Programming Puzzles

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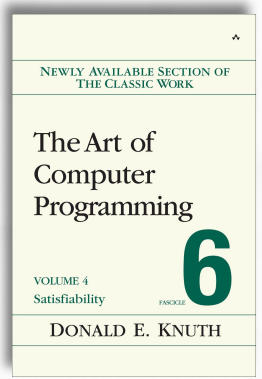
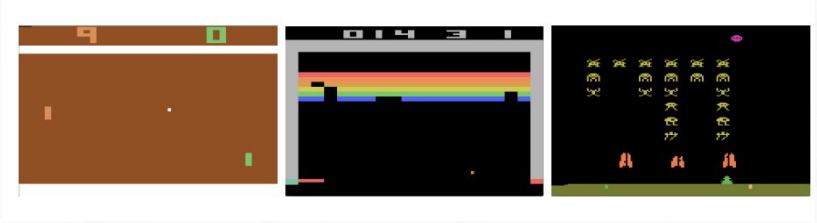
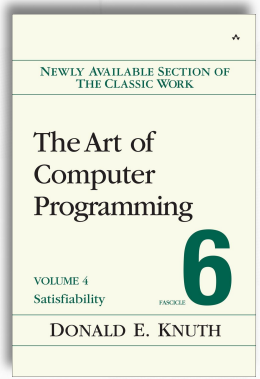
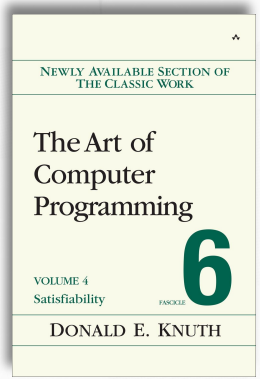
Puzzles for teaching and evaluation





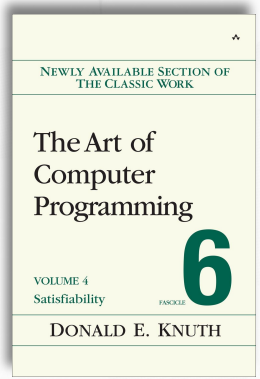


Single representation



Single representation

across many different challenge types

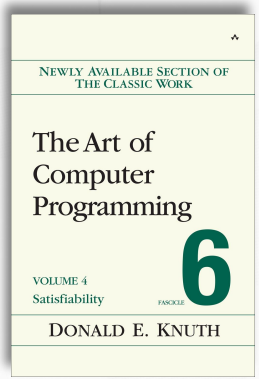


Single representation

across many different challenge types

for both humans and machines

The Guardian/ Stan Honda/AFP/Getty Images



Programming Puzzles

What is a programming puzzle?

- A **function** in any programming language (e.g., Python) that **returns a Boolean** value

- The challenge is to **find the input that satisfies the function** (i.e., makes it return **True**)

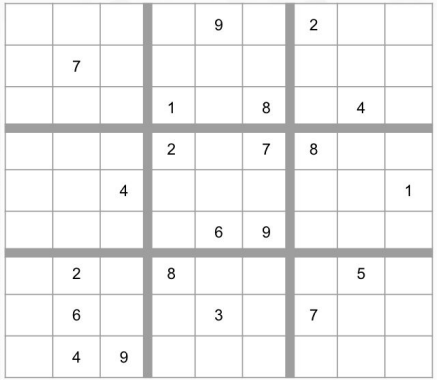
```
# Find y that solves the puzzle.
Def puzzle(y, x=[...]):
    # code defining the puzzle…
    Return solved  # Boolean.
```

Example - Sudoku

- Find the input that:
  - Is consistent with the given scheme
  - Contains only 1-9 values
  - No duplicates in rows
  - No duplicates in columns
  - No duplicates in 3x3 squares

				9		2		
	7							
			1		8		4	
			2		7	8		
		4						1
				6	9			
	2		8				5	
	6			3		7		
	4	9						

Example - Sudoku



Python Programming Puzzle

```
def sat(y: str, x="____9_2___7_________1_8_4____2_78____4_____1____69____2_8___5__6__3_7___49_____"):
    assert all(c == "_" or c == s for (c, s) in zip(x, y)), "incosistent with x"

    full = set('123456789')
    for i in range(9):
        assert {y[i] for i in range(9 * i, 9 * i + 9)} == full, "invalid row"
        assert {y[i] for i in range(i, i + 81, 9)} == full, "invalid column"
        assert {y[9 * a + b + i + 26 * (i % 3)] for a in range(3) for b in range(3)} == full, "invalid square"

    return True
```

