NYU TANDON SCHOOL OF ENGINEERING

Lost at C

Security Implications of Large Language Model Code Assistants

Brendan Dolan-Gavitt

In collaboration with: Gustavo Sandoval, Hammond Pearce, Teo Nys, Ramesh Karri, and Siddharth Garg

CENTER FOR CYBER SECURITY

Surprising Progress in Code Models

Before 2021

- 2015: Karpathy's Char-RNN, generating Linux kernel code
- 2019: GPT-2 "accidentally" learns some PHP and JavaScript

```
/*
 * Increment the size file of the new incorrect UI_FILTER group information
 * of the size generatively.
 */
static int indicate_policy(void)
{
  int error;
  if (fd == MARN_EPT) {
    /*
     * The kernel blank will coeld it to userspace.
     */
    if (ss->segment < mem_total)
      unblock_graph_and_set_blocked();
```

Char-RNN; Karpathy, 2015

```
$app = new App ();

// All GET requests that come to add_register() will be sent to this service.

$api = $app -> include(' ' );

$api -> register( new DbAppAndFNAAppRegistrationService ());

// Define any services to register. We will override any present in the external
// DB have the class of .DAO .

$service = new AppAndFNAAppService ( $app , [

array ( ' host ' => ' localhost ' )

]);
```

GPT-2; OpenAI, 2015

Surprising Progress in Code Models

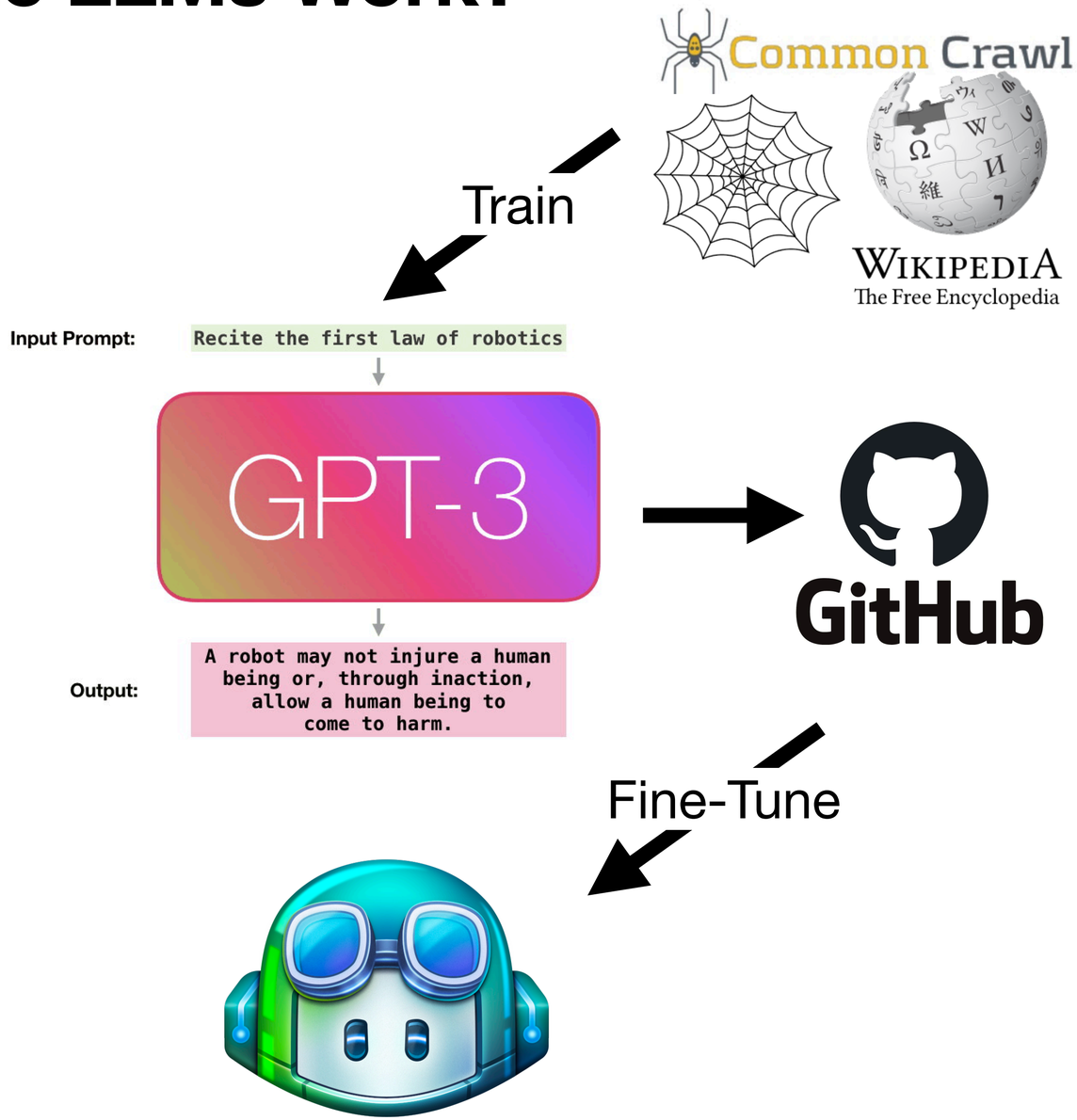
June 2021 - Present: Large Language Models (LLMs)

- **2021: OpenAI Codex** - a large GPT-3-based model fine-tuned on code
  - Released commercially as a code completion tool: **GitHub Copilot**
- **2022: DeepMind AlphaCode** - Transformer (encoder/decoder)
  - Reaches human-level (top 54%) performance in an online code competition (Codeforces)
- Both systems treat source code as plain text, “predict next token”
- Trained on **large volumes of code** (e.g. all of GitHub)

Background: How Do Code LLMs Work?

