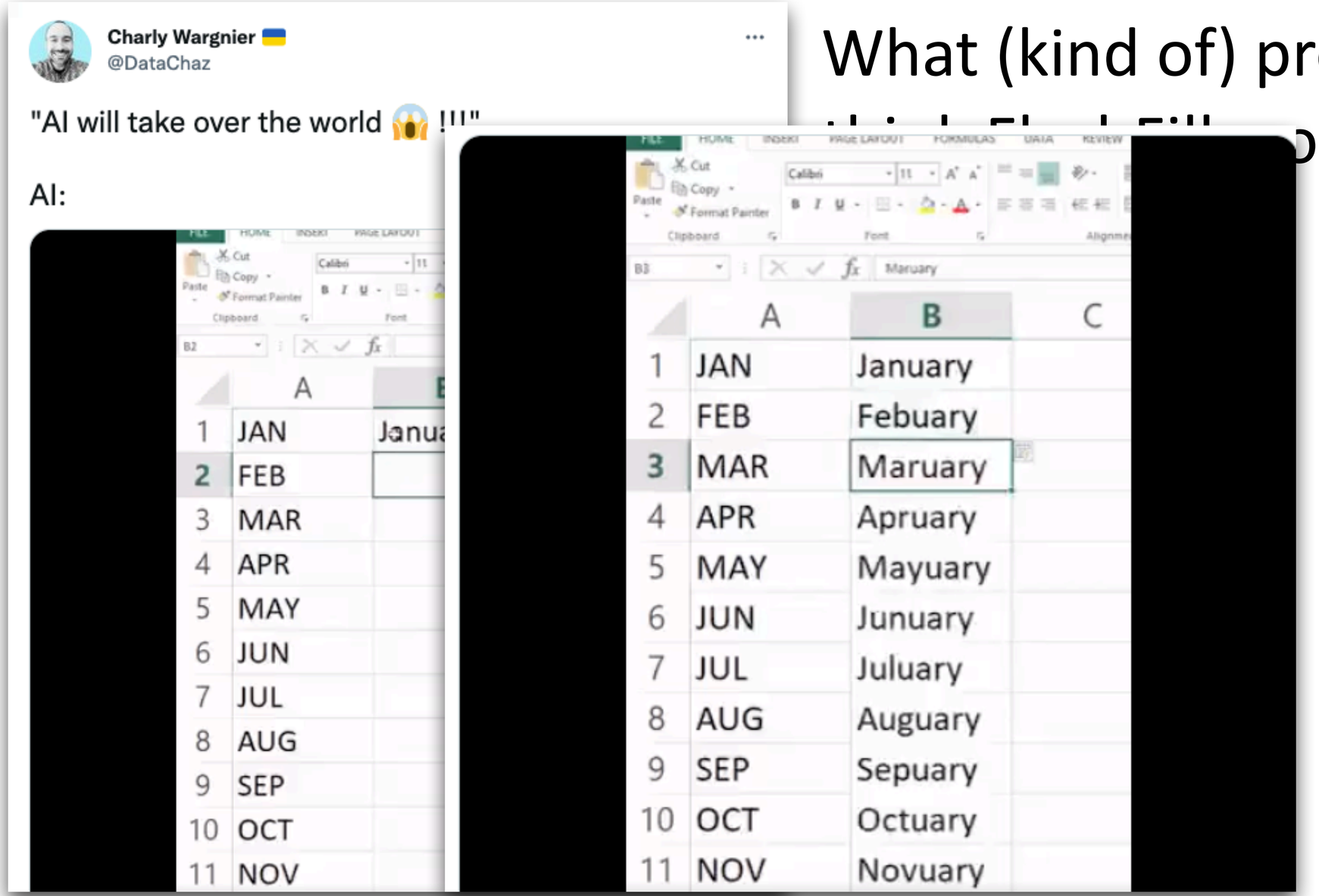


What (kind of) program do you think FlashFill would synthesize?

(no next!)

https://twitter.com/DataChaz/status/1454954213302312962?s=20&t=RRDbl1bBg0CTapPZielzhg

Guess What FlashFill Would Do?



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Why?

https://twitter.com/DataChaz/status/1454954213302312962?s=20&t=RRDbl1bBg0CTapPZielzhg

Guess What FlashFill Would Do?

What (kind of) program do you think FlashFill would synthesize?

(no next!)

https://twitter.com/Standplaats_KRK/status/1465722790481432576?s=20&t=RRDbl1bBg0CTapPZielzhg

Guess What FlashFill Would Do?

City			No. o
Austin	TX	Texas	2
Salt Lake City	UT	Utah	1
Durham	NC	North Carolina	3
Columbus	OH		35
Baton Rouge	LA		11
Omaha	NE		27
New Orleans	LA		39
Des Moines	IA		16
Seattle	WA		42
Oklahoma City	OK		14
Houston	TX		62
Charleston	SC		[illegible]
Washington	DC		225
Milwaukee	WI		528
Columbia	SC		56
San, Diego	CA		329
Orlando	FL		190
Boston	MA		489
Dallas	TX		489
Minneapolis	MN		396

City			No. o
Austin	TX	Texas	2
Salt Lake City	UT	Utah	1
Durham	NC	North Carolina	3
Columbus	OH	Oorth Carolina	35
Baton Rouge	LA	Lorth Carolina	11
Omaha	NE	North Carolina	27
New Orleans	LA	Lorth Carolina	39
Des Moines	IA	lorth Carolina	16
Seattle	WA	Worth Carolina	42
Oklahoma City	OK	Oorth Carolina	14
Houston	TX	Torth Carolina	62
Charleston	SC	Sorth Carolina	[illegible]
Washington	DC	Dorth Carolina	225
Milwaukee	WI	Worth Carolina	528
Columbia	SC	Sorth Carolina	56
San, Diego	CA	Corth Carolina	329
Orlando	FL	Forth Carolina	190
Boston	MA	Morth Carolina	489
Dallas	TX	Torth Carolina	489
Minneapolis	MN	Morth Carolina	396

Why?

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FlashFill Doesn’t Always Work As Expected…

- FlashFill has an underlying programming language
  - **Domain-specific language (DSL)** for string transformation

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Domain-specific language

From Wikipedia, the free encyclopedia

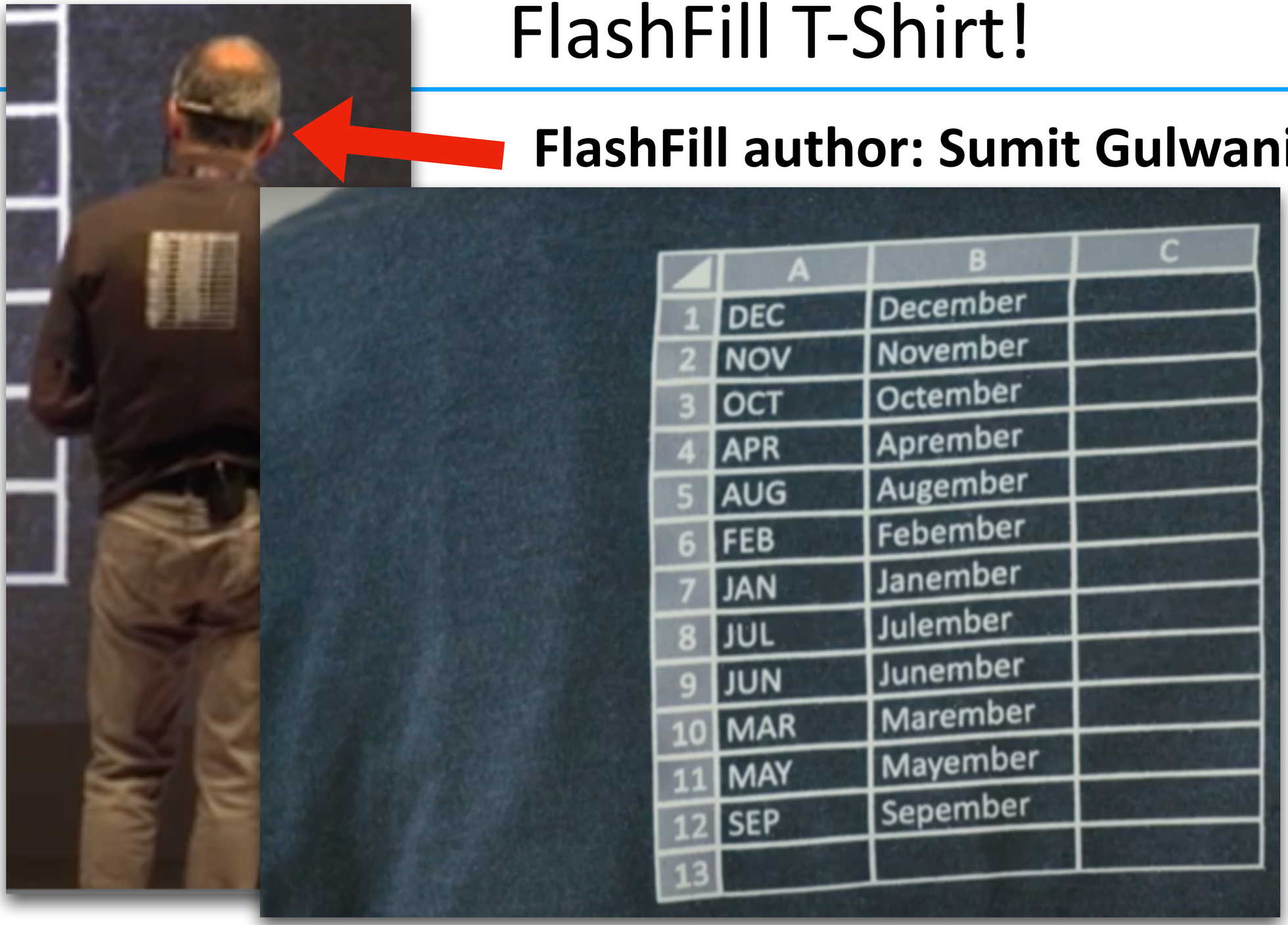
A **domain-specific language** (**DSL**) is a computer language specialized to a particular application domain. This is in contrast to a general-purpose language (GPL), which is broadly applicable across domains. There are a wide variety of DSLs, ranging from widely used languages for common domains, such as HTML for web pages, down to

Some examples: SQL, MATLAB, HTML, etc.