Formal setting

- Both puzzles and answers are strings
  - Puzzle $f(x,y)$: function (source code) with a defined input type and arguments x
  - Answer y: object
  - Correct answer: $f(x,y)$ is True within time t
- Solution $g(x)$: source code to generate y from x

```
def f(y: str, x="Hello world"):   # find a string that will make the function return "True".
    return "Hello " + y == x

def g(x):   # solution.
    y = x.split(" ")[-1]
    return y   # answer.

assert f(g())
```

- **Solver**: takes **n** puzzles and timeouts and predicts solutions

Why is it important?

- AI models are getting better at code completion and generation

GitHub Copilot

- Need objective evaluation of coding proficiency to measure and spur progress

Why is it important?

- AI models are getting better at code completion and generation

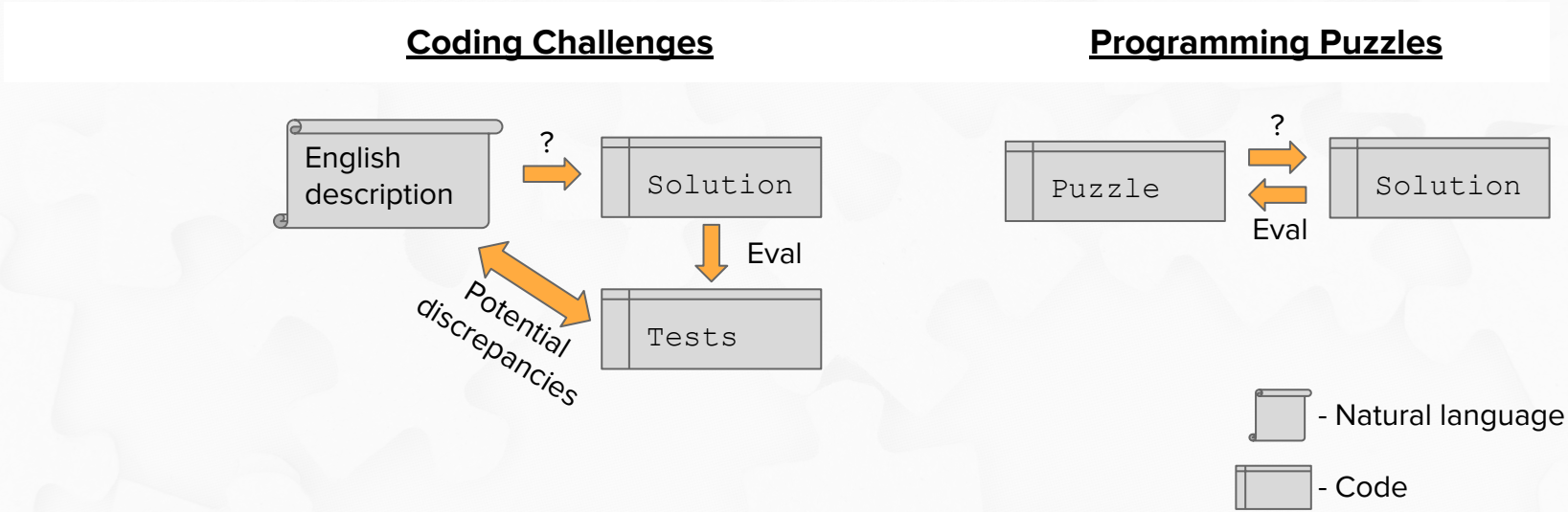
Ambiguous description

Errors indicating lack of basic understanding

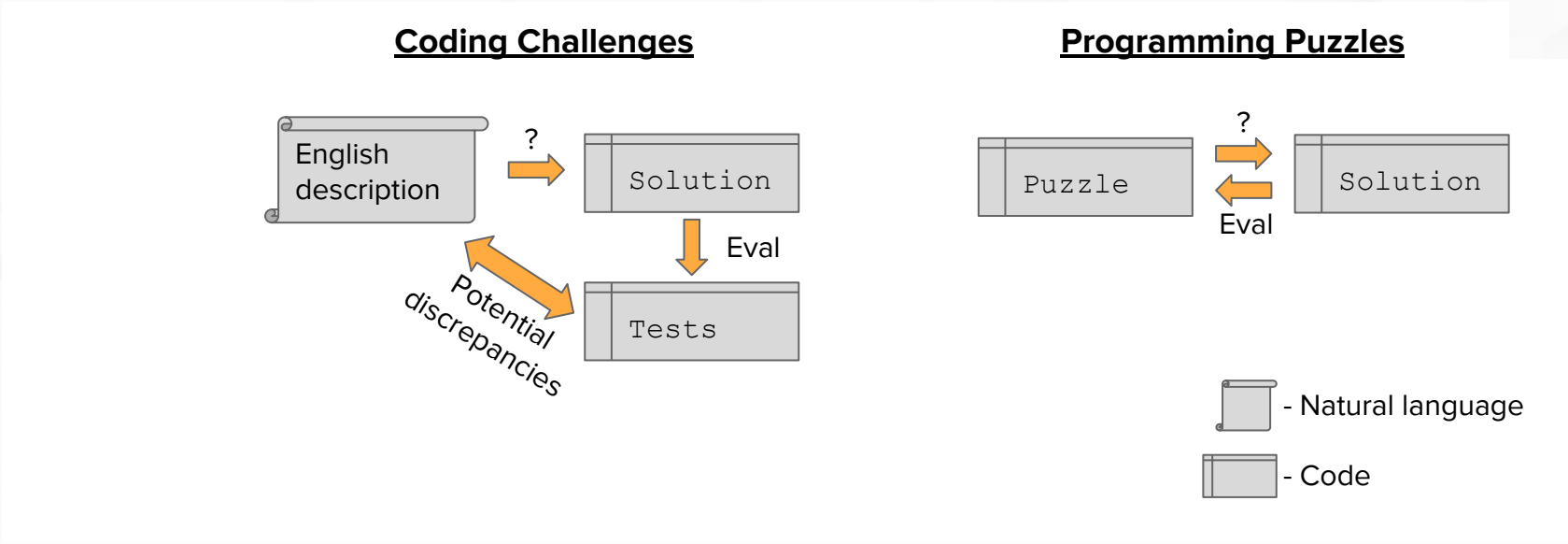
GitHub Copilot