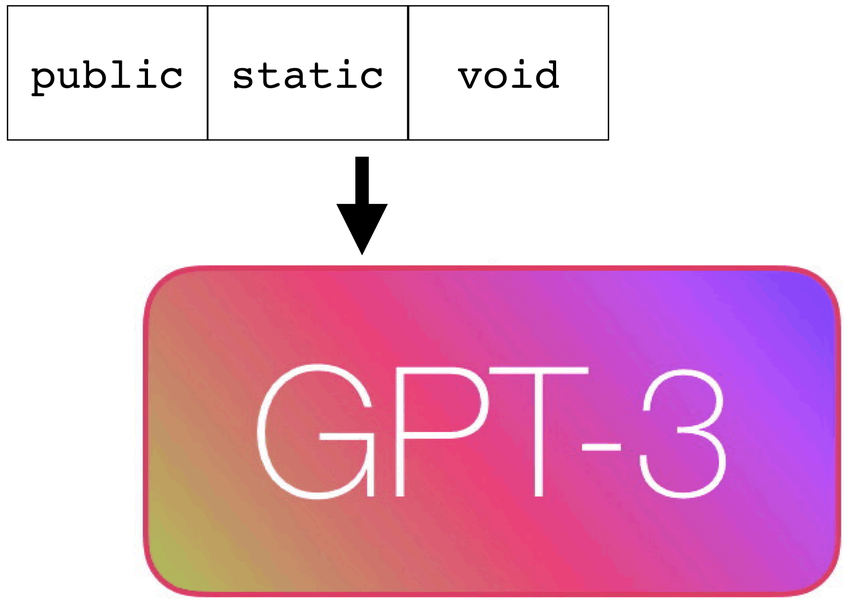
GPT-3, but on code

- **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



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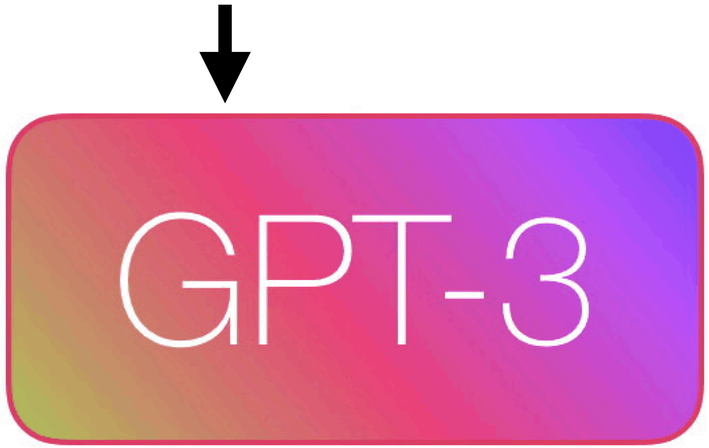
public	static	void



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

Autoregressive Sampling

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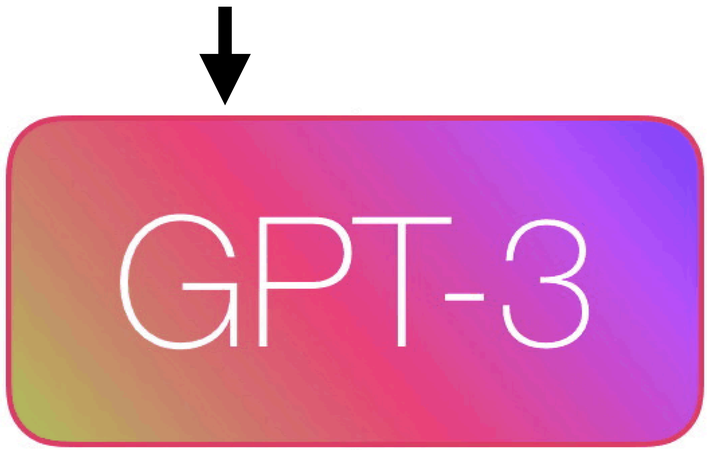

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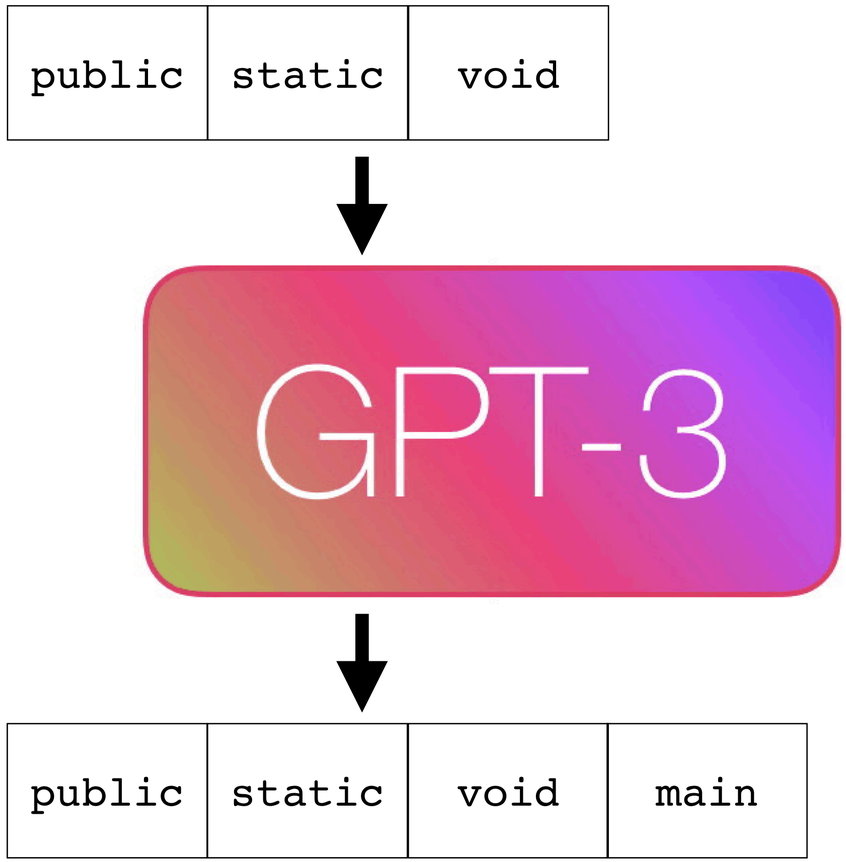

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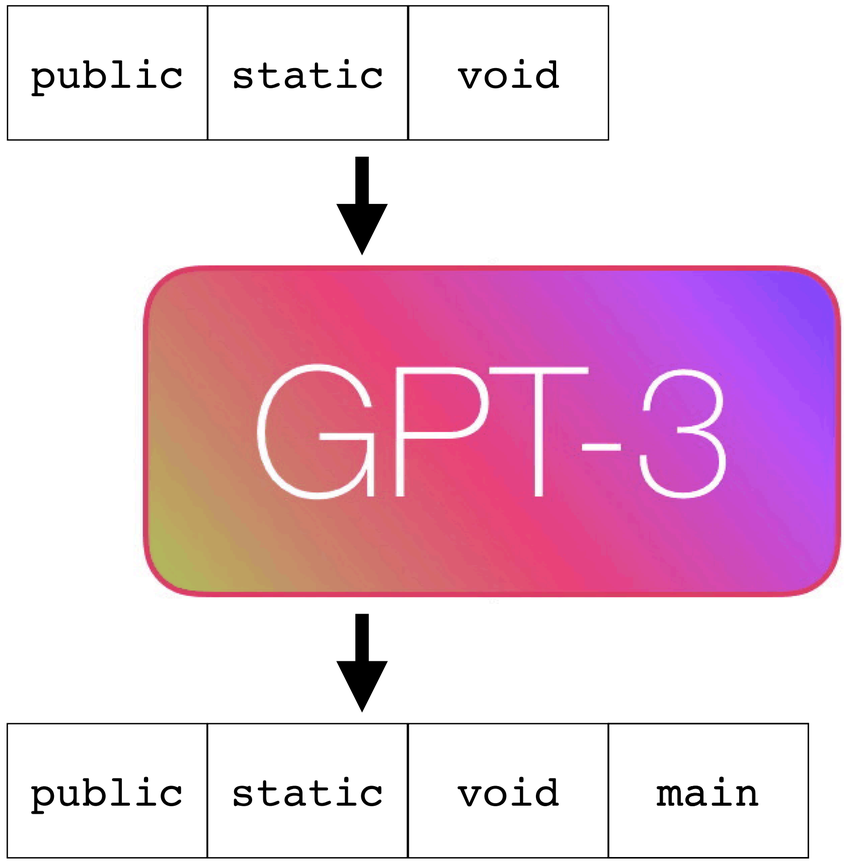

