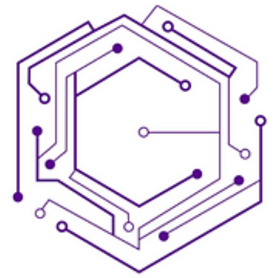
NYU TANDON SCHOOL OF ENGINEERING

The Present and Future of LLMs in Software Security

Brendan Dolan-Gavitt
NYU Tandon CSAW 2023
Nov 9, 2023



CENTER FOR CYBER SECURITY

Brave New World

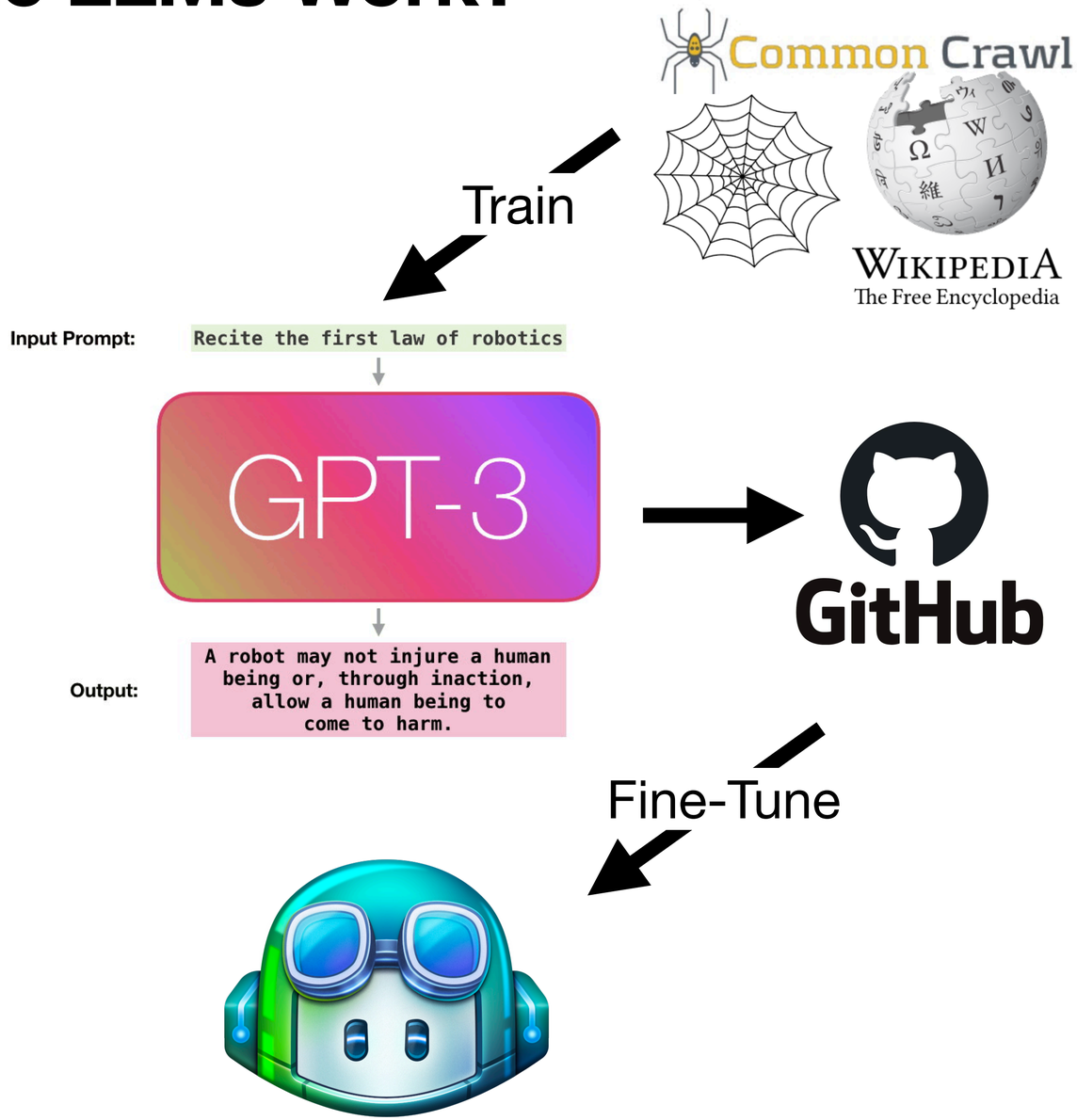
That has such chatbots in it

- Large language models (LLMs) like **ChatGPT** have exploded in popularity
- Many of these have been trained on **code** – huge amounts of it (i.e., *all of GitHub*)
- In this talk I'll try to answer:
  - What do these models mean for software security?
  - What can they do **today**?
  - What might they do **soon**?

ChatGPT

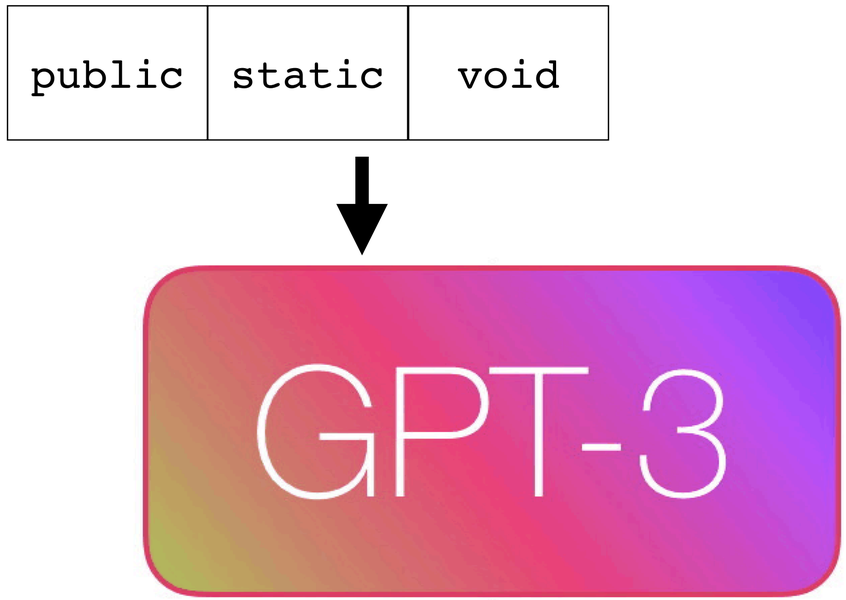
Background: How Do Code LLMs Work?