- Need objective evaluation of coding proficiency to measure and spur progress

Pure code evaluation



Pure code evaluation



- Puzzles **focus on the algorithmic challenge**; not mixing with world knowledge or English
- Verification is straightforward and objective; **no hidden test cases**

Python Programming Puzzles (P3) dataset

- Large (and growing) collection of puzzles

  v0.1: 200 puzzles / Current size: **397 puzzles**

- **Comprehensive** in

  Domain

  Algorithmic tools

  Difficulty

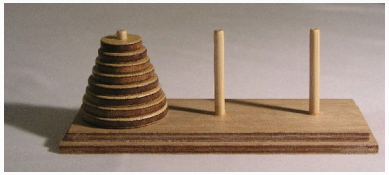
- Baselines

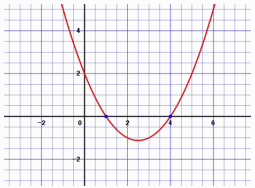
  Enumerative solvers and Language Models

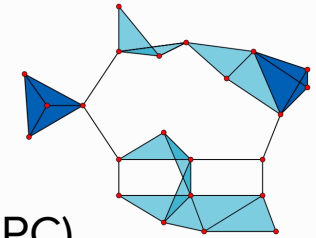
  Human programmers

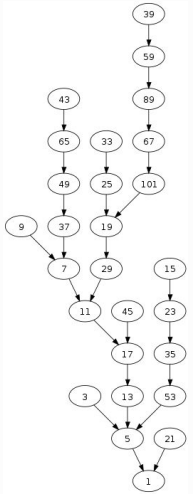
Comprehensive in domain

- Classic puzzles
- Games
- Basic Python programming
- Probability
- Algebra
- Number Theory
- Graphs
- Programming challenges
- International Collegiate Programming Contest (ICPC)
- International Mathematical Olympiad (IMO)
- ...