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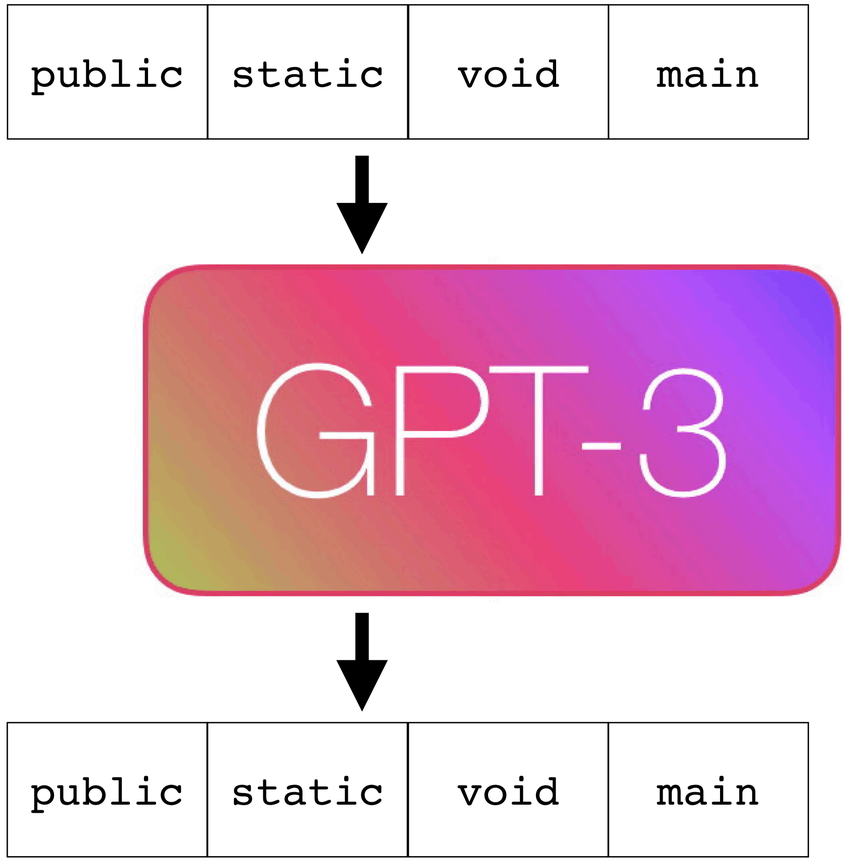

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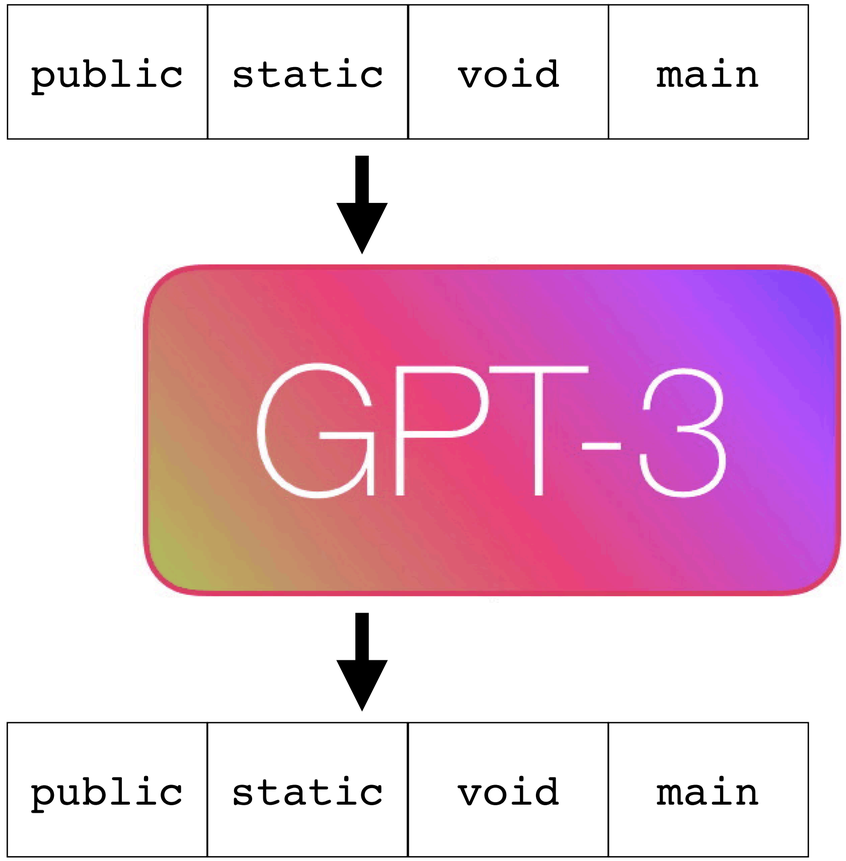
How to generate text and code



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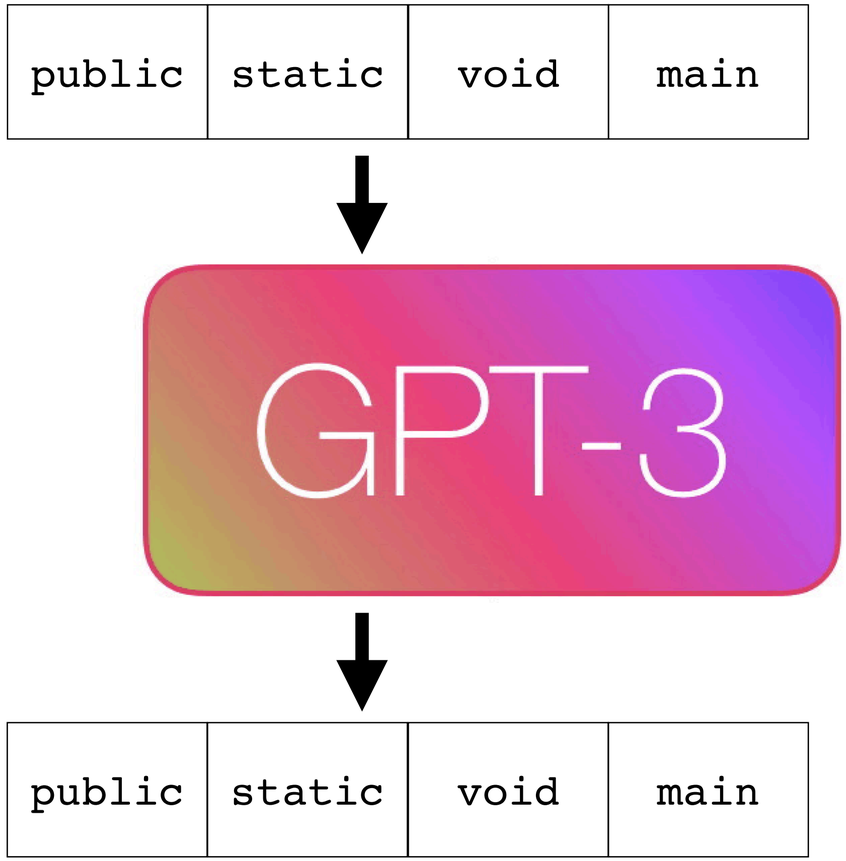