- **Objective**: predict token i given tokens {1, ..., i-1}
- **Model**: Transformer (decoder-only)
- **GPT-3** training data: WebText, Wikipedia, CommonCrawl, etc.
- **Codex**: Fine-tuned on *approximately all of GitHub public repositories*
- **Copilot**: commercial version of Codex



Autoregressive Sampling

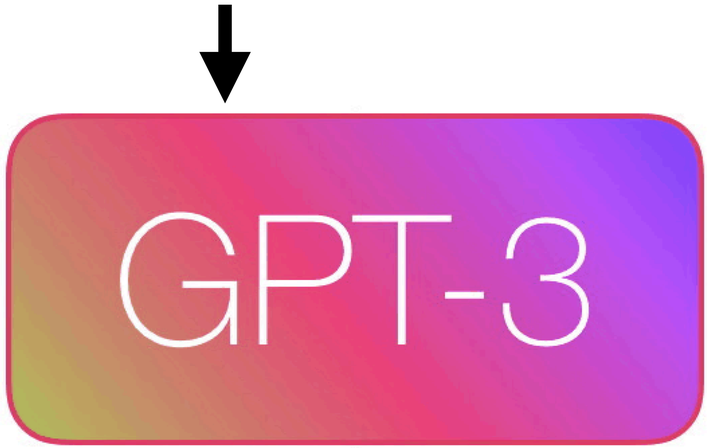
How to generate text and code



Autoregressive Sampling

How to generate text and code

public	static	void



Token	Probability
`main`	92%
`add`	6%
`update`	1%
`insert`	0.1%
`{`	0.1%
`\n`	0.04%

Autoregressive Sampling

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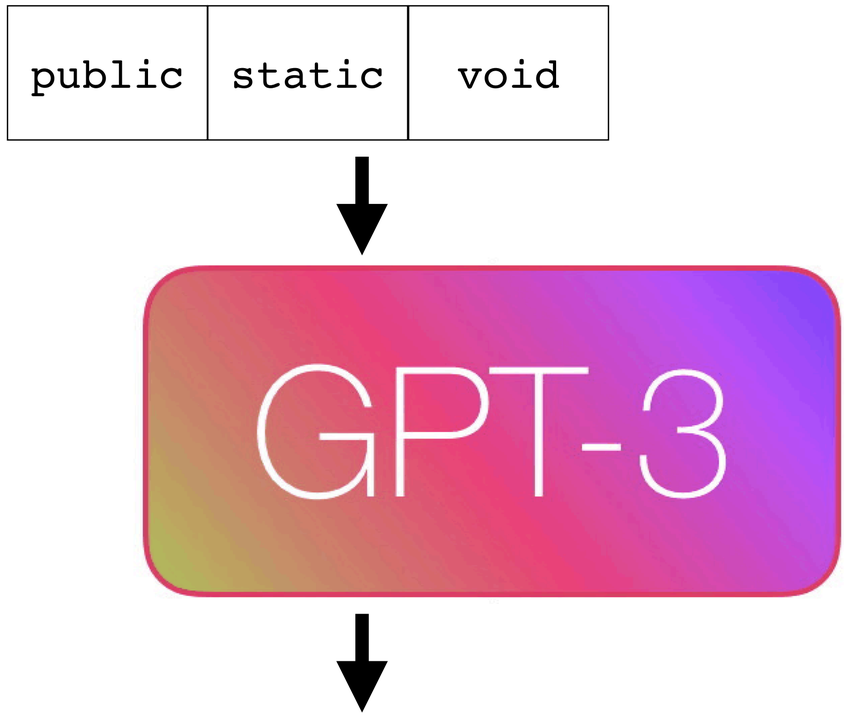

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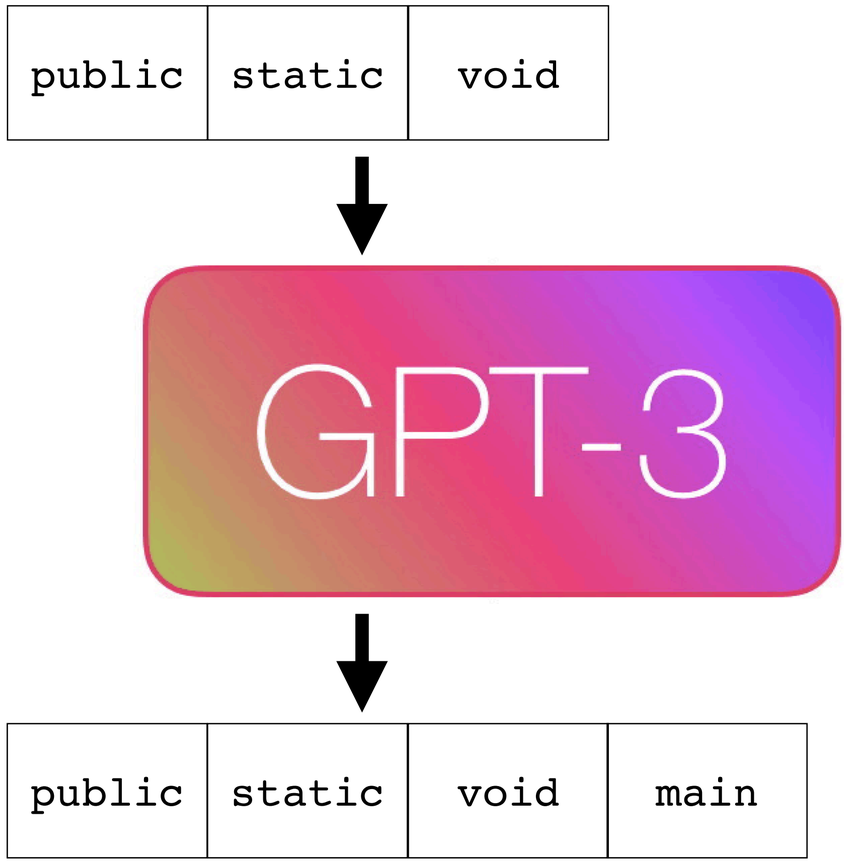

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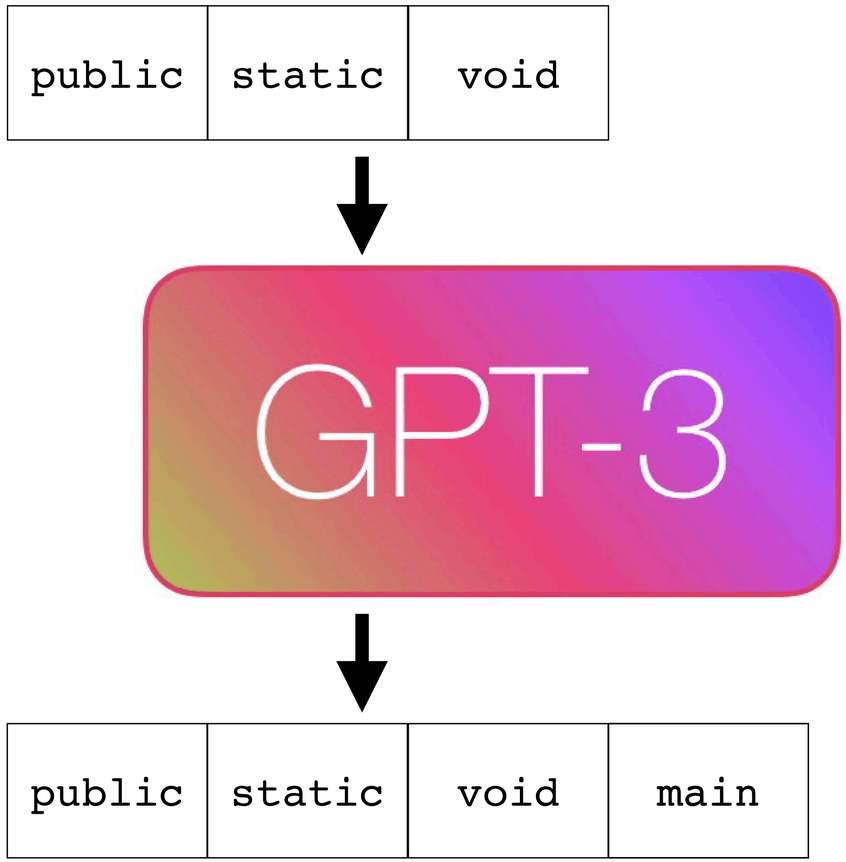