FlashFill Doesn’t Always Work As Expected…

- FlashFill has an underlying programming language
  - **Domain-specific language (DSL)** for string transformation
  - .. which means, fundamentally, it can only perform computations expressible in this language
  - In other words, FlashFill cannot synthesize programs that are not expressible in its underlying programming language
  - E.g., transforming dates is not supported, since FlashFill does not recognize dates. Same for US states.

FlashFill T-Shirt!



FlashFill author: Sumit Gulwani (Microsoft)

	A	B	C
1	DEC	December	
2	NOV	November	
3	OCT	Octember	
4	APR	Aprember	
5	AUG	Augember	
6	FEB	Febember	
7	JAN	Janember	
8	JUL	Julember	
9	JUN	Junember	
10	MAR	Marember	
11	MAY	Mayember	
12	SEP	Sepember	
13			

Latest Developments of FlashFill

FlashFill++: Scaling Programming by Example by Cutting to the Chase

JOSÉ CAMBRONERO*, Microsoft, USA
SUMIT GULWANI*, Microsoft, USA
VU LE*, Microsoft, USA

FLAME: A Small Language Model for Spreadsheet Formulas

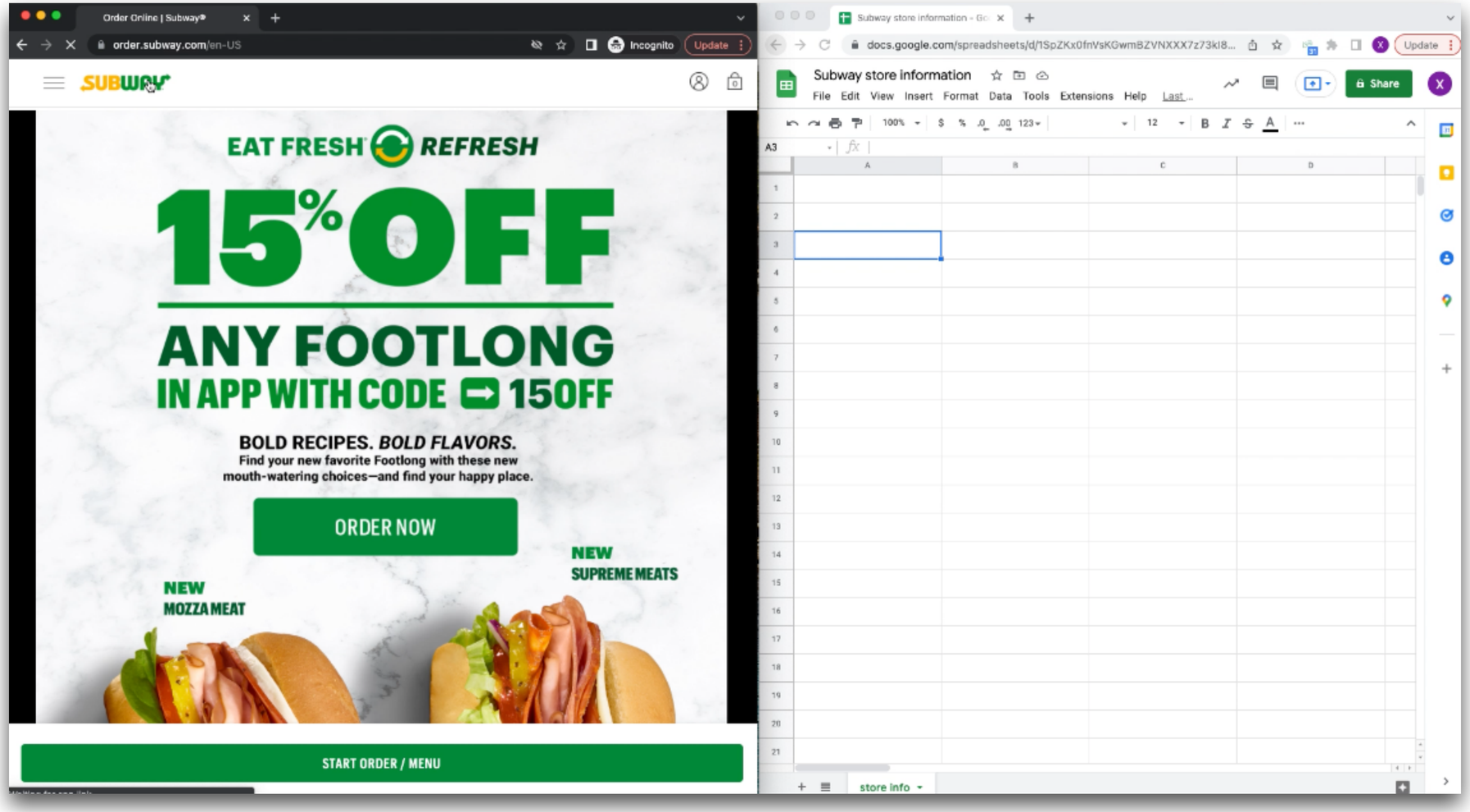
Harshit Joshi[1]*, Abishai Ebenezer[4]*, José Cambronero Sanchez[2]†, Sumit Gulwani[2]†, Aditya Kanade[3]†, Vu Le[2]†, Ivan Radiček[5]†*, Gust Verbruggen[2]†

[1] Stanford University
[2] Microsoft, USA
[3] Microsoft Research, India
[4] University of Washington
[5] Demiurg

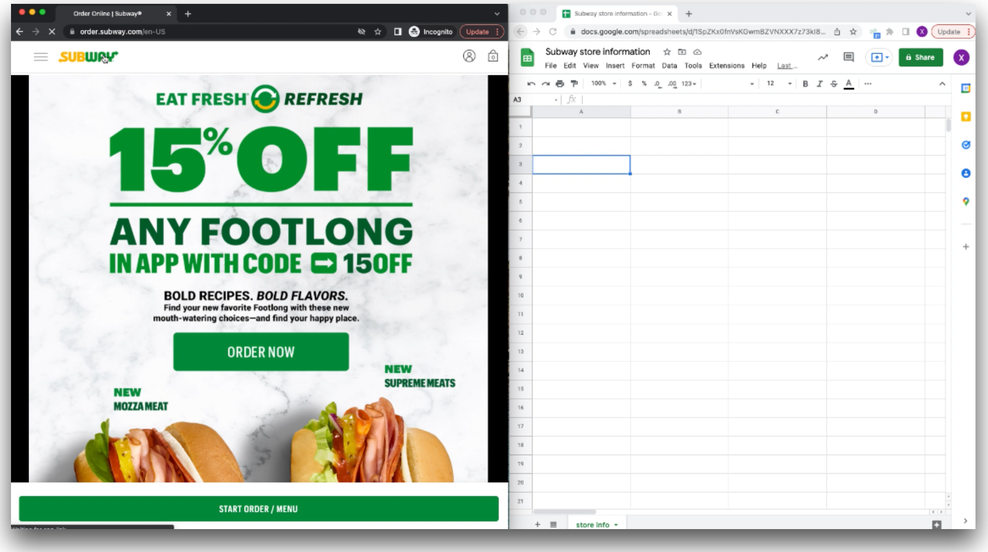
 More publications can be found: https://www.microsoft.com/en-us/research/group/prose/publications/

Example 2

Watch video..



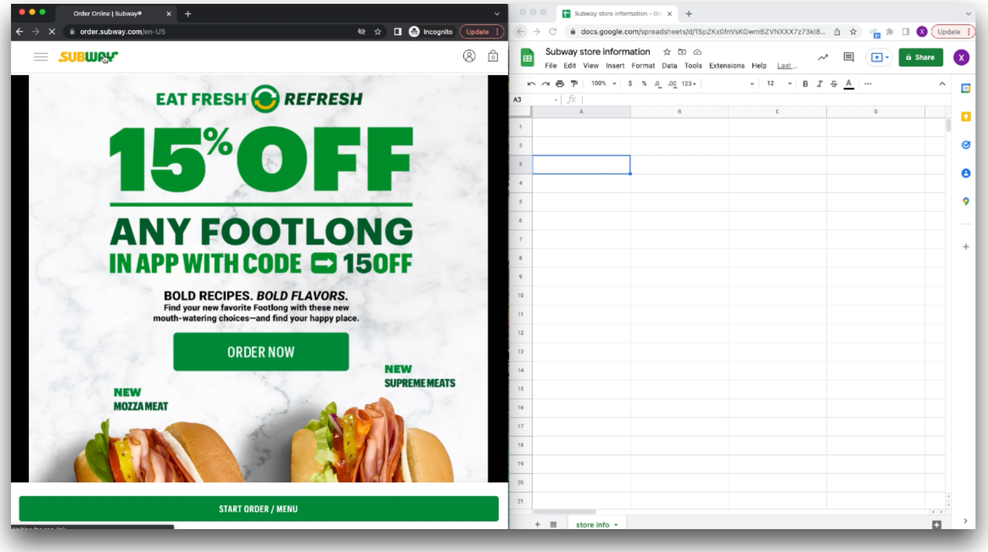
Example 2



What are we doing here?