Token	Probability
(String	97%
␣	2%
\n	0.01%
()	0.003%
{	0.001%
[	0.0006%

How Secure is the Code LLMs Write?

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WILL KNIGHT BUSINESS SEP 20, 2021 7:00 AM

AI Can Write Code Like Humans—Bugs and All

New tools that help developers write software also generate similar mistakes.

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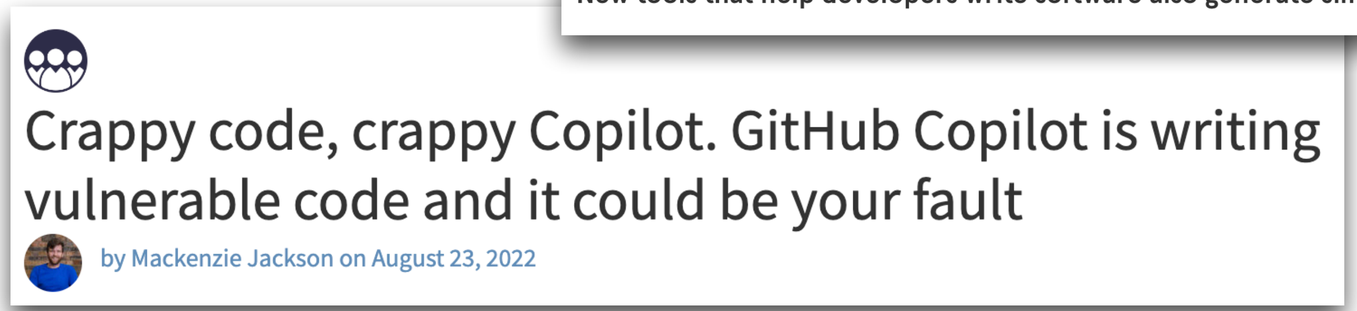

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by Mackenzie Jackson on August 23, 2022

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Developers beware: AI pair programming comes with pitfalls

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By **Stephanie Glen,** News Writer Published: **22 Jul 2022**

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FEATURE

Why you can't trust AI-generated autocomplete code to be secure

Artificial intelligence-powered tools such as GitHub Pilot and Tabnine offer developers autocomplete suggestions that help them write code faster. How do they ensure this code is secure?

By **Andrada Fiscutean**

CSO | MAR 15, 2022 2:00 AM PDT

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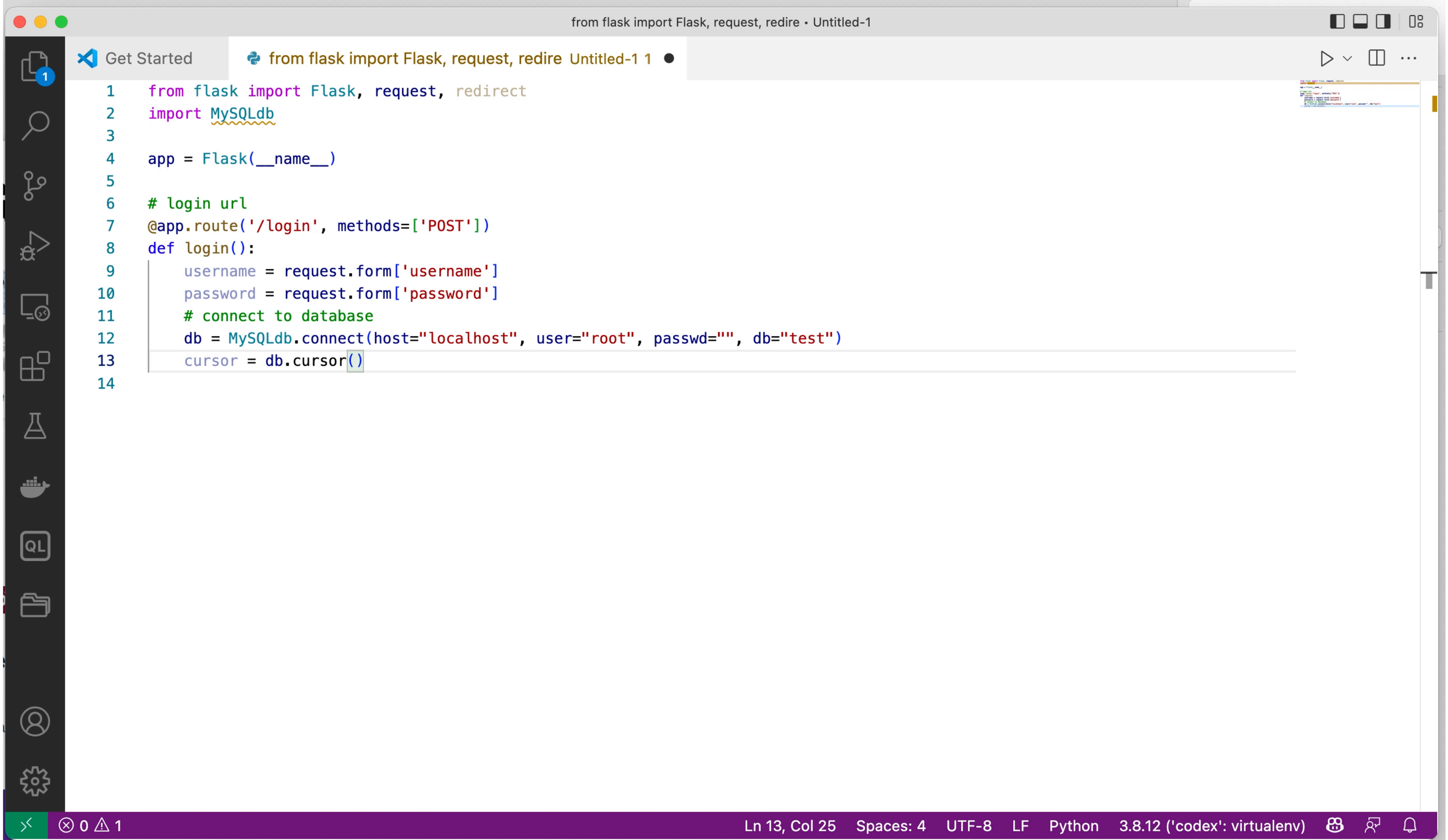
GitHub Copilot Security Study: 'Developers Should Remain Awake' in View of 40% Bad Code Rate