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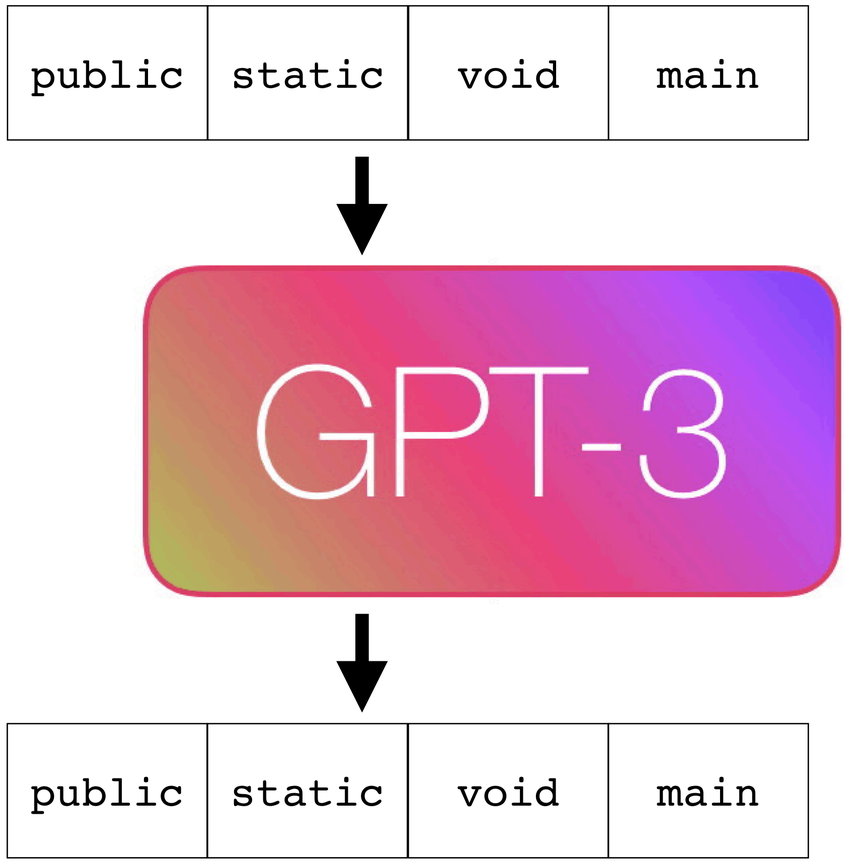

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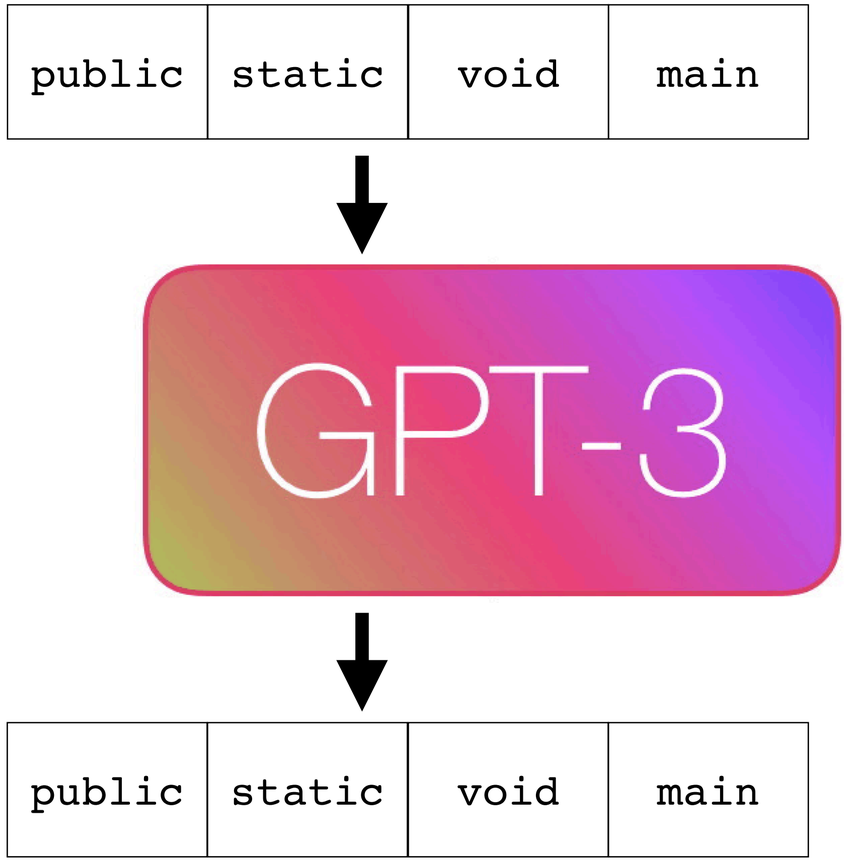
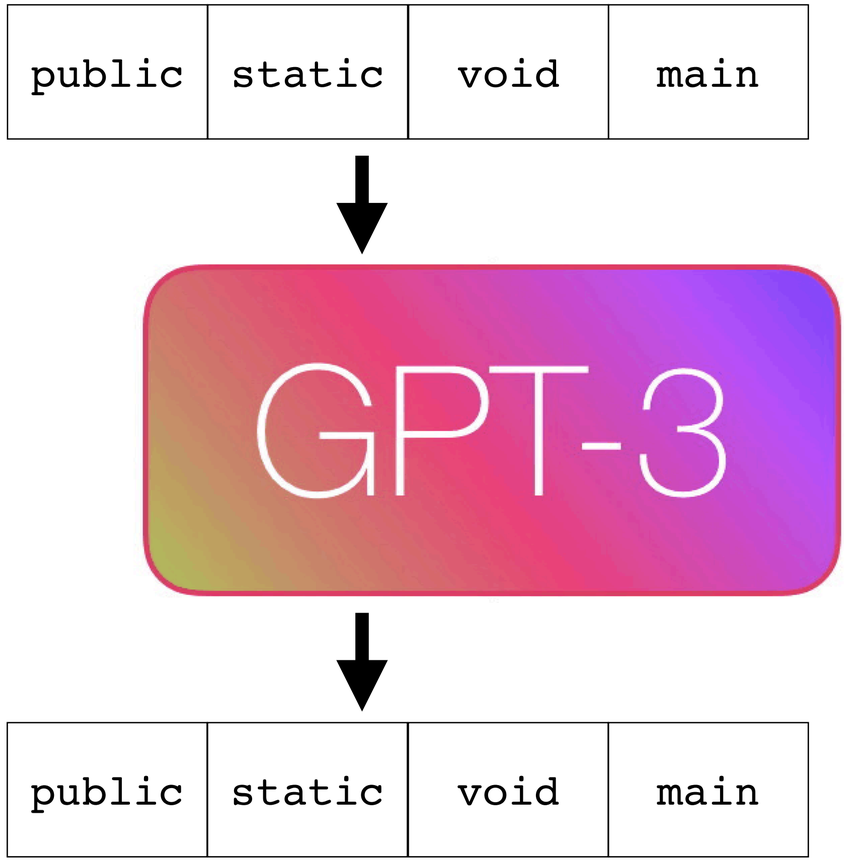