Scraping Subway store information

Example 2



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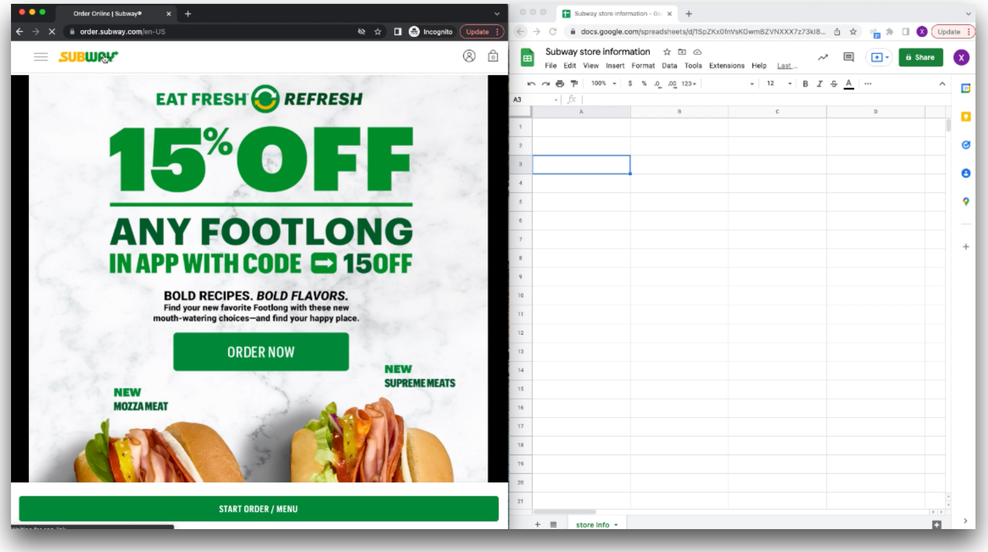

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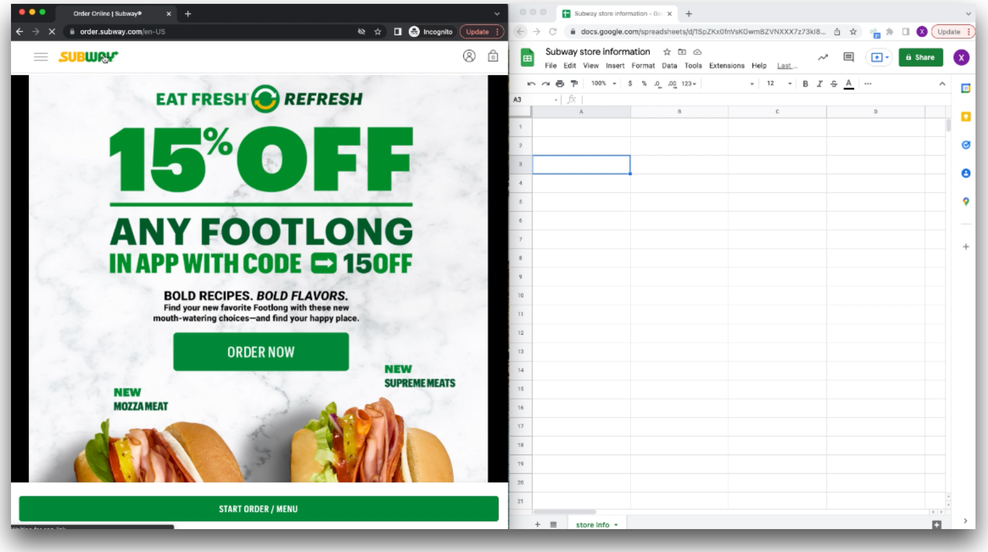

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What are some problems with each idea?

WebRobot

- No (very little) manual work
- No need to write Selenium programs
- Highly automated

WebRobot: Web Robotic Process Automation using Interactive Programming-by-Demonstration

Rui Dong
University of Michigan, USA

Zhicheng Huang
University of Michigan, USA

Ian Iong Lam
University of Michigan, USA

Yan Chen
University of Toronto, Canada

Xinyu Wang
University of Michigan, USA

Follow-Ups of WebRobot

WebRobot: Web Robotic Process Automation using Interactive Programming-by-Demonstration

SemanticOn: Specifying Content-Based Semantic Conditions for Web Automation Programs

MIWA: Mixed-Initiative Web Automation for Better User Control and Confidence

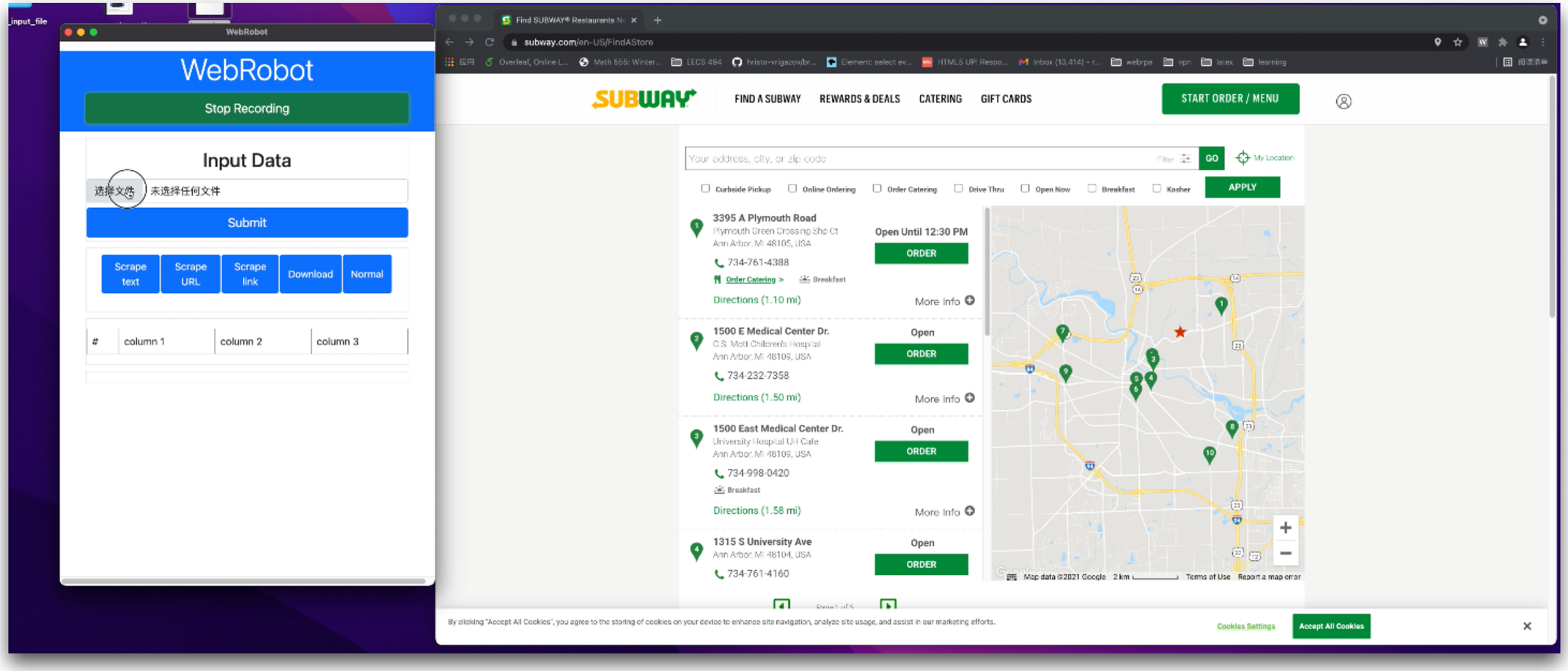
DiLogics: Creating Web Automation Programs With Diverse Logics

Efficient Bottom-Up Synthesis for Programs with Local Variables

XIANG LI*, University of Michigan, USA
XIANGYU ZHOU*, University of Michigan, USA
RUI DONG, University of Michigan, USA
YIHONG ZHANG, University of Washington, USA
XINYU WANG, University of Michigan, USA

WebRobot Demo

Watch video demo..



How Does WebRobot Work?

- Idea: Programming-by-Demonstration (PBD)
- Record a **trace** of user-performed actions, then synthesize a **program with loops** that generalizes the trace

Trace → **PBD** → **Program**

```
1  EnterData /../input x[zips][1]
2  Click /../button

3  ScrapeText /../div[1]/div[2]/div[1]/div[1]/div/h3
4  ScrapeText /../div[1]/div[2]/div[1]/div[2]/div[1]/div[4]/a/div
5  ScrapeText /../div[2]/div[2]/div[1]/div[1]/div/h3
6  ScrapeText /../div[2]/div[2]/div[1]/div[2]/div[1]/div[4]/a/div
7  ScrapeText /../div[3]/div[2]/div[1]/div[1]/div/h3
8  ScrapeText /../div[3]/div[2]/div[1]/div[2]/div[1]/div[4]/a/div
```

```
EnterData /../input x[zips][1]
Click /../button
foreach ϱ in Dscts(ϵ, div[@class='rightContainer']) do
  ScrapeText ϱ//h3
  ScrapeText ϱ//div[@class='locatorPhone']
```

Recap.. FlashFill vs. WebRobot

	FlashFill	**WebRobot**
Problem	String editing in Excel	Web automation
Idea	Programming-by-Example	Programming-by-Demonstration
DSL	For string editing	For web automation

FlashFill vs. WebRobot: What's In Common?

FlashFill vs. WebRobot: What's In Common?

- Share same "interface".

FlashFill vs. WebRobot: What's In Common?

- Share same "interface".

- Differ in:
  - Application domains / use cases.
  - Definitions of "specification".
  - Programming languages.

“Program Synthesis”

New terminology, but not totally unfamiliar.