By David Ramel 08/26/2021


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
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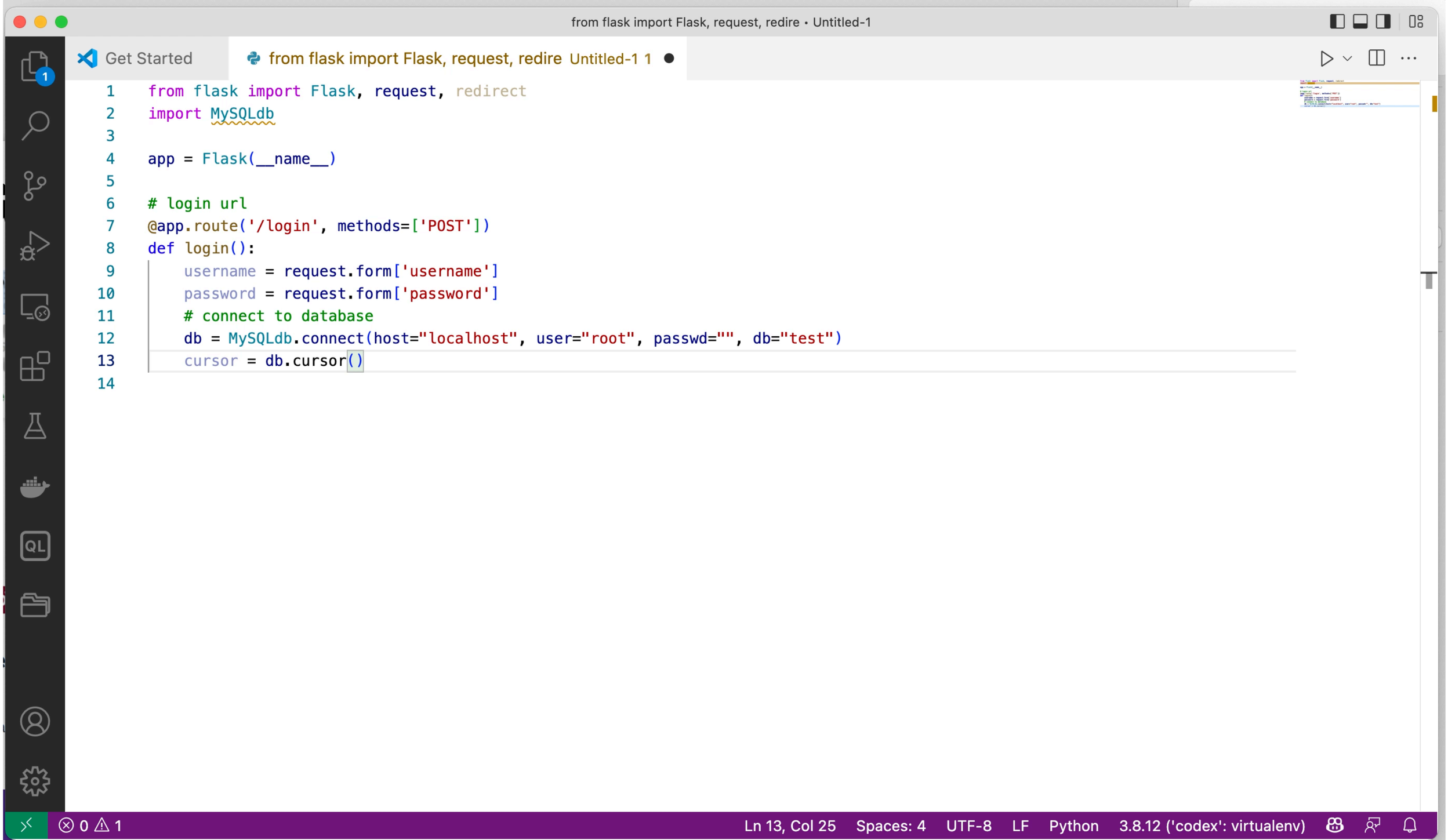
LF
Python
3.8.12 ('codex': virtualenv)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0 1
Ln 13, Col 25
Spaces: 4
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Copilot Writes Vulnerable Code

Asleep at the Keyboard

Prior work at IEEE Security and Privacy 2022

- We did a systematic study of Copilot's code completions in security-sensitive scenarios, measuring vulnerability rates with GitHub CodeQL
- Key findings:
  - Across all scenarios, **42%** of the generated programs were vulnerable
  - Features of the **prompt**, including comments, affects the rate of vulnerable code
  - The strongest predictor of whether Copilot will produce a vulnerability is the **presence of an existing vulnerability** in the prompt

But Wait!

Some objections from Reviewer #2

- In the real world, Copilot works with human assistance
- Maybe humans would spot and fix these mistakes?
- For that matter, maybe *unassisted* humans would write bugs at the same rate!
- **Strong reject**

Time for a User Study

Oh no, IRB forms

- We ran a user study using NYU students (undergraduate and graduate) and asked them to implement a linked list API
  - Participants were randomly assigned to the **Assisted (AI code assistant enabled)** or **Control** group
  - Participants had **two weeks** to complete the assigned task, and were given **$50** as compensation upon completion
  - Recruitment: an undergraduate Operating Systems class, an Application Security course (mixed undergraduate/graduate), and an informal NYU CS Discord server
  - **105** participants signed up, but only **58** actually signed in to our web IDE and wrote code for us to analyze

Participant Demographics

Enrollment

	Control	Assisted	Total
Undergraduates (UG)			
UG Y2 (Sophomores)	*1*	*8*	
UG Y3 (Juniors)	*8*	*5*	
UG Y4 (Seniors)	*4*	*5*	
UG (Unspecified)	*2*	*0*	
UG (Total)	**15**	**18**	**N (UG) = 33**
Postgraduates (PG)			
PG (MS)	*10*	*10*	
PG (PhDs)	*1*	*0*	
PG (Unspecified)	*1*	*1*	
PG (Total)	**12**	**11**	**N (PG) = 23**
Other Participants			
Other (Total)	**1**	**1**	**N (Other) = 2**
Total	**N (Control) = 28**	**N (Assisted) = 30**	N (Total) = 58