Autoregressive Sampling

How to generate text and code



Token	Probability
(String	97%
␣	2%
\n	0.01%
()	0.003%
{	0.001%
[	0.0006%

Github Copilot

reddit PROGRAMMING comments other discussions (18)

2660

GitHub Copilot · Your AI pair programmer (copilot.github.com)

submitted 2 months ago by violinclipper 4 & 14 more

581 comments share save hide give award report crosspost

The Verge

GitHub and OpenAI launch an AI Copilot tool that generates its own code

GitHub and OpenAI have launched a technical preview of a new AI tool called Copilot, which lives inside the Visual Studio Code editor and ...

Jun 29, 2021

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Blog

What OpenAI and GitHub's "AI pair programmer" means for the software industry

By **Ben Dickson** - July 5, 2021

Hacker News new | threads | past | comments | ask | show | jobs | submit

GitHub Copilot (copilot.github.com)

2905 points by todsacerdoti 75 days ago | hide | past | favorite | 1272 comments

June 29, 2021 — Open Source, Product

Introducing GitHub Copilot: your AI pair programmer

Nat Friedman

InfoWorld UNITED STATES INSIDER

Developers react to GitHub Copilot

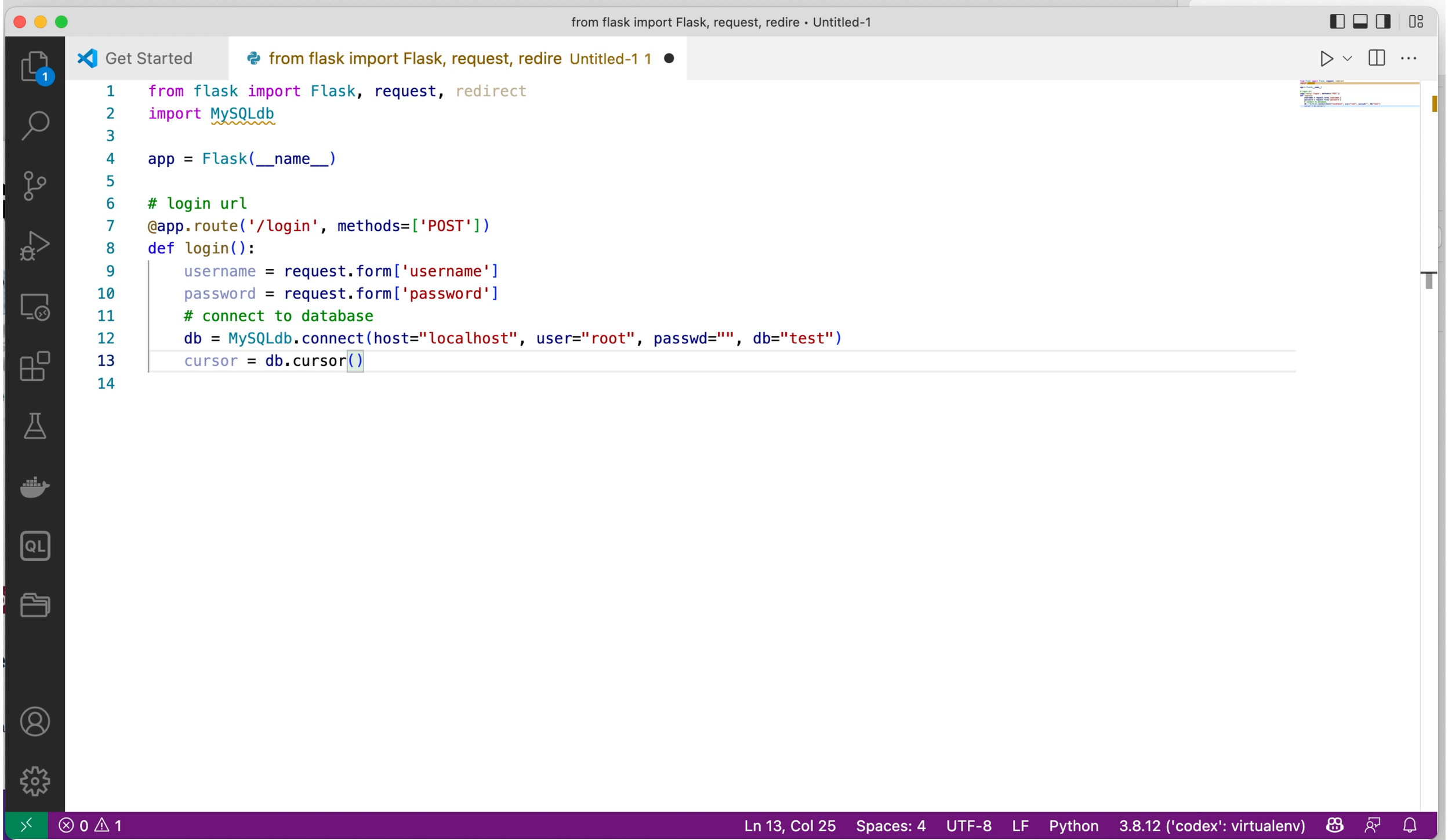
The Microsoft subsidiary has been working with OpenAI to build an AI tool that helps developers write code by making automated suggestions. Here's what the early users make of it.