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What do I want to do? → Human → Program

“Program Synthesis”

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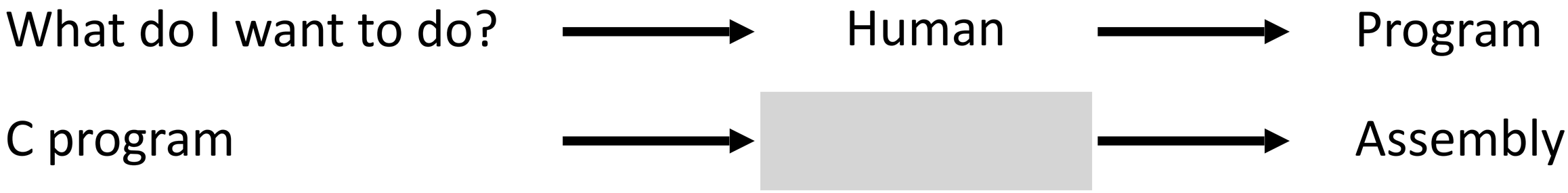

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What do I want to do?	→	Human	→	Program
C program	→	GCC	→	Assembly

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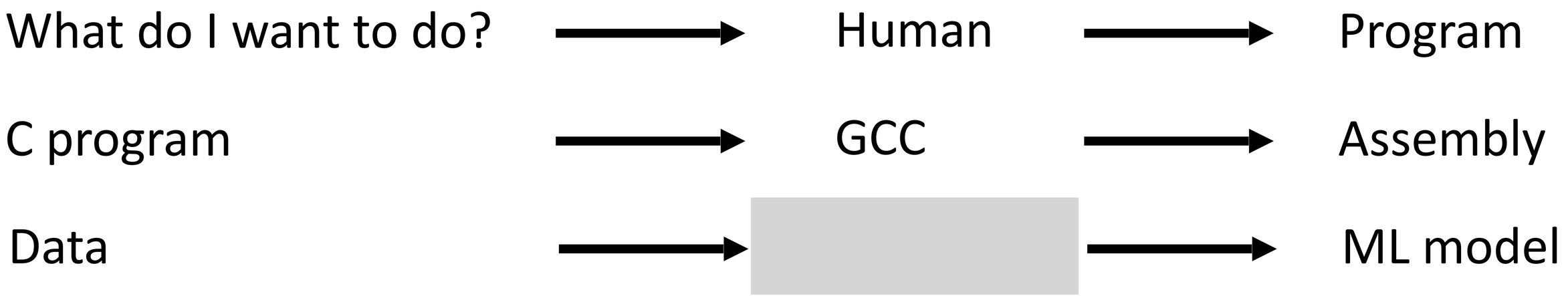

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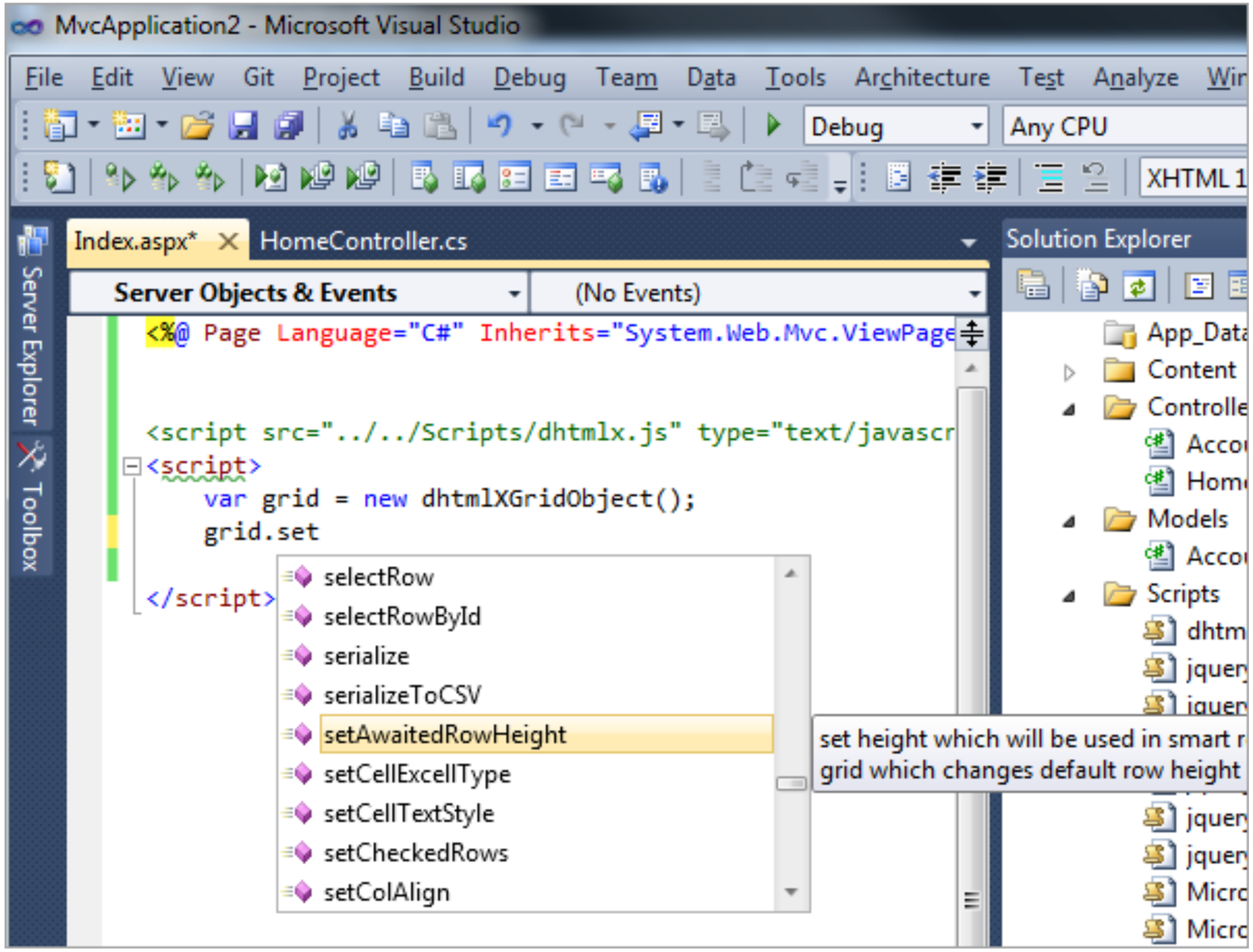
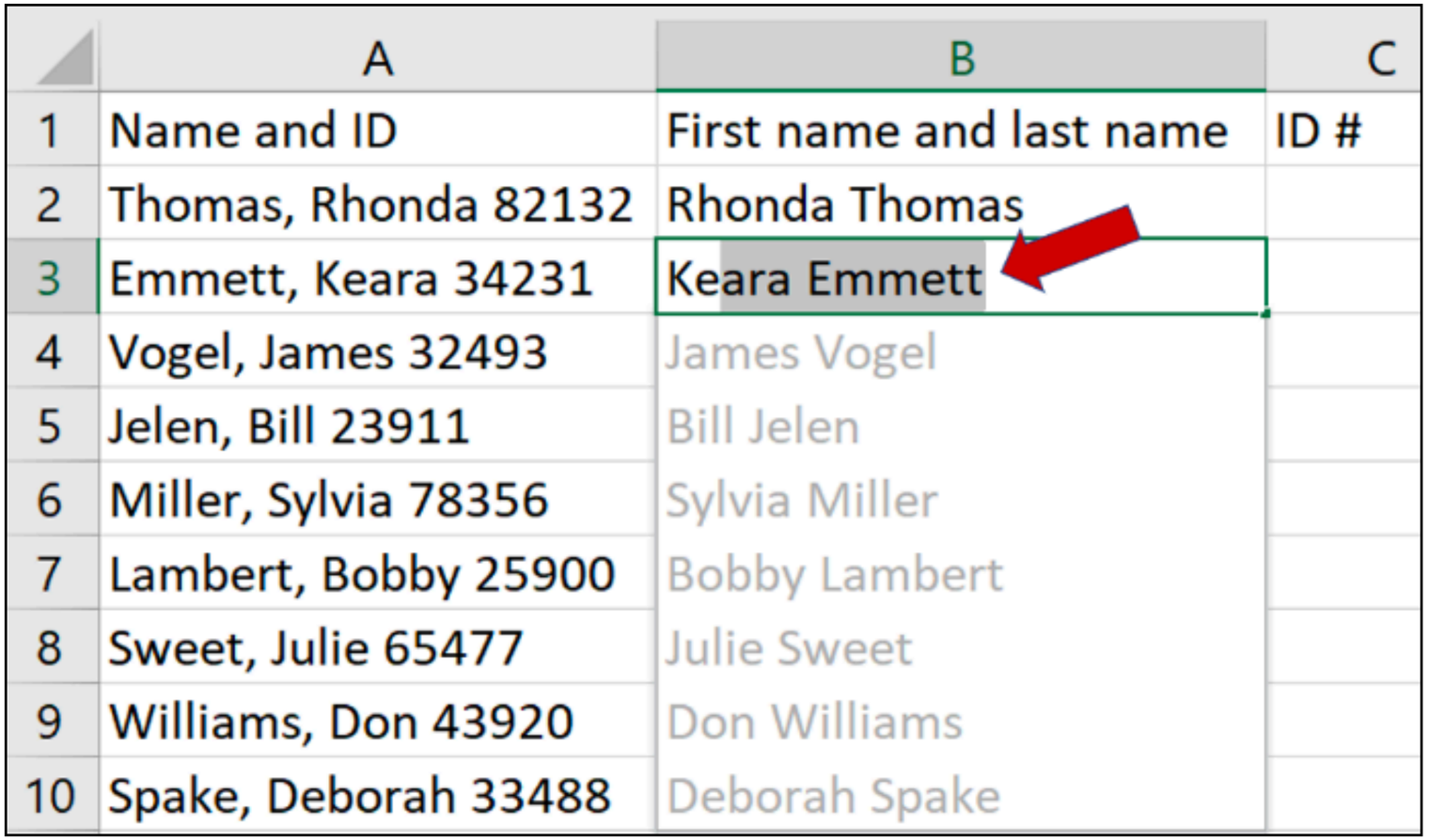
Data	→	Training Alg.	→	ML model

“Program Synthesis”



How about this?