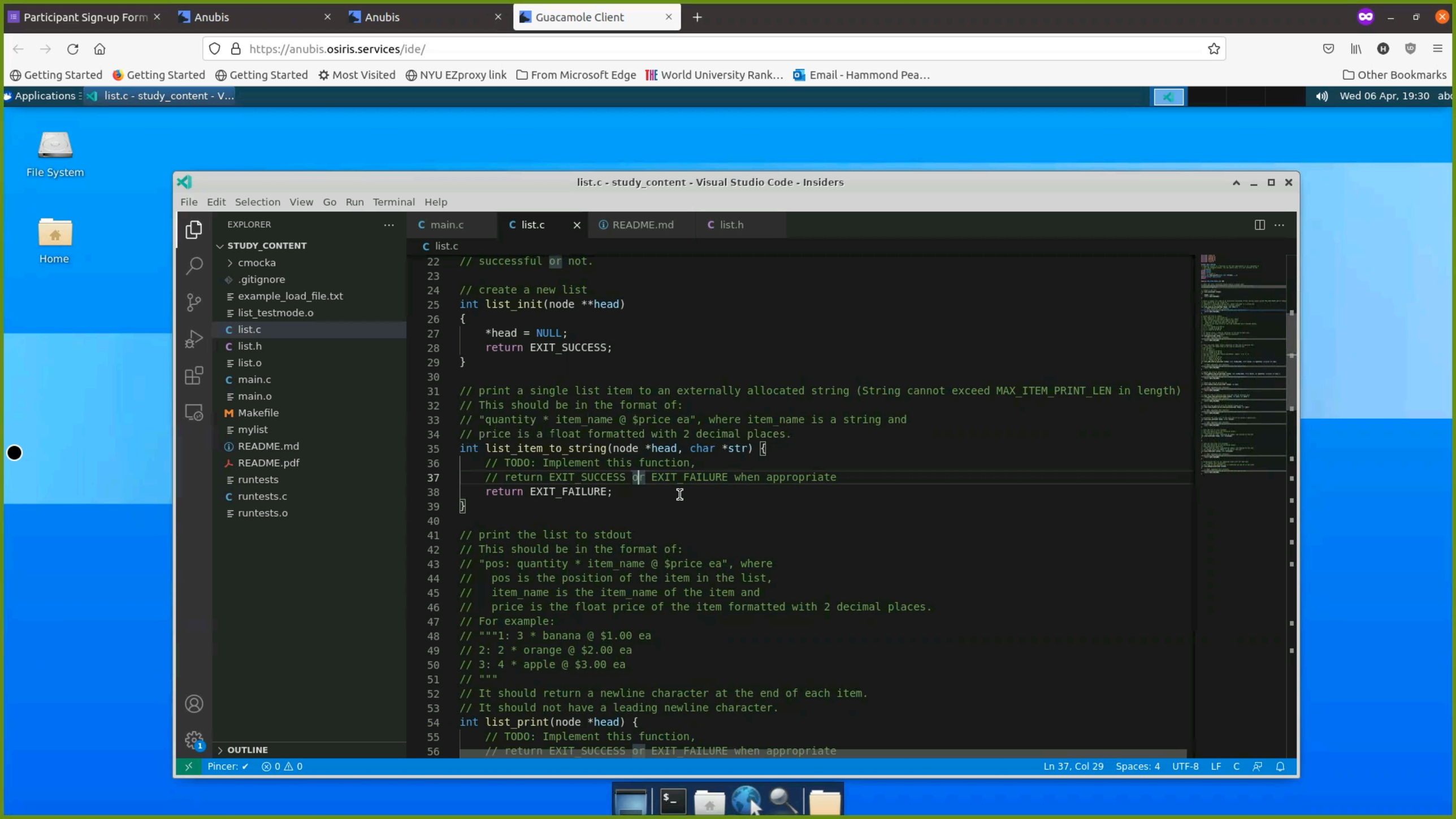
Participant Demographics

Experience Level

	Control	Assisted	Total
Is this the first linked list implementation you have ever made in C?			
Yes (first list)	*14*	*16*	30
No (not first list)	*11*	*12*	23
Declined to answer	*3*	*2*	5
Is this the first time that you have ever programmed in C?			
Yes (first time)	*3*	*4*	7
No (not first time)	*22*	*23*	45
Declined to answer	*3*	*3*	6
Are you taking, or have you ever taken a data structures or algo. class?			
Currently taking	2	3	5
Previously taken	21	25	46
Never taken	2	1	3
Declined to answer	3	1	4

Study Environment

- **Goals**:
  - Minimize environment setup hassle
  - Log all the things
- Participants were asked to use our **Anubis** web-based IDE, which provides a VNC session to a Linux desktop with **VSCode** and a C compiler
- Created a VSCode plugin that mimics Copilot, but uses suggestions provided by the Codex API
- **Logged**: document snapshots every minute, prompt+suggestion data (including accepted/ not accepted)