acm International Collegiate Programming Contest

Comprehensive in algorithmic tools

- Learning PL specific operations (e.g. string manipulation)
- Recursion
- Linear programming
- Dynamic programming
- Convex optimization
- Sorting
- Graph search
- ...

```python
# Find a string that when reversed and concatenated with "world" gives "Hello world"
def f1(y: str):
    return y[::-1] + "world" == "Hello world"

# Tower of Hanoi, often teaches recursion. Move [i, j] means move top disk on tower i to j, with 1 ≤ i,j ≤ 3
def f2(moves: List[List[int]], num_disks=8):
    state = [1] * num_disks  # All disks start at tower 1.
    for [i, j] in moves:
        assert state.index(i) <= (state + [1, 2, 3]).index(j), "bigger disk on top"
        state[state.index(i)] = j  # Move smallest disk from tower i to tower j.
    return state == [3] * num_disks  # All disks must end on tower 3.
```

Comprehensive in difficulty

- From trivial coding operations to major open algorithms and math problems
- Beating humans would mean scientific breakthroughs

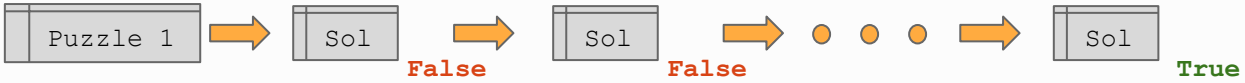
```python
def f1(s: str):   # find a string with 1000 o's but no consecutive o's.
    return s.count("o") == 1000 and s.count("oo") == 0

def f2(x: List[int]): # find the *indices* of the longest monotonic subsequence
    s = "Dynamic programming solves this classic job-interview puzzle!!!"
    return all(s[x[i]] <= s[x[i+1]] and x[i] < x[i+1]  for i in range(25))

def f3(d: int):   # find a non-trivial integer factor
    n = 100433627766186892221372630609062766858404681029709092356097
    return 1 < d < n and n % d == 0
```

Collatz conjecture (unsolved)

```python
def sat(n: int):
    """
    Consider the following process. Start with an integer `n` and repeatedly applying the operation:
    * if n is even, divide n by 2,
    * if n is odd, multiply n by 3 and add 1
    Find n > 4 which is part of a cycle of this process
    """
    m = n
    while n > 4:
        n = 3 * n + 1 if n % 2 else n // 2
        if n == m:
            return True
```

Evaluation (zero-shot)

- Number of required tries for finding a correct solution



Evaluation

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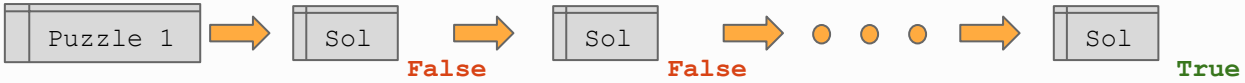
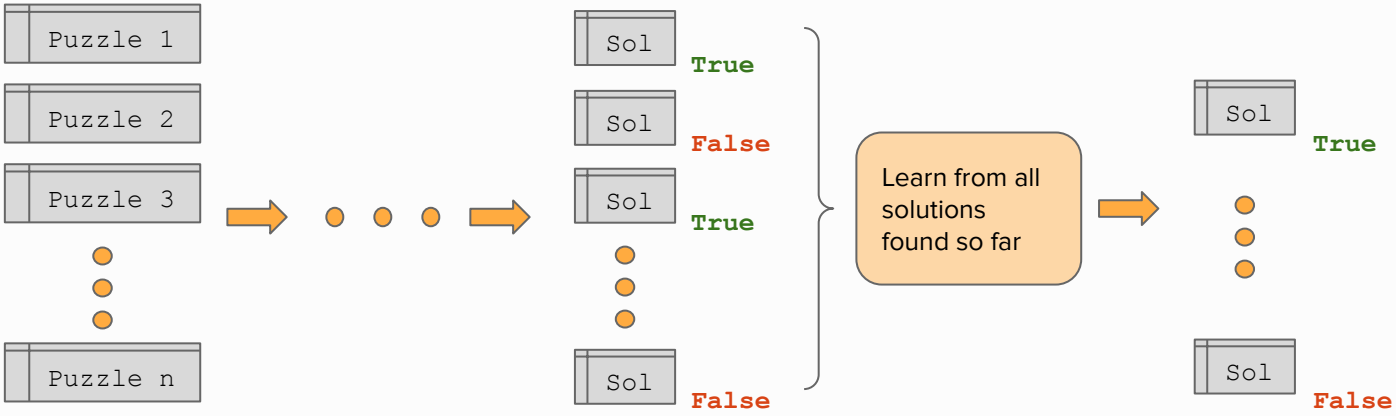