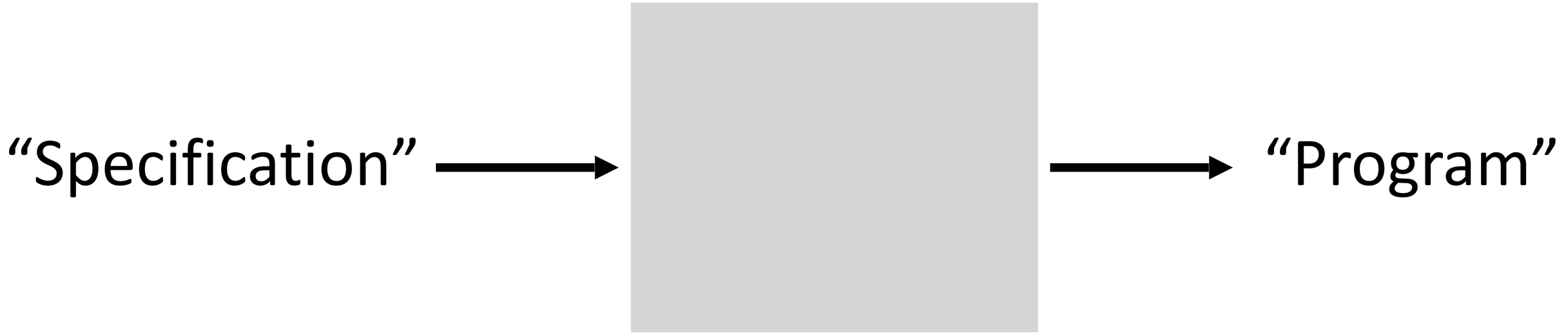
“Program Synthesis”



	A	B	C
1	Name and ID	First name and last name	ID #
2	Thomas, Rhonda 82132	Rhonda Thomas	
3	Emmett, Keara 34231	Keara Emmett	
4	Vogel, James 32493	James Vogel	
5	Jelen, Bill 23911	Bill Jelen	
6	Miller, Sylvia 78356	Sylvia Miller	
7	Lambert, Bobby 25900	Bobby Lambert	
8	Sweet, Julie 65477	Julie Sweet	
9	Williams, Don 43920	Don Williams	
10	Spake, Deborah 33488	Deborah Spake	

How about this?

“Program Synthesis”



What do I want to do?	→	Human	→	Program
C program	→	GCC	→	Assembly
Data	→	Training Alg.	→	ML model
Partial prog.	→	Autocomplete	→	Complete prog.
Examples	→	FlashFill	→	FlashFill prog.
Demonstrations	→	WebRobot	→	Selenium prog.

Working Definition of Program Synthesis

High-level intent

Specification

Program synthesis

Typically involves search

Lower-level code

Program

I/O examples, demonstrations, natural language, reference implementation, etc.

In some programming language (grammar + semantics)

Program Synthesis vs. Machine Learning/Deep Learning

- Is ML/DL also program synthesis?

Program Synthesis vs. Machine Learning/Deep Learning

- Is ML/DL also program synthesis?
  - ML/DL: data is spec, model is program, try to learn a model that matches data
  - At a high-level, yes

Program Synthesis vs. Machine Learning/Deep Learning

- Is ML/DL also program synthesis?
  - ML/DL: data is spec, model is program, try to learn a model that matches data
  - At a high-level, yes
  - But not really..
    - Definitions of “programs” are very different (e.g., grammar vs. neural nets)
    - Data is noisy but spec is less noisy (but there is a trend in program synthesis to tolerate noise in spec)
    - Typically continuous in ML/DL vs. discrete search space in program synthesis
    - The line is getting blurry

Program Synthesis vs. Compilers

- Are program synthesizers compilers? Are compilers synthesizers?

Program Synthesis vs. Compilers

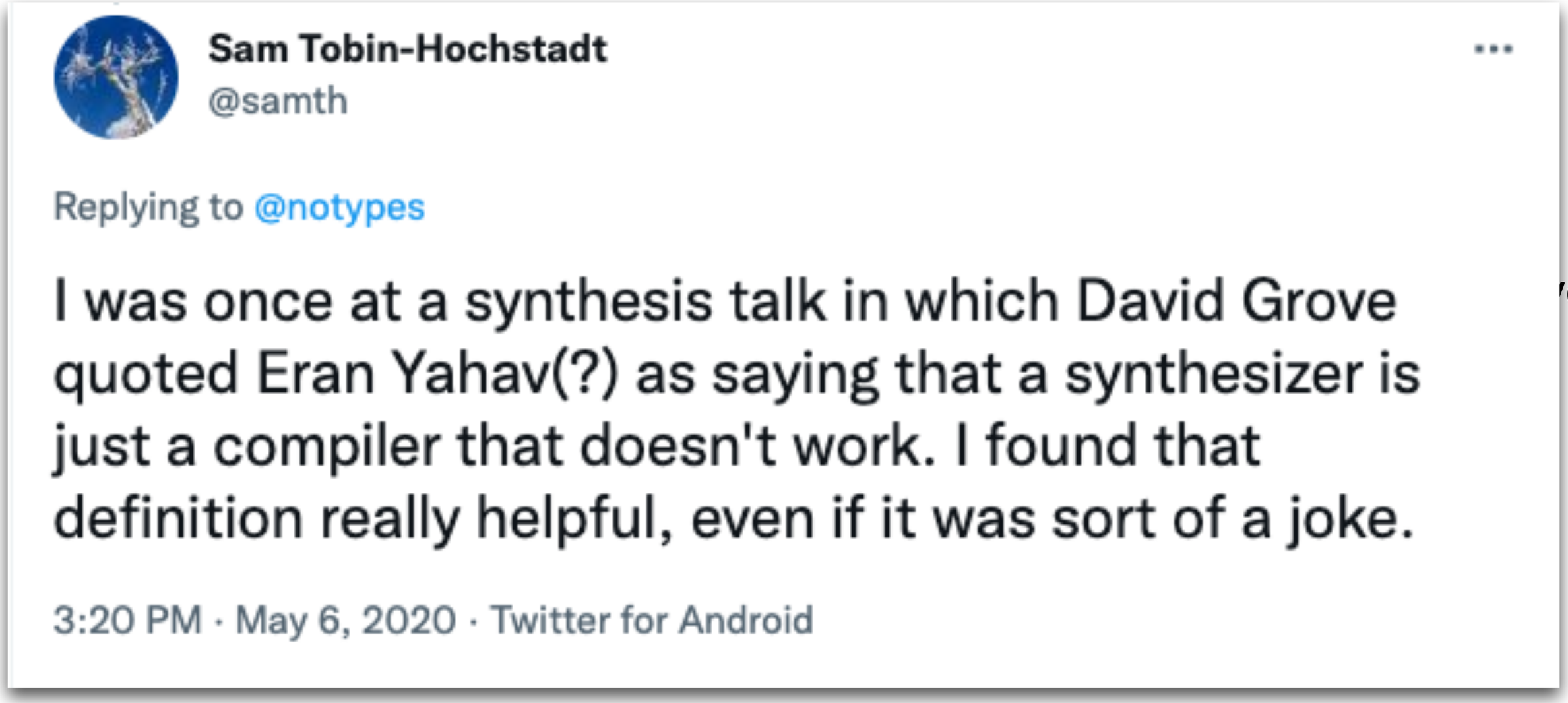
- Are program synthesizers compilers? Are compilers synthesizers?
  - Compilers also convert high-level intent (code) to lower-level code
  - At a high-level, yes

Program Synthesis vs. Compilers

- Are program synthesizers compilers? Are compilers synthesizers?
  - Compilers also convert high-level intent (code) to lower-level code
  - At a high-level, yes
  - But not really..
    - Compilers translate (not really true anymore) but synthesizers discover
    - Compilers apply predefined transformations (again, not really true nowadays) whereas synthesizers perform search
    - The line is getting blurry

Program Synthesis vs. Compilers

- Are program synthesizers compilers? Are compilers synthesizers?