Participant Sign-up Form
Anubis
Anubis
Guacamole Client
https://anubis.osiris.services/ide/
Getting Started
Getting Started
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NYU EZproxy link
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Email - Hammond Pea...
Other Bookmarks
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main.o
Makefile
mylist
README.md
README.pdf
runtests
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runtests.o
OUTLINE
main.c
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list.h
list.c
// successful or not.
// create a new list
int list_init(node **head)
{
*head = NULL;
return EXIT_SUCCESS;
}
// print a single list item to an externally allocated string (String cannot exceed MAX_ITEM_PRINT_LEN in length)
// This should be in the format of:
// "quantity * item_name @ $price ea", where item_name is a string and
// price is a float formatted with 2 decimal places.
int list_item_to_string(node *head, char *str) {
// TODO: Implement this function,
// return EXIT_SUCCESS or EXIT_FAILURE when appropriate
return EXIT_FAILURE;
}
// print the list to stdout
// This should be in the format of:
// "pos: quantity * item_name @ $price ea", where
// pos is the position of the item in the list,
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// For example:
// """1: 3 * banana @ $1.00 ea
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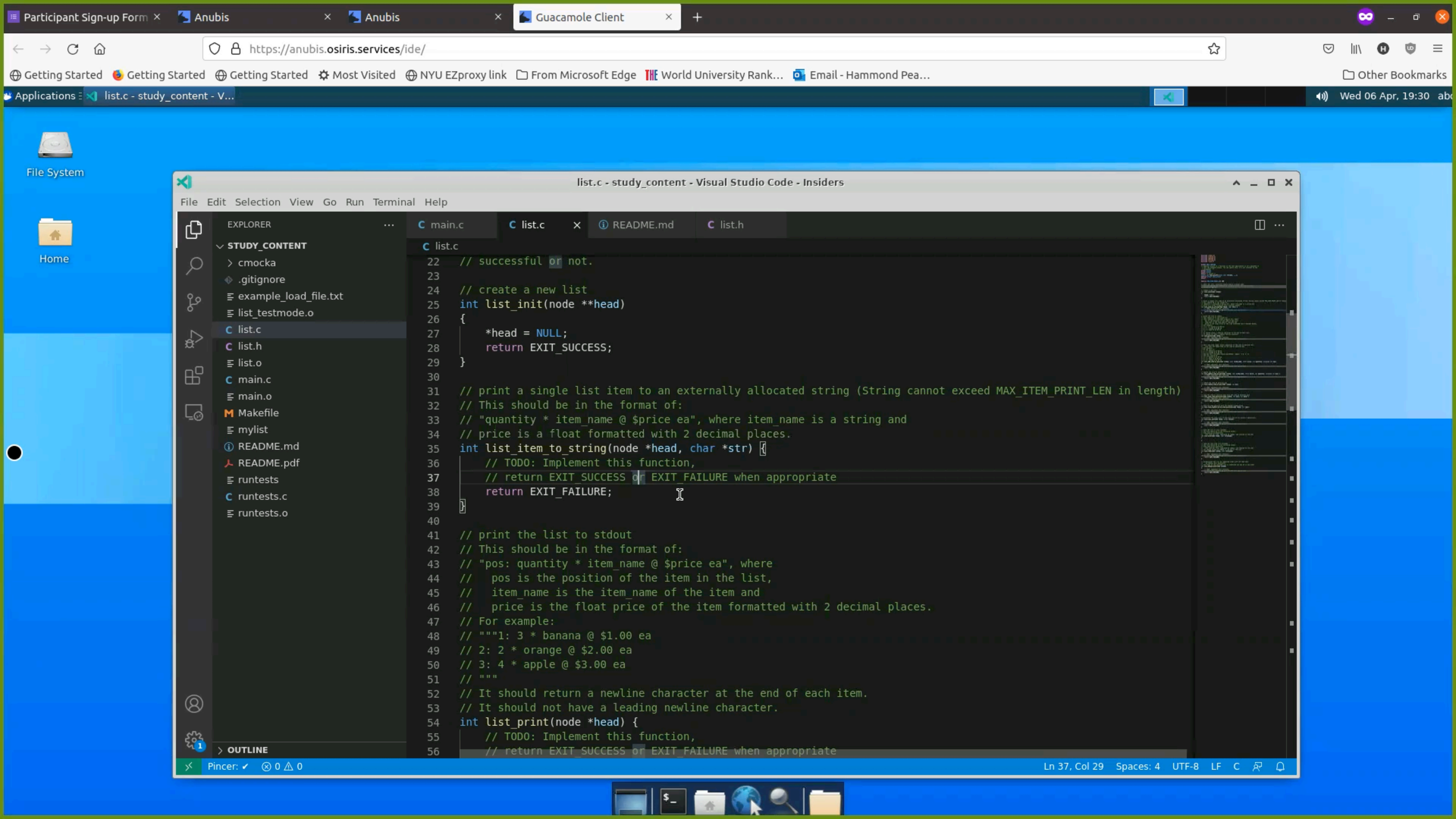
Pincer: ✔ 0 0
Ln 37, Col 29 Spaces: 4 UTF-8 LF C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Pincer: ✔ 0 0
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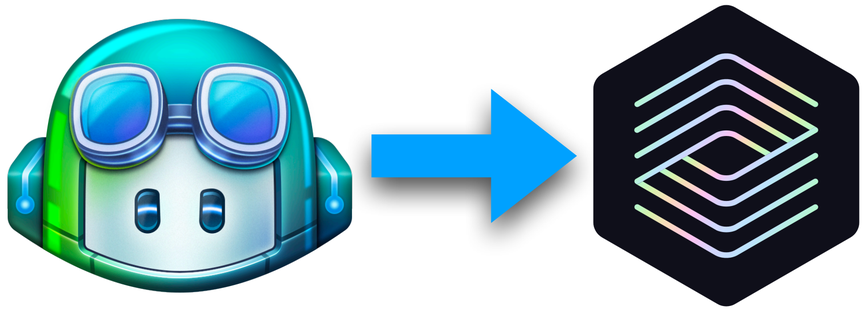
Code Assistant Setup

- To get better logging and instrumentation, we decided to use **OpenAI Codex** for our study rather than Copilot
  - OpenAI generously provided an non-rate limited API token for the duration of the study (Thanks OpenAI!)
- Code model: cushman-code-001
  - Weaker model, but **very low latency**
- Temperature: 0.6, top-p: 1.0
  - Relatively high temp to get more diverse solutions



Study Task: “Shopping List”

The *Worst* Singly Linked List API (11 functions total)

- Since we’re studying security chose C because it’s a “target-rich environment”
- We deliberately included some pitfalls in the data structure and API to further broaden the range of possible errors
- Singly linked list: lots of opportunity for pointer mistakes
- Includes a string field (buffer overflows, etc.)

```c
// Node of the singly linked list
typedef struct _node {
    char* item_name;
    float price;
    int quantity;
    struct _node *next;
} node;
```

Uh oh, strings

(a) Node definition (in `list.h`)

```c
#include <stdio.h>
#include <stdlib.h>
#include <getopt.h>
#include <string.h>
#include "list.h"

#define MAX_ITEM_PRINT_LEN 100

// Note: All list_ functions should return a status code
// EXIT_FAILURE or EXIT_SUCCESS to indicate whether the
    operation was
// successful or not.
```

Fixed length

(b) `#includes` and implementation hints (in `list.c`)

Study Task: “Shopping List”

API: Basic List Manipulation

- Concepts tested:
  - Basic list traversal
  - List manipulation
  - Managing lifetime of item_name
- Pitfalls: *updates* the list via a double-pointer to head, item_name needs to be freed/ copied, one-indexed, position is *sometimes* a signed int

One-indexed

Need to *copy* the string

Double pointer

```c
// create a new list
int list_init(node **head);

// add a new item (name, price, quantity) to the list at position pos,
//   such that the added item is the item
// For example:
// If the list is:
// 1: 3 * banana @ $1.00 ea
// 2: 2 * orange @ $2.00 ea
// and you call list_add_item_at_pos(&head, "apple", 3.0, 4, 2)
// the list should be:
// 1: 3 * banana @ $1.00 ea
// 2: 4 * apple @ $3.00 ea
// 3: 2 * orange @ $2.00 ea
int list_add_item_at_pos(node **head, char *item_name, float price, int quantity, unsigned int pos);

// update the item at position pos
int list_update_item_at_pos(node **head, char *item_name, float price, int quantity, unsigned int pos);

// remove the item at position *pos*
int list_remove_item_at_pos(node **head, int pos);

// swap the item at position pos1 with the item at position pos2
int list_swap_item_positions(node **head, int pos1, int pos2);
```

Study Task: “Shopping List”

API: String Manipulation

- Concepts tested:
  - Basic list traversal
  - Correct format string usage
  - Copying into a buffer provided externally without overflow
- A bit tricky because the maximum length is given as a constant: MAX_ITEM_PRINT_LEN