- **Test time bootstrapping**

  At step m, learn from the puzzles that were solved in $<m$ steps



Evaluation

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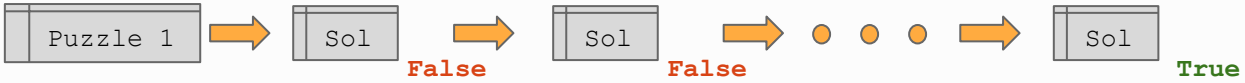
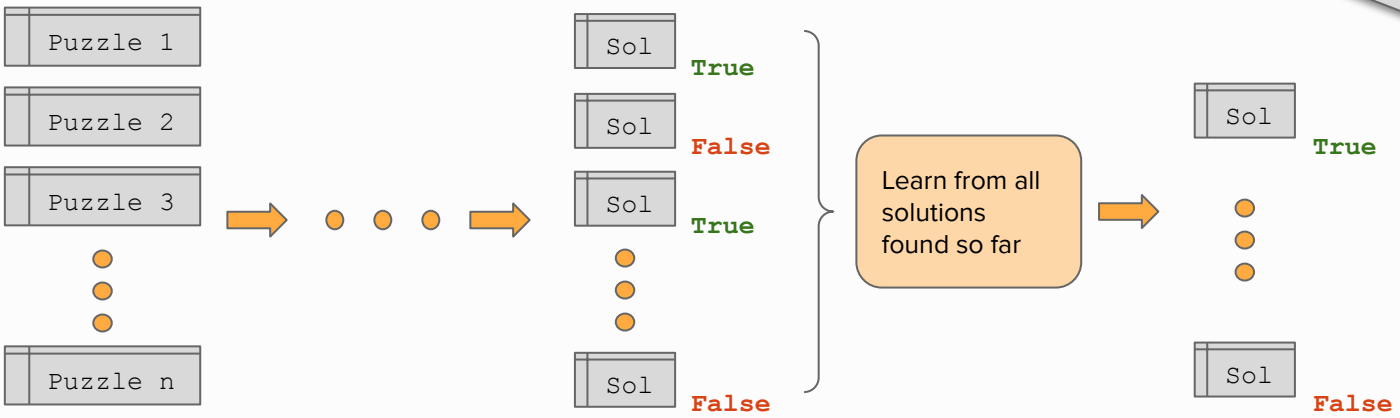


- **Test time bootstrapping**

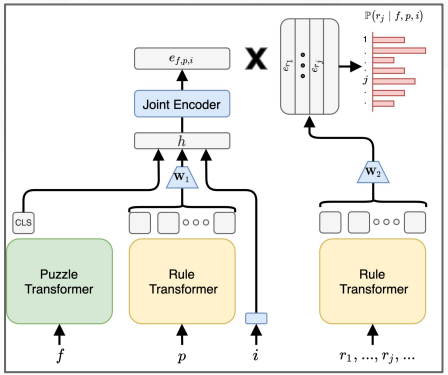
  At step m, learn from the puzzles that were solved in $<m$ steps

How many puzzles were solved with up to k tries



Solvers

- Enumerative
  - Uniform
  - Ranform forest
  - Transformer



Enumerative Transformer

- Language Models (GPT-3/ Codex)
  - Short (zero-shot)
  - Medium (five-shot)
  - Long (five-shot + EN description)

```
def f(li: List[int]):
    return len(li) == 10 and li.count(li[3]) == 2

assert True == f(...
```

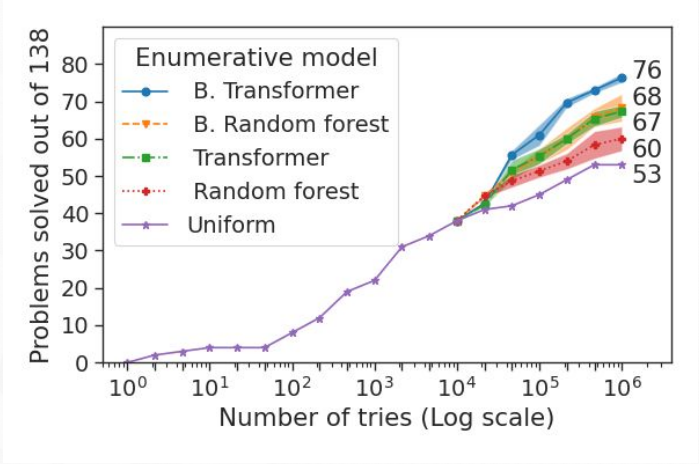
LM short prompt (zero-shot)