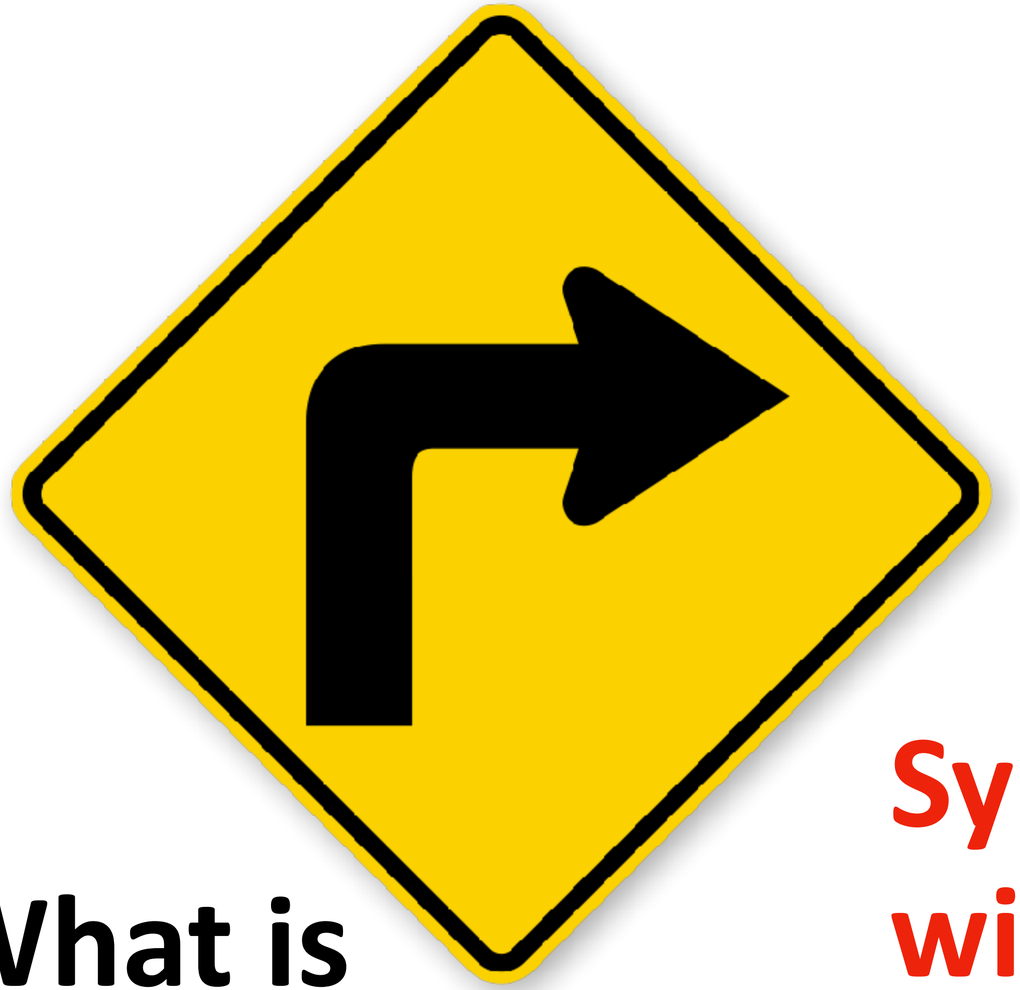
Sam Tobin-Hochstadt
@samth

Replying to @notypes

I was once at a synthesis talk in which David Grove quoted Eran Yahav(?) as saying that a synthesizer is just a compiler that doesn't work. I found that definition really helpful, even if it was sort of a joke.

3:20 PM · May 6, 2020 · Twitter for Android

Switch Gears..



What is synthesis?

How to synthesize?

Math!

Synthesis algorithms will NOT be covered in Exam 2

Systematically Search Programs in Grammar

- Context-Free Grammar (CFG):

$$e \rightarrow x \mid 1 \mid e + e$$

Non-terminal symbol

Terminal symbol

"All programs that can use x, 1 and +."

Systematically Search Programs in Grammar

- Context-Free Grammar (CFG):

$$e \rightarrow x \mid 1 \mid e + e$$

"All programs that can use x, 1 and +."

- This CFG defines a set of programs

x 1

$x + x$ $x + 1$ $1 + x$

$x + x + x$ $x + x + 1$ $x + 1 + x$ $1 + x + x$ ...

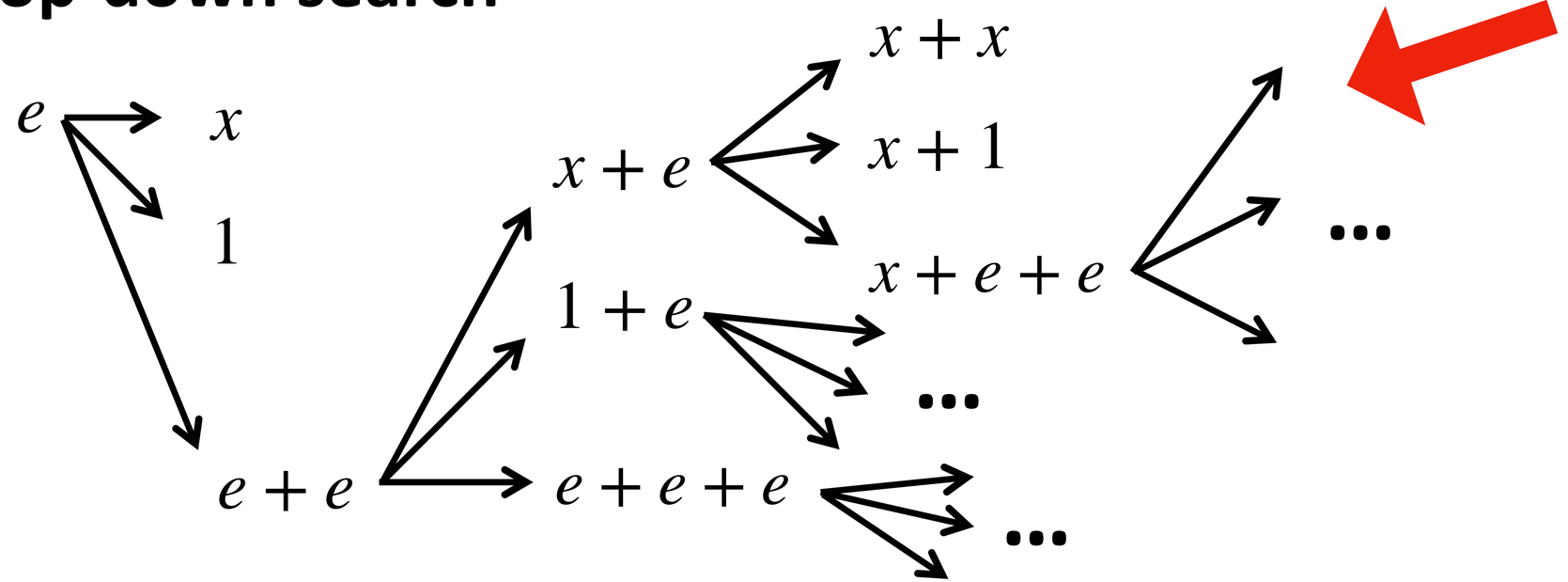
- Goal: find a program in this set that satisfies a given example

How to Search Systematically?

- Context-Free Grammar (CFG): $e \rightarrow x \mid 1 \mid e + e$

- **Top-down search**

This is a “search tree”

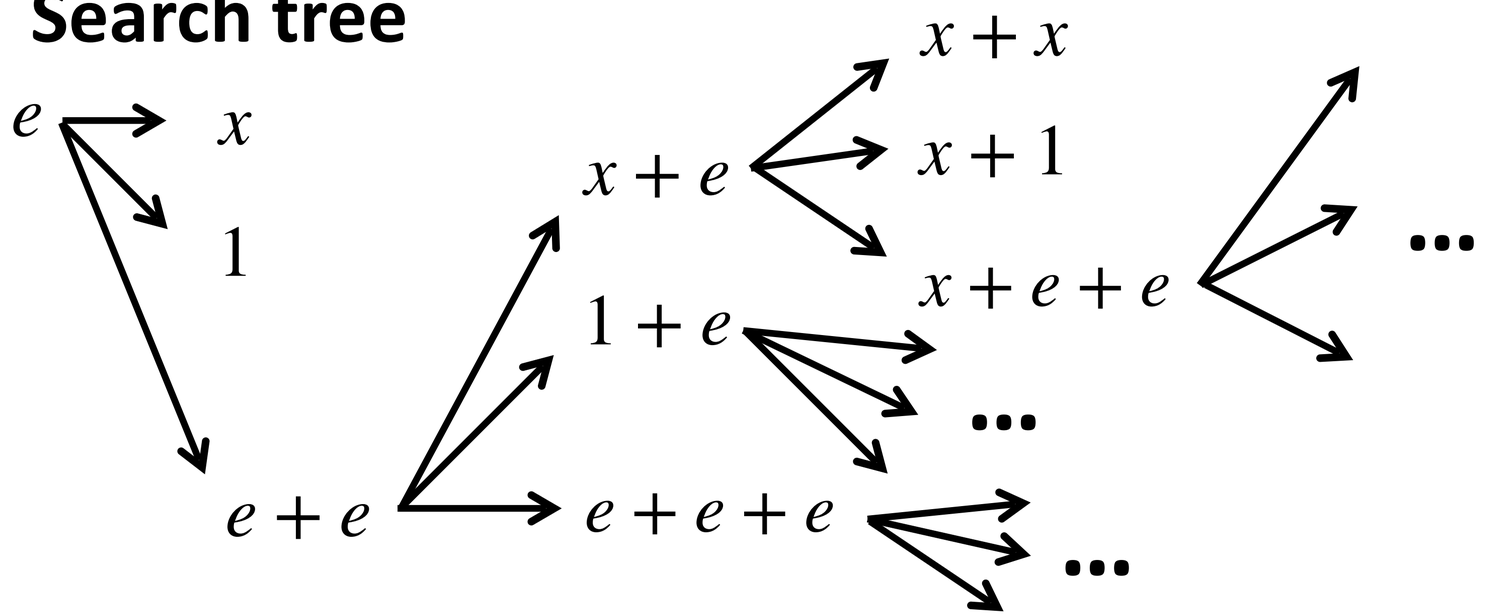


Top-Down Search In Action

Context-Free Grammar

$$e \rightarrow x$$
$$\mid 1$$
$$\mid e + e$$

Search tree



How to generate this search tree?