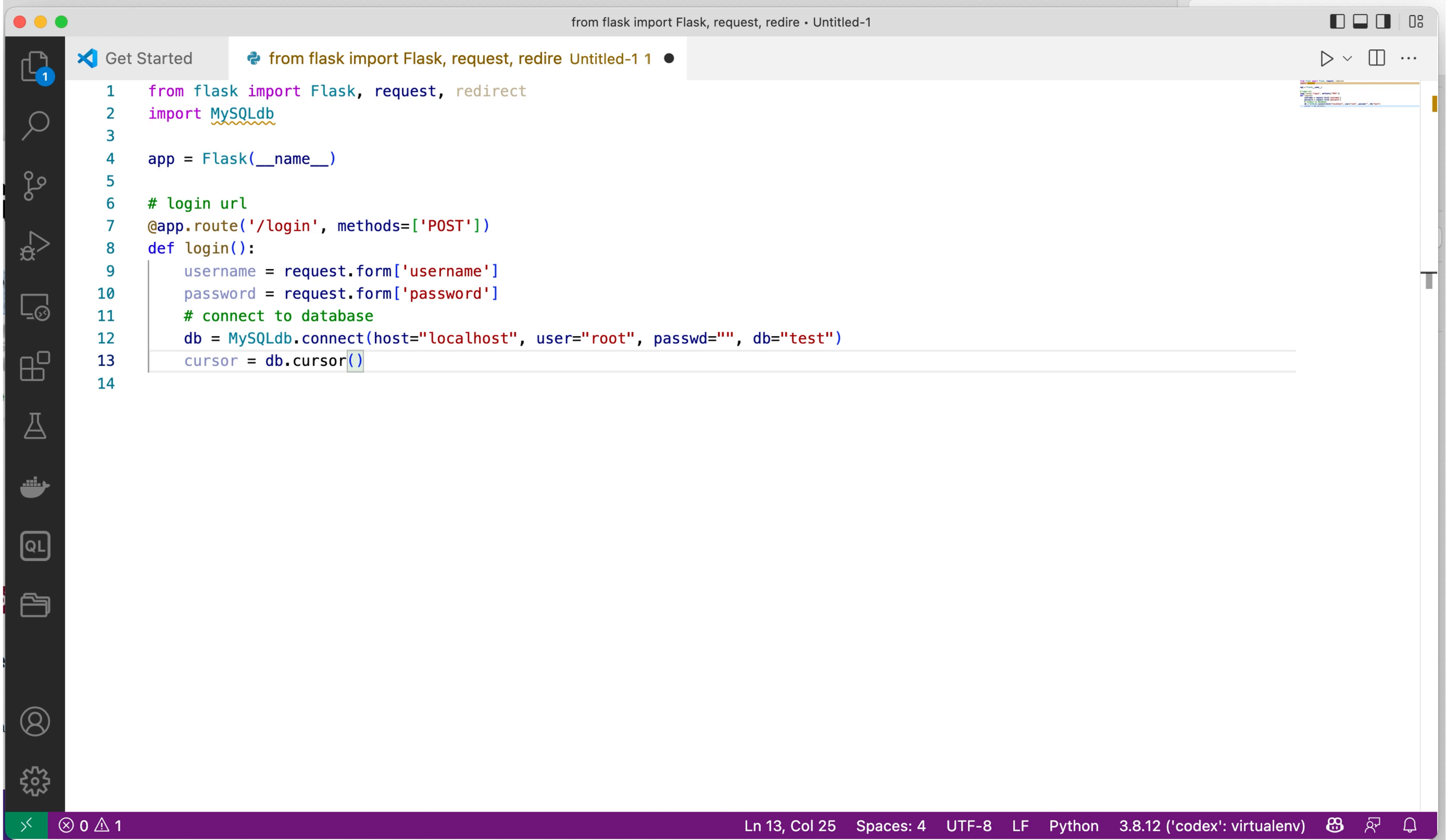
VB VentureBeat

GitHub launches Copilot to power pair programming... AI

Copilot, as the new GitHub tool is called, uses contextual cues to suggest new code, with users able to flip through alternatives if they ...

Jun 29, 2021


from flask import Flask, request, redire • Untitled-1
Get Started
from flask import Flask, request, redire Untitled-1 1
1 from flask import Flask, request, redirect
2 import MySQLdb
3
4 app = Flask(__name__)
5
6 # login url
7 @app.route('/login', methods=['POST'])
8 def login():
9 username = request.form['username']
10 password = request.form['password']
11 # connect to database
12 db = MySQLdb.connect(host="localhost", user="root", passwd="", db="test")
13 cursor = db.cursor()
14
0 1
Ln 13, Col 25
Spaces: 4
UTF-8
LF
Python
3.8.12 ('codex': virtualenv)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7 @app.route('/login', methods=['POST'])
8 def login():
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0 1
Ln 13, Col 25
Spaces: 4
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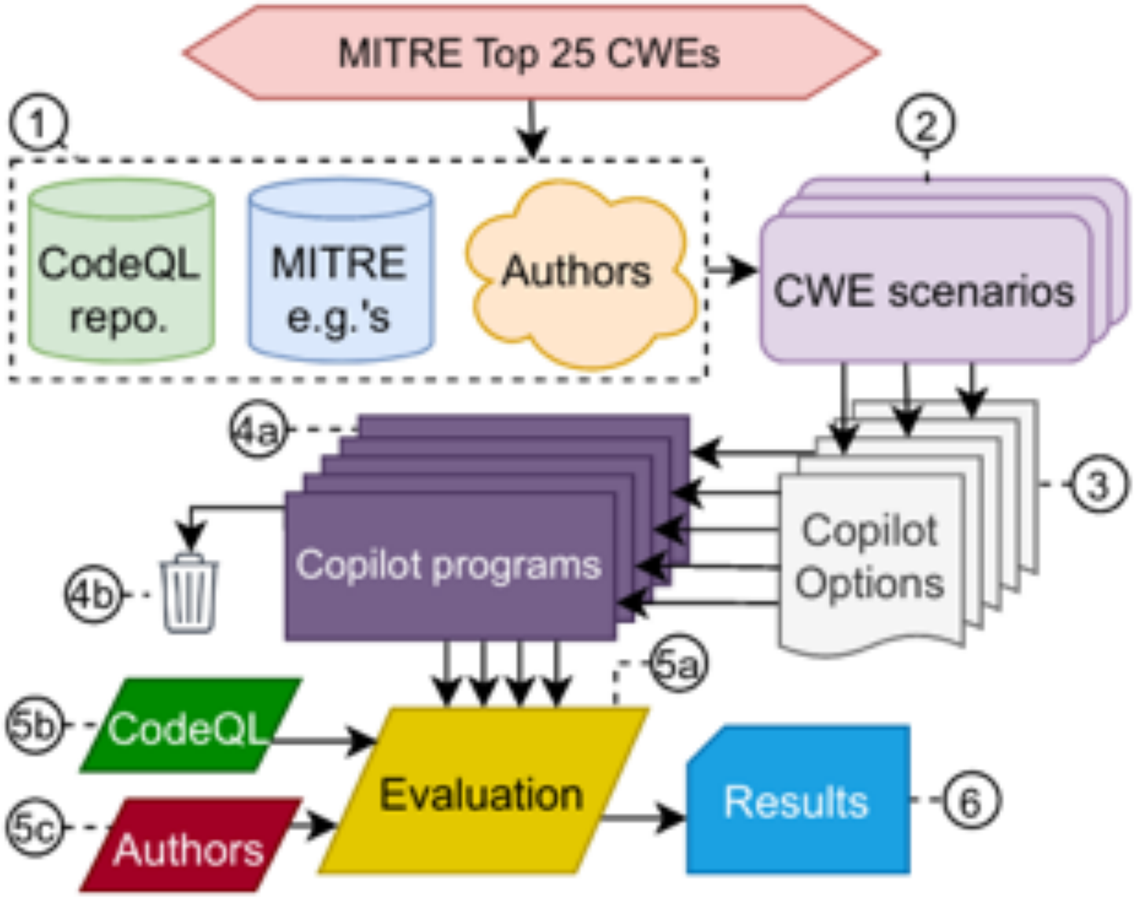
Copilot Writes Vulnerable Code

Measuring Copilot Vulnerabilities

- Created scenarios (code snippets to complete) for **MITRE CWE Top 25**
- Ask Copilot for 25 completions for each
- How to evaluate vulnerability? **CodeQL**
  - Extensible query language, built-in queries for many CWEs
  - Free for academic use
  - Static analysis tool owned by GitHub; seems fair to use it to test Copilot :)



CWE Top 25 Results

- Examined 18 different vulnerability classes (CWEs) and 54 scenarios, used Copilot to generate 1,084 total valid programs
  - **42% of generated programs were vulnerable**
- Notable findings
  - Higher vulnerability rates for **C (51%)** than **Python (38%)**
  - Common problems: sequence/attention errors (UAF), pointers & array lengths, bad hashing algorithms
  - Best at avoiding web flaws: auth, XSS, permissions, etc.