- Bootstrapping setting
  - Retrain model with new solutions (enumerative)/ add examples to prompt (LM)

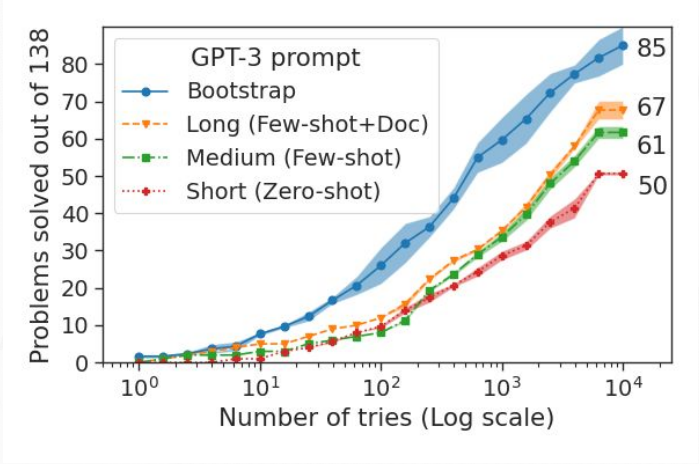
* See paper for more details

Results

Enumerative

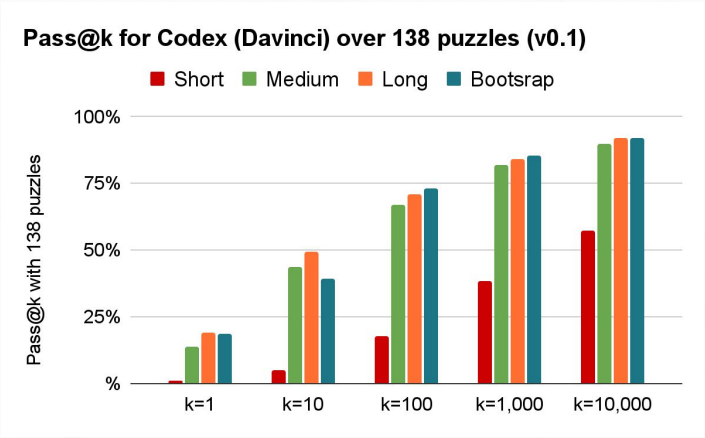


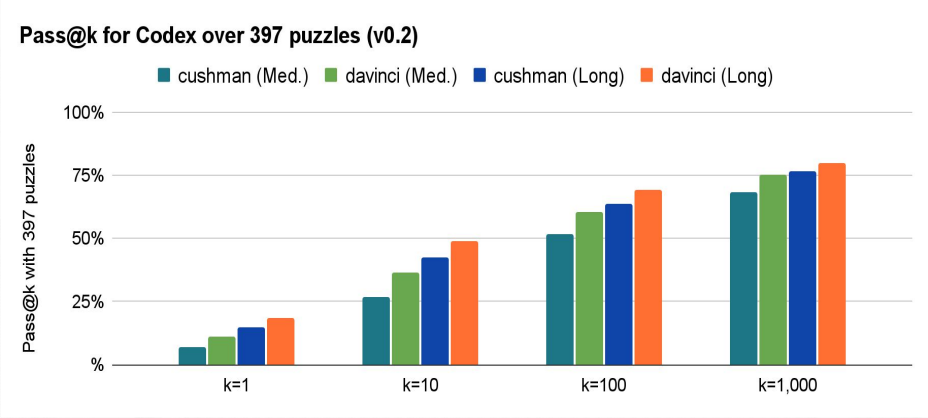
GPT-3



- More complex models perform better
- Large LMs outperform our enumerative baselines
- Learning from past solutions (bootstrapping) helps