- Step 1: begin with the start symbol
- Step 2: pick a non-terminal in current result and replace it with one of its productions
- Step 3: continue step 2 until no more non-terminal remains (i.e., only terminals)

Top-Down Search In Action

Context-Free Grammar

$$e \rightarrow x$$
$$| \, 1$$
$$| \, e + e$$

Search tree

e

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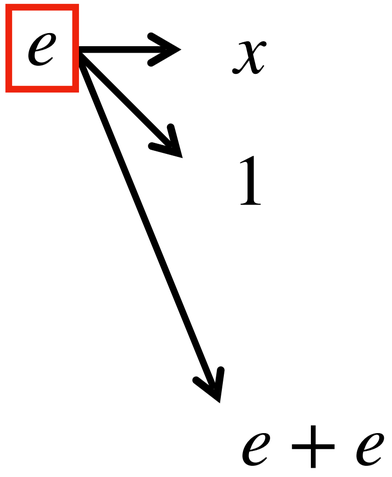

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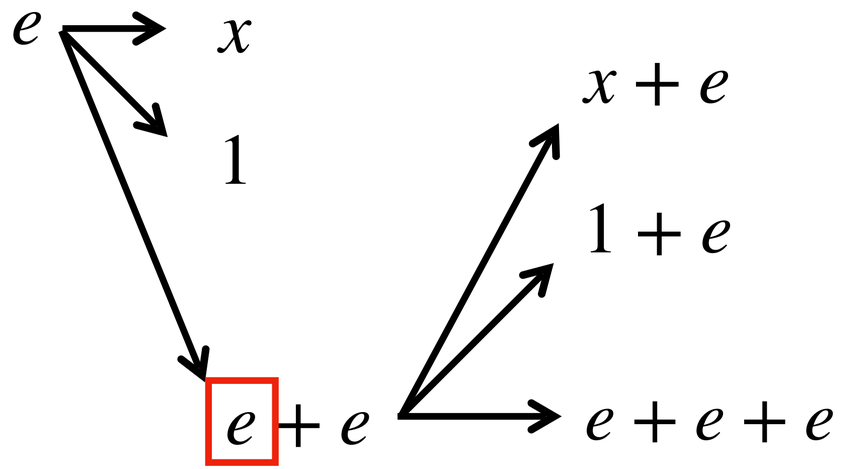

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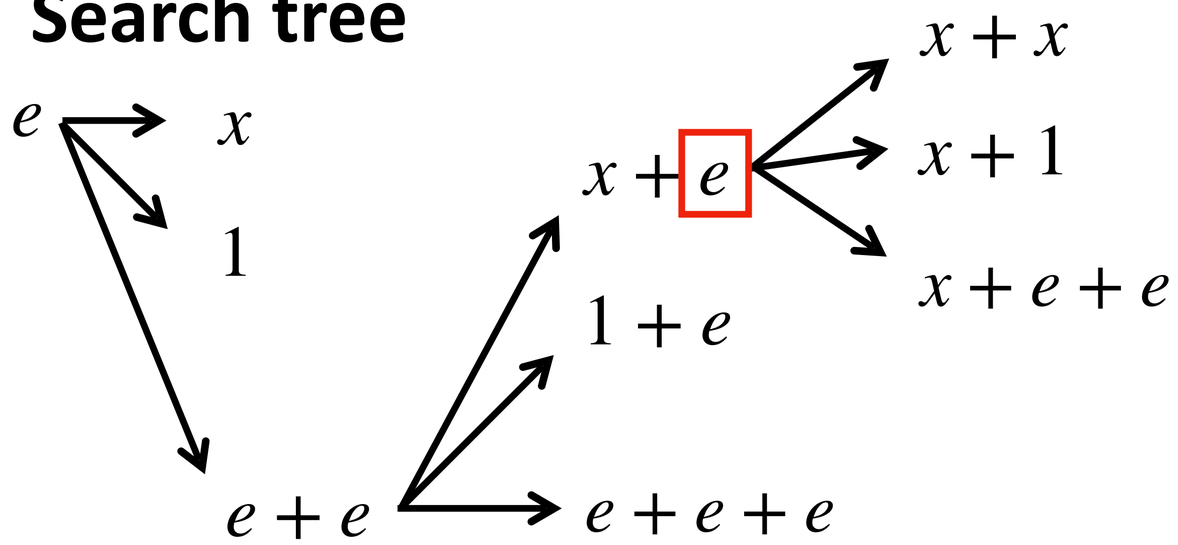

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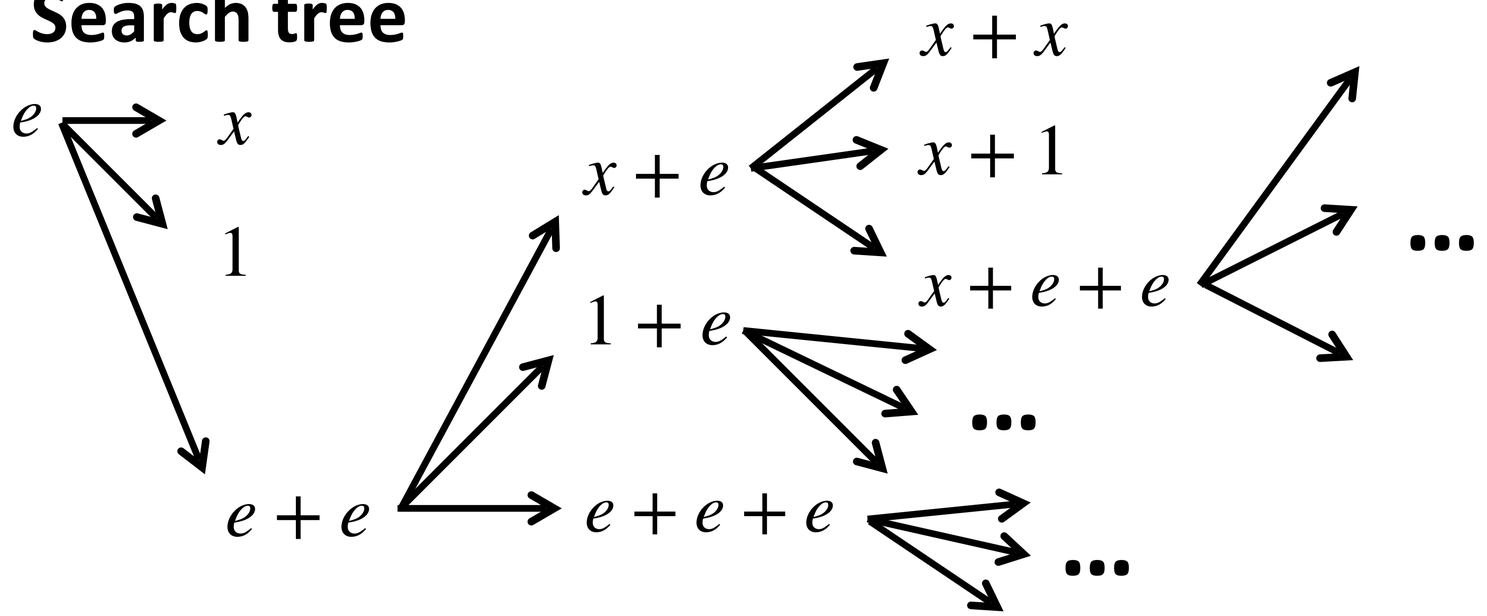

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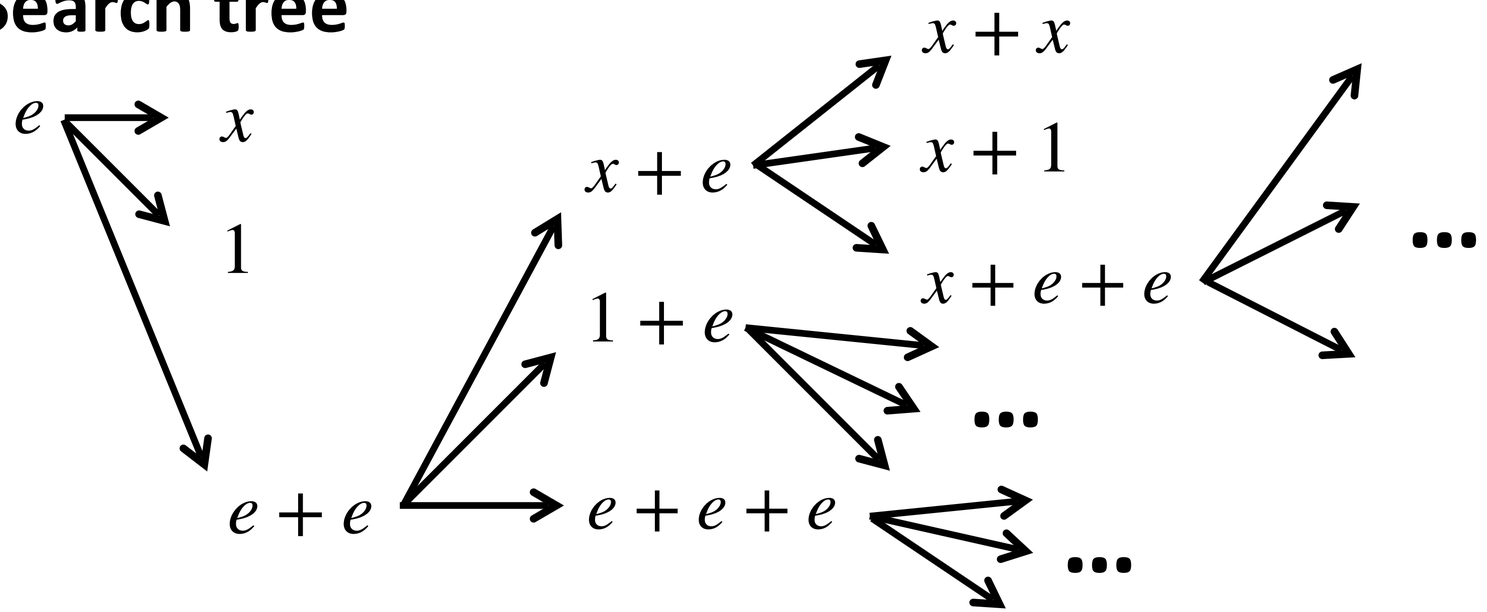
Top-Down Search Recap..