Vuln Repair: Fixing CVE-2023-40296

CVE-2023-40296 PUBLISHED

View JSON

Important CVE JSON 5 Information +

Not in training data!

Assigner: MITRE Corporation
Published: 2023-08-14 **Updated:** 2023-08-14

async-sockets-cpp through 0.3.1 has a stack-based buffer overflow in ReceiveFrom and Receive in udpsocket.hpp when processing malformed UDP packets.

The Vulnerability

A classic off-by-one

If recv() returns BUFFER_SIZE bytes, a NULL is written one byte past the end of tempBuffer

```
static void Receive(UDPSocket* udpSocket)
{
    char tempBuffer[BUFFER_SIZE];
    ssize_t messageLength;

    while ((messageLength = recv(udpSocket->sock, tempBuffer, BUFFER_SIZE, 0)) != -1)
    {
        tempBuffer[messageLength] = '\0';
        if (udpSocket->onMessageReceived)
            udpSocket->onMessageReceived(std::string(tempBuffer, messageLength), \
                ipToString(udpSocket->address), ntohs(udpSocket->address.sin_port));

        if (udpSocket->onRawMessageReceived)
            udpSocket->onRawMessageReceived(tempBuffer, messageLength, \
                ipToString(udpSocket->address), ntohs(udpSocket->address.sin_port));
    }
}
```

Asking ChatGPT4

Full transcript: https://chat.openai.com/share/c382940f-14e9-4fdd-97df-52ee4429854e

GPT-4

BR

Identify the vulnerability in the following file:

```
#pragma once

#include "basesocket.hpp"
#include <string.h>
#include <thread>

template <uint16_t BUFFER_SIZE = AS_DEFAULT_BUFFER_SIZE>
class UDPSocket : public BaseSocket
{
public:
   std::function<void(std::string, std::string, std::uint16_t)> onMessageReceived;
   std::function<void(const char*, ssize_t, std::string, std::uint16_t)>
onRawMessageReceived;
```

[...]

ChatGPT4: Vulnerability Discovery

The code implements a UDP socket class in C++ and appears to be dealing with low-level network communication. While I can't run the code to test it, I can identify a few areas of concern that could lead to vulnerabilities or issues:

1. **Buffer Overflow Vulnerability**: The most glaring issue is in the `Receive` and `ReceiveFrom` methods, where the code uses a statically-sized buffer `tempBuffer` of size `BUFFER_SIZE` to receive incoming messages. After reading `messageLength` bytes into `tempBuffer`, it null-terminates the buffer with `tempBuffer[messageLength] = '\0';`. If `messageLength` happens to be equal to `BUFFER_SIZE`, this would write past the end of the array, causing undefined behavior and posing a security risk.

ChatGPT4 Repair

BR

Please fix the buffer overflow vulnerability and show me just the new code for Receive and ReceiveFrom

Certainly, one way to mitigate the buffer overflow vulnerability is to ensure that the null-terminator is only written within the bounds of `tempBuffer`. This can be achieved by not writing past `BUFFER_SIZE - 1` for the data and setting the last element to `\0` for string termination. Here's the modified code:

```
static void Receive(UDPSocket* udpSocket)
{
    char tempBuffer[BUFFER_SIZE];
    ssize_t messageLength;

    while ((messageLength = recv(udpSocket->sock, tempBuffer, BUFFER_SIZE - 1, 0)) != -1)
    {
        tempBuffer[messageLength] = '\0';
```

ChatGPT4 Repair

BR

Please fix th … e and
ReceiveFro…

Certainly, o… …ll-
terminator i… …y not
writing past … …string
termination…

```
static void
{
    char tem
    ssize_t

    while ((
    {
        temp
```

…1, 0)) != -1)

Official Developer Patch

eminfedar commented last month • edited

About this, you are right:

async-sockets-cpp/async-sockets/include/udpsocket.hpp
Line 143 in 78641cf

```
143     tempBuffer[messageLength] = '\0';
```

I pushed a commit and increased the buffers' length plus 1:

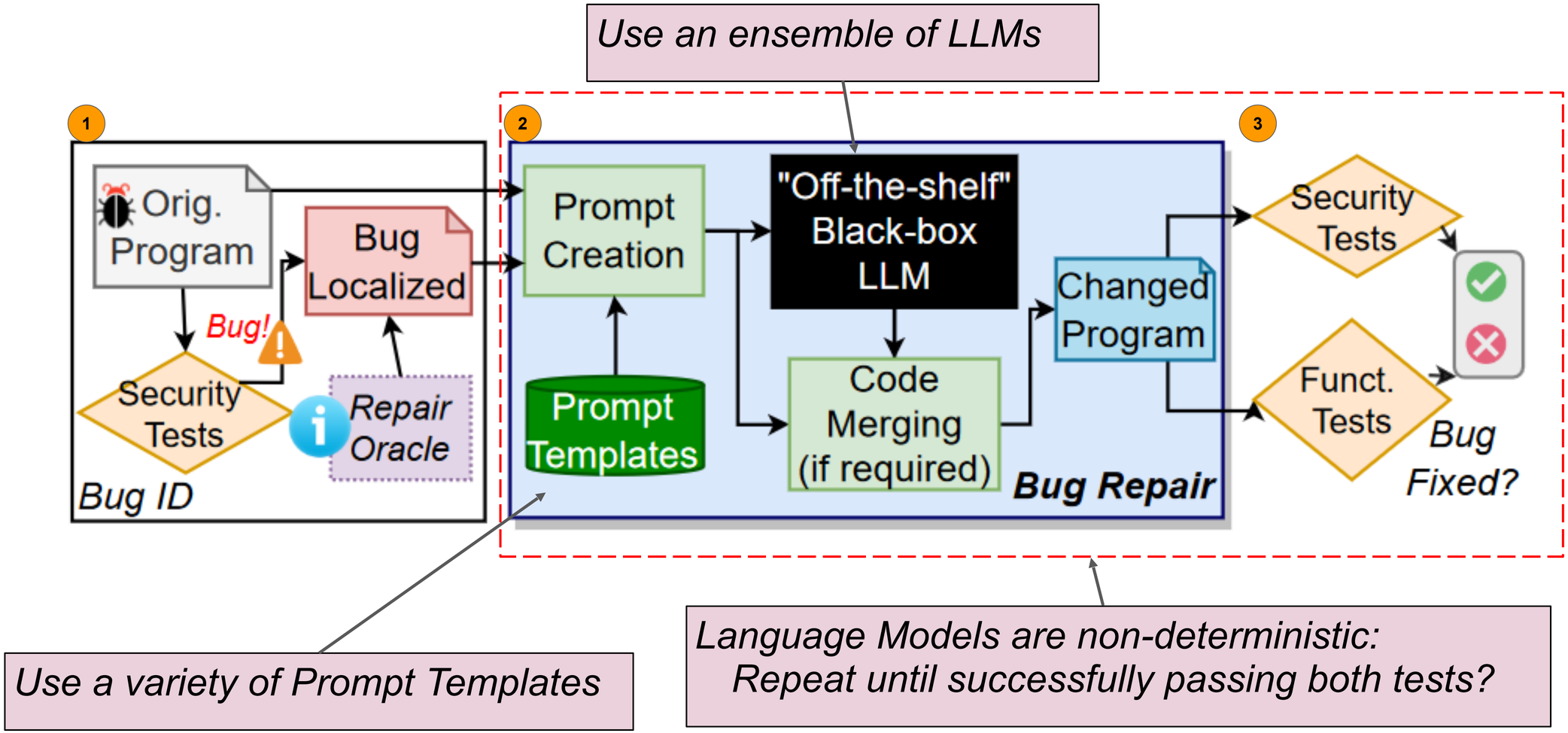
async-sockets-cpp/async-sockets/include/tcpsocket.hpp
Line 99 in 78641cf

```
99      char tempBuffer[BUFFER_SIZE+1];
```