Results - Codex model





- Larger version (Davinci) performs better
- Solves most of the puzzles (with enough tries)
- **Future challenges**:

  improve Pass@*k* for small *k*

  Add harder puzzles

Human study

- 21 participants with varying experience in Python
- Interface based on Jupyter notebook
- Up to 6 minutes per puzzle
- 30 puzzles

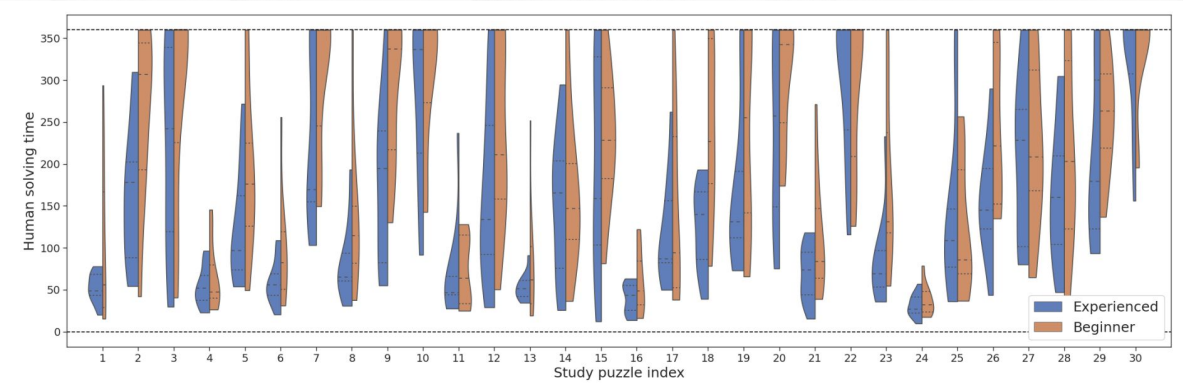
- Very positive feedback

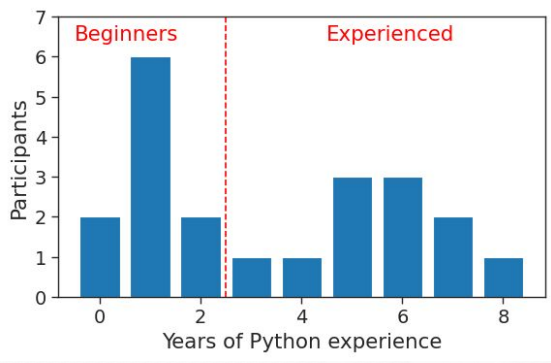

```
In [4]: # The first 3 puzzles are warmup. Begin the warmup part by running this cell.

        next_puzzle()

              Time:

        PUZZLE 1/3 (WARM UP)
        ============

        def puzzle(s: str):
            """
            Warmup problem.
            """
            return "Hello " + s == 'Hello world'
```

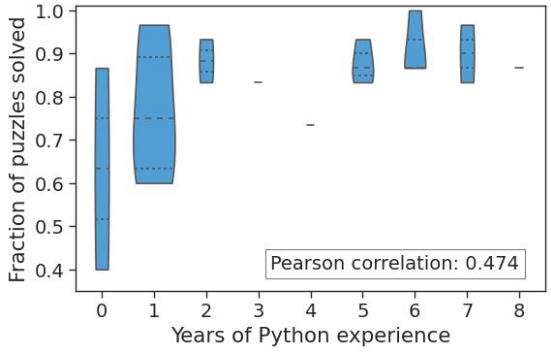
```
In [5]: # Solve the first puzzle by running this cell.

        puzzle('world')

        CORRECT in 00:39 sec.

Out[5]: True
```