Context-Free Grammar

$$
\begin{aligned}
e &\rightarrow x \\
&\mid 1 \\
&\mid e + e
\end{aligned}
$$

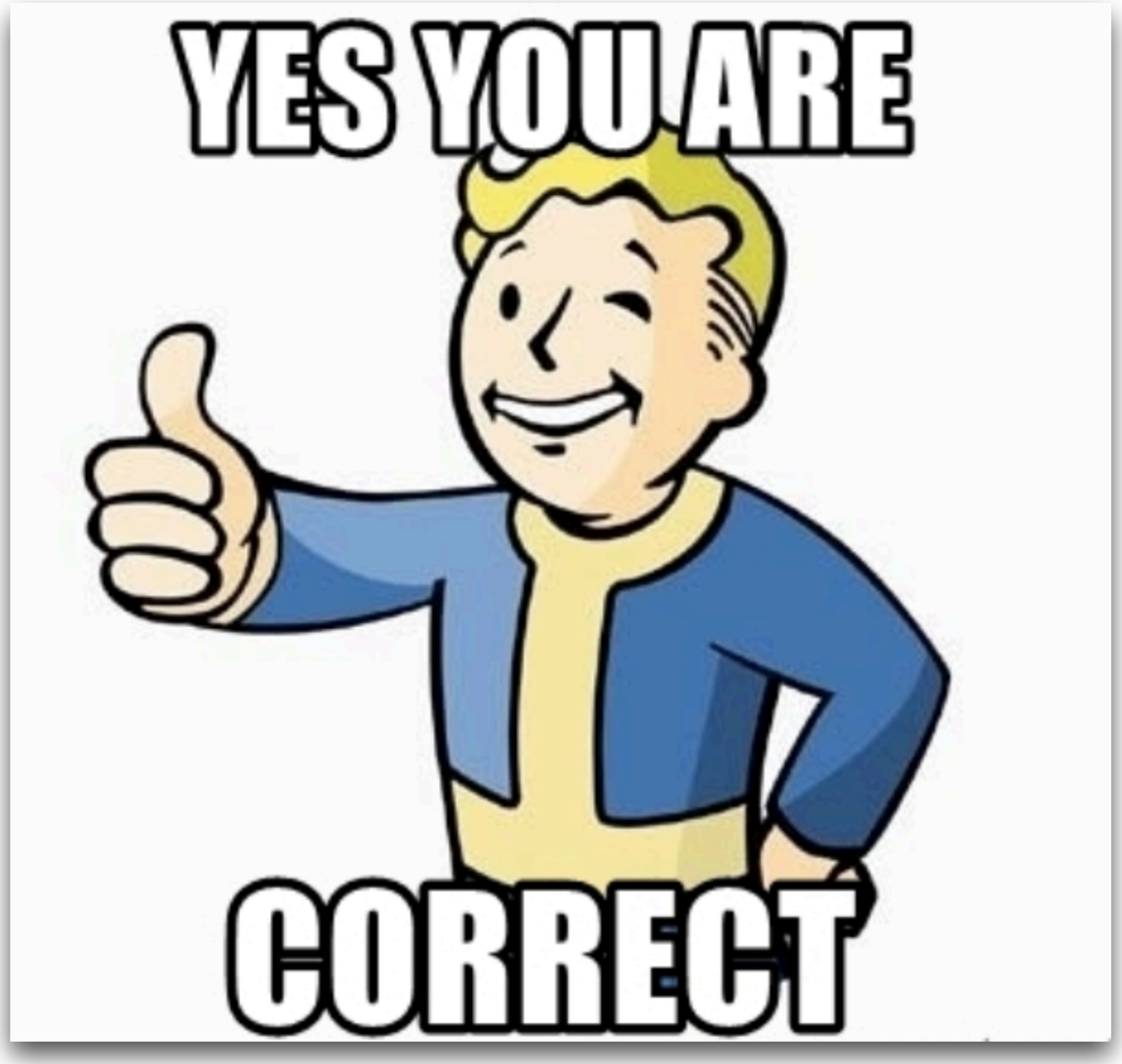
Search tree



What if my grammar gets bigger?

$$
\begin{aligned}
e &\rightarrow x \\
&\mid 1 \\
&\mid e + e \\
&\mid e - e \\
&\mid \ldots
\end{aligned}
$$

Synthesis Seems Computationally Expensive?!



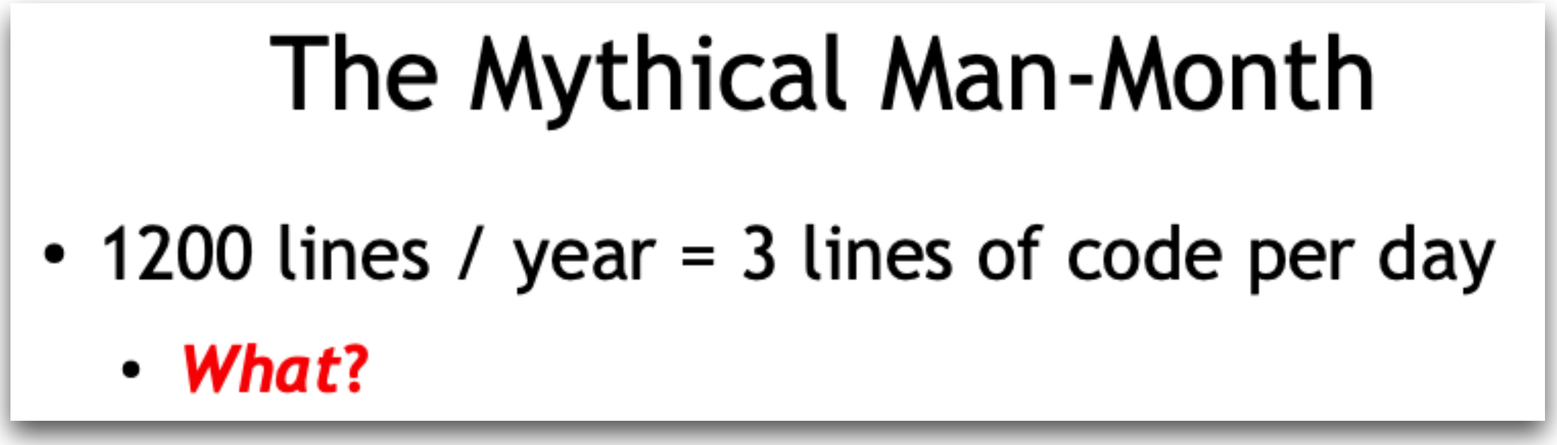
- Top-down search has exponential time complexity (to program size)
- In general, program synthesis is computationally intractable, if not undecidable

.. which means synthesis <u>in theory</u> does not scale to complex problems..

But, recent advances lead to <u>empirically</u> efficient synthesis!

State-of-the-Art

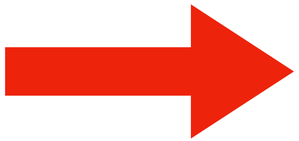
- How many lines of code can be **automatically synthesized** within a reasonable amount of time?
  - This depends on the domain, but in general, a few dozens in minutes
  - This might sound too few / too slow?



State-of-the-Art

To give you a concrete idea..

What WebRobot
synthesized in a few seconds



```
from traceCollector.traceCollector import TraceCollector
from selenium.common.exceptions import NoSuchElementException, StaleElementReferenceException, TimeoutException
from selenium.webdriver.common.by import By
import traceback
import os
import time

driver_path = "./chromedriver"

trace_name = "89971"
starting_website = "https://lrv.nassaucountyny.gov/"
description = """
Given a list of tuples (section, block, lot), for each, enter them in the search, then in the search result, extract "Address", "Village", "School", "Town"
"""

# init the trace collector and name it
trace_collector = TraceCollector(driver_path=driver_path,
                                 trace_name=trace_name,
                                 starting_website=starting_website,
                                 description=description,
                                 script_file=__file__,
                                 input_file=os.path.dirname(
                                     os.path.realpath(__file__))+"/input.json"
                                 )

driver = trace_collector.get_driver()

# Sleeps for 20 seconds so that users can log in.

time.sleep(20)

# WARNING: This script requires that the user has signed up for and logged into an account (free).

for i in range(7):
    def data_path(identifier):
        return "tuples[{}].{}".format(i, identifier)

    # Sends section to appropriate box
    trace_collector.perform_send_data(
        trace_collector.get_full_xpath_from_element(
            driver.find_element_by_id("sec")
        ),
        data_path('section')
    )

    # Sends block to appropriate box
    trace_collector.perform_send_data(
        trace_collector.get_full_xpath_from_element(
            driver.find_element_by_id("blk")
        ),
        data_path("block")
    )

    # Sends lot to appropriate box
    trace_collector.perform_send_data(
        trace_collector.get_full_xpath_from_element(
            driver.find_element_by_id("lot")
        ),
        data_path("lot")
    )

    # Press "Search"
    trace_collector.perform_click(
        trace_collector.get_full_xpath_from_element(
            driver.find_element_by_id("singlebuttonsh")
        )
    )

    # Scrape address, village, school, town
    trace_collector.perform_scrape_text(
        trace_collector.get_full_xpath_from_element(
            driver.find_element_by_xpath(
                '//*[@id="right"]/section[1]/div[1]/div"
            )
        )
    )
    trace_collector.perform_scrape_text(
        trace_collector.get_full_xpath_from_element(
            driver.find_element_by_xpath(
                '//*[@id="right"]/section[1]/div[2]/div"
            )
        )
    )
    trace_collector.perform_scrape_text(
        trace_collector.get_full_xpath_from_element(
            driver.find_element_by_xpath(
                '//*[@id="right"]/section[1]/div[3]/div"
            )
        )
    )
    trace_collector.perform_scrape_text(
        trace_collector.get_full_xpath_from_element(
            driver.find_element_by_xpath(
                '//*[@id="right"]/section[1]/div[4]/div"
            )
        )
    )

    # Go back and initiate another search
    trace_collector.perform_go_back()

trace_collector.output()
```

(This is an equivalent Selenium program.)

Looking into the Future

- Synthesis as an atomic functionality in Software Engineering
  - Already come true in Excel (also “software dev”?)
  - Will come true in more and more domains
- “Programming Copilot” (ChatGPT etc.) is already here…
- Symbolic vs. Neural
  - Symbolic: search in DSL to find programs that match examples…
  - Neural: machine learning and neural nets

Looking into the Future

- Symbolic vs. Neural: both have pros and cons
  - Symbolic: highly interpretable, but slow (not scalable)..
  - Neural: generalization, but hallucinations and not interpretable..
- Many other orthogonal problems to work on
  - Usability
  - Killer apps and specialized techniques