so this is ok now: `tempBuffer[messageLength] = '\0';`

Systematic Study: A Repair Framework

From "Examining Zero-Shot Vulnerability Repair with Large Language Models", Pearce et al., IEEE S&P 2023



Promising Results?

Real-world vulns from ExtractFix dataset

	LLM	EF
EF01: LibTIFF Out-of-bounds read	✓	✓
EF02a: LibTIFF Out-of-bounds write	✗	✓
EF02b: LibTIFF Out-of-bounds write	✗	✗
EF07: LibTIFF Off-by-one error	✓	✓
EF08: LibTIFF Shift exp. type error	✓	✓
EF09: LibTIFF DoS by divide by zero	✓	✓
EF10: LibTIFF DoS by divide by zero	✓	✓
EF15: LibXML2 Buffer over-read	✓	✓
EF17: LibXML2 Buffer underflow	✓	✓
EF18: LibXML2 Null pointer deref.	✗	✓
EF20: LibJPEG Buffer over-read	✓	✗
EF22: LibJPEG Buffer overflow	✗	✓

- 12 real-world CVEs:
  - **432** Model/Prompt combinations
  - 19,600 attempted patches,
  - 982 repairs,
  - **8 of 12 scenarios repaired by ensemble.**
    - Cushman-001: 8/12
    - Davinci-001: 7/12
    - Davinci-002: 7/12
    - J1-large: 5/12
    - GPT-CSRC (ours): 4/12
    - Polycoder: 6/12

Reality Check: Do the Patches Work?
(Remember GenProg/RSRepair from program repair?)

TABLE VII
AUTHOR OPINIONS OF LLM-PROVIDED PATCHES: IDENTICAL OR SEMANTICALLY EQUIVALENT TO THE DEVELOPER PATCH; REASONABLE IF THEY APPEAR TO FIX THE BUG; OR NOT REASONABLE IF NOT.

Scenario	Engine	Plausibile
EF01	code-cushman-001	Not R.
	code-davinci-001	Sem. Eq.
	code-davinci-002	Not R.
	j1-large	Not R.
	gpt2-csrc	Not R.
	polycoder	Sem. Eq.
EF07	code-cushman-001	Sem. Eq.
	code-davinci-002	R.
EF08	code-cushman-001	Not R.
	code-davinci-001	Not R.
	code-davinci-002	Not R.
	j1-large	Not R.
	gpt2-csrc	Not R.
	polycoder	Not R.
EF09	code-cushman-001	R.
	code-davinci-001	R.
	code-davinci-002	R.
	j1-large	Not R.
	gpt2-csrc	Not R.
	polycoder	Not R.

Scenario	Engine	Plausible
EF10	code-cushman-001	R.
	code-davinci-001	R.
	code-davinci-002	R.
	j1-large	Not R.
	gpt2-csrc	Not R.
	polycoder	Not R.
EF15	code-cushman-001	Not R.
	code-davinci-001	Not R.
	code-davinci-002	Not R.
	polycoder	Not R.
EF17	code-cushman-001	Not R.
	code-davinci-001	Ident.
	code-davinci-002	Sem. Eq.
	j1-large	Sem. Eq.
	gpt2-csrc	Not R.
	polycoder	Not R.
EF20	code-cushman-001	R.
	code-davinci-001	Not R.

- Testing cannot verify *absence* of bugs
- Manual inspection of top-scoring ‘fixes’ reveals that many fixes ‘**unreasonable**’
- Reduces ‘success’ to 6 of 12 (50%).
- Davinci-001: 4/12
- Davinci-002: 4/12

Demo: Reverse Engineering

Full transcript: https://chat.openai.com/share/b41bcd92-80f8-4aa4-9086-e8aede516ace

- Anecdote: I was doing my taxes with TurboTax (closed source) on OS X, but it kept crashing at a particular point
- Using ChatGPT4, I was able to:
  - Get instructions for attaching the XCode debugger and getting a backtrace
  - Feed the backtrace to GPT4 to identify the problematic code
  - Decompile functions along the way to Objective C / Swift
  - Identify and fix the problem (a missing JSON file in the installation)
- (I don't have much experience with OS X or Swift/Objective C reverse engineering)

Crash Source Identification

The crash occurs on the main thread (thread #1) with the stop reason: **`Fatal error: Unexpectedly found nil while implicitly unwrapping an Optional value`**. The issue seems to be related to the unwrapping of an optional value without proper checking for **`nil`**.

The relevant stack trace line is:

`frame #6: 0x0000000107814d1d TurboTax 2020``static TurboTax_2020.FDPContingencyHandler.readAndReturnExperimentInConfig() -> Swift.Dictionary<Swift.String, Swift.AnyObject> + 637`

This line is within the **`TurboTax_2020.FDPContingencyHandler.readAndReturnExperimentInConfig()`** function, which returns a dictionary. It appears that the crash is due to an implicitly unwrapped optional value being **`nil`** when it was expected to have a value. To resolve this issue, it's necessary to find out why the optional value is **`nil`** and ensure proper handling of optional values within the code. This can be done by using optional binding (if let or guard let) or providing a default value with the nil-coalescing operator (??).