Performance correlates with experience

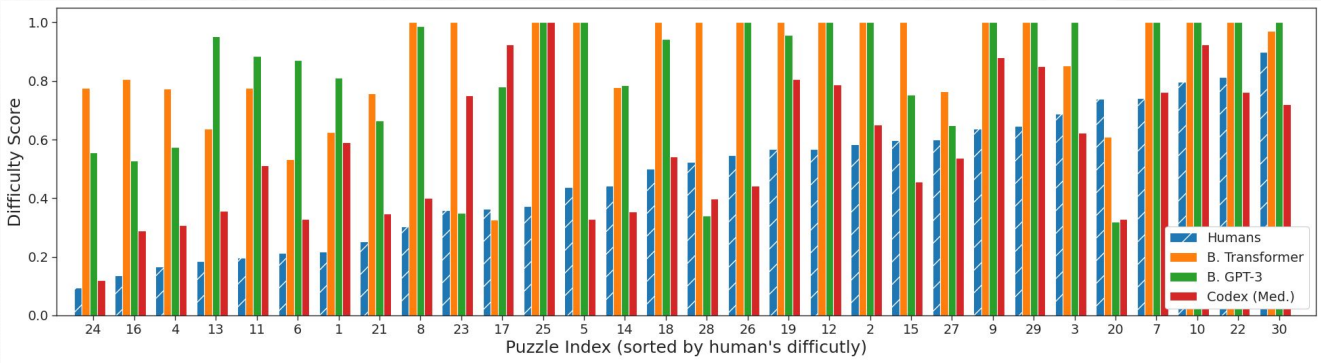
- Experienced coders solved more puzzles, faster







Human/ AI perceived difficulty

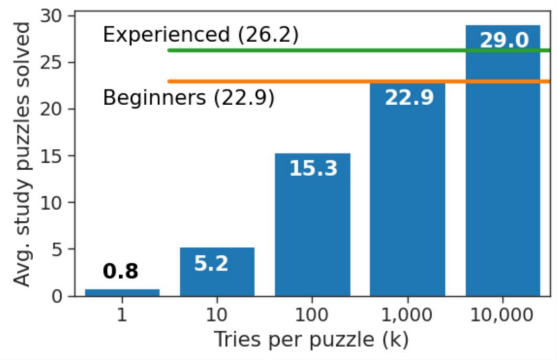


Pearson rank correlation (Human/ AI):

Model	All humans	Beginners	Experienced
Transformer	0.443	0.493	0.433
GPT-3	0.512	0.541	0.470
Codex	**0.563**	0.562	0.544

Human/ AI perceived difficulty

- Codex-davinci vs. human coders:



- Codex required up to 1K tries per puzzle to match the performance of beginner coders with up to 6 minutes per puzzle

Example

Puzzle:

- **Study_10** (1 instance)

```
def sat(s: str):
    """Find a palindrome of length greater than 11 in the decimal representation of 8^1818."""
    return s in str(8 ** 1818) and s == s[::-1] and len(s) > 11
```

Human-written solution:

▼ 1 hand-written solution

```
def sol():
    s = str(8 ** 1818)
    return next(s[i: i + le]
                for le in range(12, len(s) + 1)
                for i in range(len(s) - le + 1)
                if s[i: i + le] == s[i: i + le][::-1]
                )
```

Codex solutions:

▼ 16 AI solutions from codex (shortest and longest ones below)

```
def sol():
    x = str(8 ** 1818)
    return [x[i:(i+13)] for i in range(len(x)-11) if x[i:(i+13)] == x[i:(i+13)][::-1]][0]
```

```
def sol():
    s = str(8 ** 1818)
    n = len(s)

    pal = set()
    for i in range(11, 55):
        for j in range(n-i+1):
            pal.add(s[j:j+i])

    for p in pal:
        if p == p[::-1] and len(p) > 11:
            return p
```

Example 2: Recursion

Puzzle:

```
assert f5(g5())

def f6(moves: List[List[int]], num_disks=8):
    state = [1] * num_disks
    for [i, j] in moves:
        assert state.index(i) <= (state + [1, 2, 3]).index(j), "bigger disk
     on top"
        state[state.index(i)] = j
    return state == [3] * num_disks

def g6(num_disks=8):
```

Codex (Med.) solution:

```
    # Algorithm is equivalent to moving all disks.
    # From https://en.wikipedia.org/wiki/Tower_of_Hanoi#Advanced_computer_algorithm
    def hanoi(n, p, q, r):
        if n > 0:
            hanoi(n - 1, p, r, q)
            moves.append([p, r])
            hanoi(n - 1, q, p, r)
    moves = []
    hanoi(num_disks, 1, 2, 3)
    assert f6(moves, num_disks)
    return moves
```

Conclusion

- P3: Large (and growing) collection of Programming Puzzles
  - Evaluating advancements of AI systems in programming proficiency
  - Can lead to scientific breakthroughs
- High correlation between AI and human perceived difficulty

- Dataset, solvers and online demos are available:

`Github.com/Microsoft/PythonProgrammingPuzzles`

- **Contributions are welcomed!**