Swift Decompilation

It's quite challenging to reconstruct the exact original Swift code from assembly, but I can provide you with a rough outline of what the code might have looked like. The details and syntax might be different from the actual code. Here's an attempt to reconstruct the code:

swift Copy code

```swift
class TurboTax_2020 {
    // ...

    static func FDPContingencyHandler() -> [String: AnyObject] {
        var dictionary: [String: AnyObject] = [:]

        let experimentServiceController = ExperimentServiceController()
        let experimentSettings = experimentServiceController.loadExperimentS

        if let settings = experimentSettings {
            // Code to process experimentSettings and populate the dictionar
            // ...
        }

        return dictionary
    }
```

Systematic Study: Answering True/False Questions

From "Pop Quiz! Can a Large Language Model Help With Reverse Engineering?", Pearce et al. (arXiv preprint)

True/False Question ID

Scenario	Encrypt?	nEncrypt?	XOR?	nXOR?	AES?	nAES?	Delete?	nDelete?	Network?	nNetwork?	Downld?	nDownld?	Upload?	nUpload?	EtcPswd?	nEtcPswd?	MD5?	nMD5?	FIR1?	nFIR1?	FIR2?	nFIR2?	IIR1?	nIIR1?	IIR2?	nIIR2?	PID1?	nPID1?	PID2?	nPID2?	PI?	nPI?	PD?	nPID?	CSum?	nCSum?
delete_listen (o. src)	8	7	2	6	7	4	9	7	10	9	3	4	8	2	7	10	6	4	4	3	2	8	3	7	7	7	2	0	6	9	7	8	3	9	3	7
delete_listen (r. src)	0	1	0	7	6	5	10	7	10	5	2	3	6	2	5	7	2	2	1	6	1	6	2	2	2	4	0	1	6	9	2	8	3	7	0	7
delete_listen -o1 -g	6	3	2	3	8	5	10	8	7	1	8	6	4	3	7	8	2	1	1	0	4	7	7	2	5	2	2	0	9	4	7	8	3	3	7	4
delete_listen -o1	6	6	6	4	6	4	10	8	6	0	5	6	6	2	7	10	4	0	3	3	5	4	2	2	5	6	2	2	8	8	7	6	5	4	6	6
delete_listen -o1 -s	3	3	1	7	8	2	9	8	10	1	3	3	5	3	6	9	1	5	0	1	1	5	0	2	2	5	0	1	8	8	6	4	3	7	0	6
pid_d (o. src)	6	5	6	7	8	5	9	3	10	5	10	7	10	8	10	10	6	4	0	4	1	3	2	8	1	4	9	10	10	8	0	6	1	5	3	5
pid_d (r. src)	2	4	5	8	6	4	6	5	9	9	10	9	8	7	10	7	9	4	1	2	1	4	0	7	0	7	10	9	10	6	1	4	0	7	1	2
pid_d -o1 -g	5	1	7	2	9	3	9	2	10	8	8	9	8	9	9	8	5	1	2	3	1	4	4	3	1	4	10	9	10	9	0	6	0	8	4	5
pid_d -o1	4	2	6	5	10	2	9	7	9	8	10	8	8	9	9	8	4	3	0	2	0	3	2	5	0	3	9	10	9	8	0	6	0	6	4	3
pid_d -o1 -s	1	0	2	5	5	1	5	6	9	7	6	8	8	9	7	6	0	1	0	0	0	2	1	1	1	3	10	9	9	7	1	6	1	6	0	4

- Wrote small programs and asked Codex (DaVinci-001) **true/false** questions
- Both about source (with and w/o var rename) and Ghidra-decompiled code
- **Result: only ~53% accuracy overall – not much better than chance**

Emerging Trend: Improvements in Code Security

A Benchmark Revisited

- Since we published our Copilot benchmark in 2021, GPT-3.5 and GPT-4 came out
- Encouragingly, **both got much better at writing secure code**!
- As far as I know, there is no public documentation on *how* they did this :(

DaVinci: 417 insecure, 550 secure, 33 invalid (31.7% valid but insecure)
GPT-3.5: 269 insecure, 722 secure, 9 invalid (20.1% valid but insecure)
GPT-4: 57 insecure, 943 secure, 0 invalid (4.2% valid but insecure)

Emerging Trend: Open, Local Models

Code Llama

Mistral 7B

Phind-CodeLlama 34B

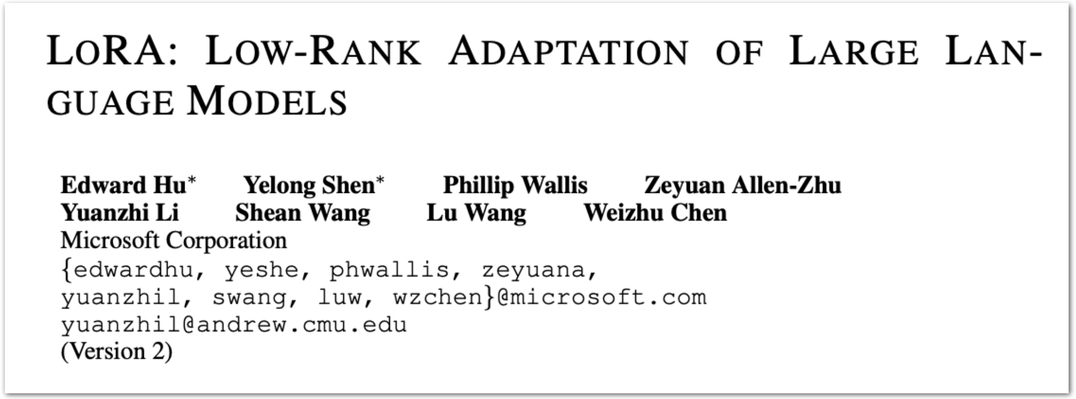
CodeGen2

replit-code v1.3b

- For a while OpenAI was the only game in town – that has changed!
- There are now many high quality, "open" (weights available) models
- Model compression (e.g. quantization) means you can run them on your laptop
- This is great for multiple reasons:
  - Local models can be used in environments where sending your code to MS/OpenAI isn't allowed
  - Local models can be **fine-tuned** for your specific task, language, or codebase

Emerging Trend: PEFT

Parameter-Efficient Fine Tuning



LoRA: Low-Rank Adaptation of Large Language Models

Edward Hu* **Yelong Shen*** **Phillip Wallis** **Zeyuan Allen-Zhu**
Yuanzhi Li **Shean Wang** **Lu Wang** **Weizhu Chen**
Microsoft Corporation
{edwardhu, yeshe, phwallis, zeyuana,
yuanzhil, swang, luw, wzchen}@microsoft.com
yuanzhil@andrew.cmu.edu
(Version 2)

- Until recently, **fine-tuning** an LLM on your data required huge amounts of GPU memory and disk space
- Recent *parameter-efficient fine tuning methods* change that
- Techniques like LoRA allow you to tune models faster, with much less memory – and the new weights can be saved as a small *adapter*
  - Training goes ~25% faster
  - Uses less GPU memory: ~66% reduction
  - Checkpoints: 350 **GB** -> 35 **MB**

Conclusions

- I am **extremely optimistic** about the promise of LLMs in security applications
  - Naïve extrapolation: from 2019→2023, we went from GPT2 to GPT4
  - Open models + advances in fine tuning (PEFT/LoRA) have made it much **cheaper** and **easier** to experiment with LLMs on domain specific data
- Some guesses about what's coming:
  - Vulnerability **detection** and **repair** with LLMs
  - **Rewriting** software in safer languages
  - **Reverse engineering** of code from multiple languages
  - **Automated exploit generation**

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Check out the CSAW LLM Attack Competition!