Externally provided buffer with no length!

```c
// print a single list item to an externally allocated string
// This should be in the format of:
// "quantity * item_name @ $price ea", where item_name is a string and
// price is a float formatted with 2 decimal places.
int list_item_to_string(node *head, char *str);

// print the list to stdout
// This should be in the format of:
// "pos: quantity * item_name @ $price ea", where
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// """
// It should return a newline character at the end of each item.
// It should not have a leading newline character.
int list_print(node *head);
```

Study Task: “Shopping List”

API: Advanced Tasks

- Concepts tested:
  - Saving/loading data from disk
  - Handling errors from system APIs (fopen, etc.)
  - Advanced traversal and updates
  - Freeing and updating entries
- Many people just skipped the harder APIs

```c
// find the item position with the highest single price
int list_find_highest_price_item_position(node *head, int *pos);

// calculate the total cost of the list (sum of all prices * quantities)
int list_cost_sum(node *head, float *total);

// de-duplicate the list by combining items with the same name
//   by adding their quantities
// The order of the returned list is undefined and may be in any order
int list_deduplicate(node **head);
```

Output parameters

(b) Advanced traversal functions

```c
// save the list to file filename
// the file should be in the following format:
// item_name,price,quantity\n
//   (one item per line, separated by commas, and newline at the end)
int list_save(node *head, char *filename);

// load the list from file filename
// the file should be in the following format:
// item_name,price,quantity\n
//   (one item per line, separated by commas, and newline at the end)
// the loaded values are added to the end of the list
int list_load(node **head, char *filename);
```

(c) Saving and Loading the list

Autopilot Mode

Let the AI do all the work!

- As another baseline comparison we also had three code models (Cushman-001, DaVinci-001, and DaVinci-002) complete the assignment automatically
- Procedure:
  - Complete one API function at a time, whole file (up to context limits) up to the function prototype as the prompt
  - Check if it compiles; if not, try again (up to 10 tries)
  - Same temp/top-p settings as the IDE plugin
  - Added a comment at the top with the node member names

Research Questions

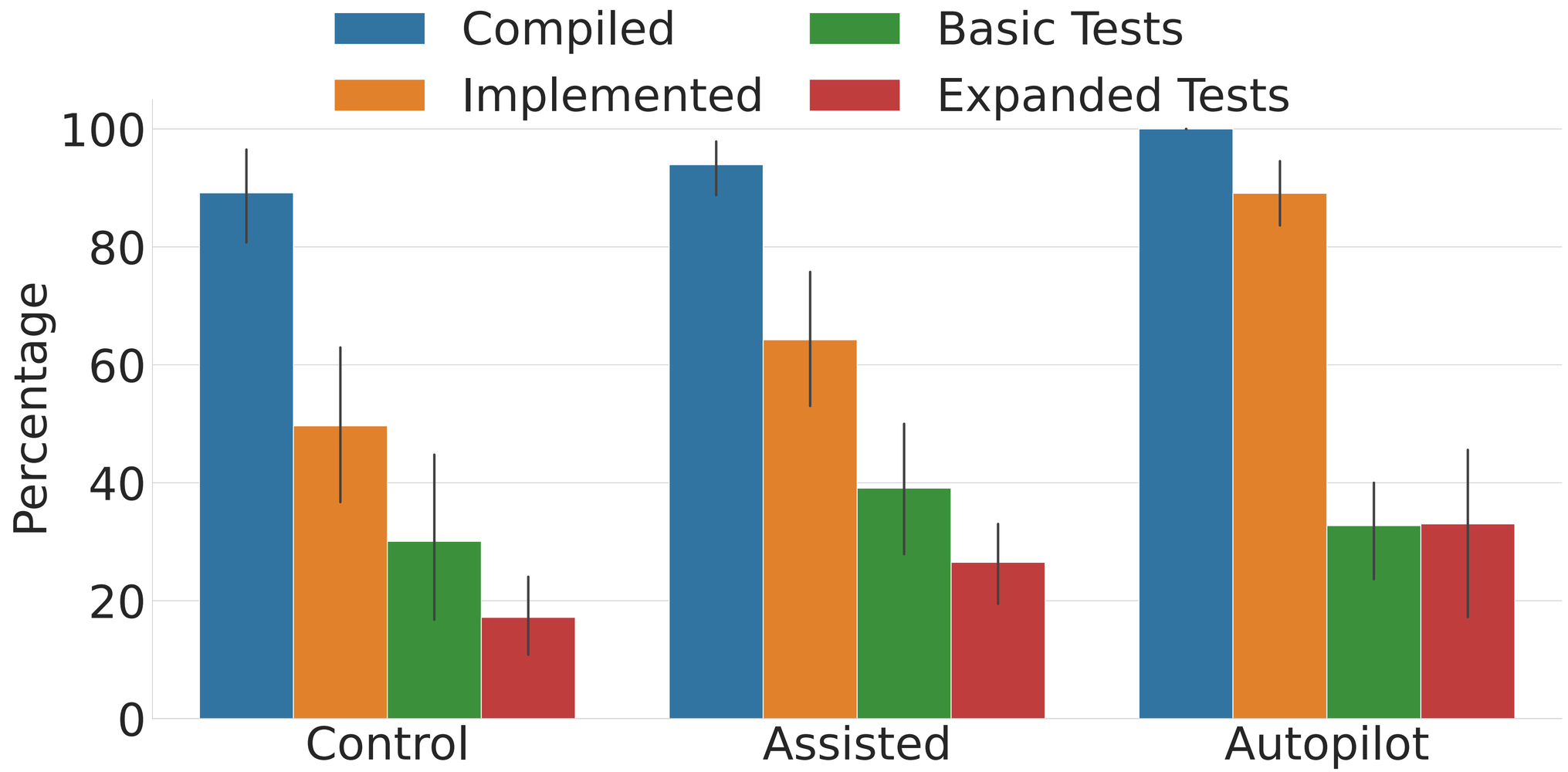
- **RQ1**: Does the AI code assistant help novice users write better code in terms of ***functionality***?
- **RQ2**: Is the code that novice users write with AI assistance more or less ***secure*** than the control group?
- **RQ3**: Are there systematic differences in the ***coding style*** of AI-assisted users and that of control group?
- **RQ4**: How do AI assisted users interact with potentially vulnerable code suggestions, i.e., where do bugs originate in an LLM-assisted system?

Measuring Functionality

- We provided users with a **basic** test suite with one test per function (12 tests)
- We also wrote an **expanded** test suite with 45 tests checking all the edge cases we could think of
- To reduce inter-test dependencies, we split the users' code into individual functions and tested them in isolation, with our known-good (🤞) reference implementation
  - Also allows us to test users who submitted non-compiling code, as long as *some* of their functions compiled

Functionality Results

Rise of the Machines

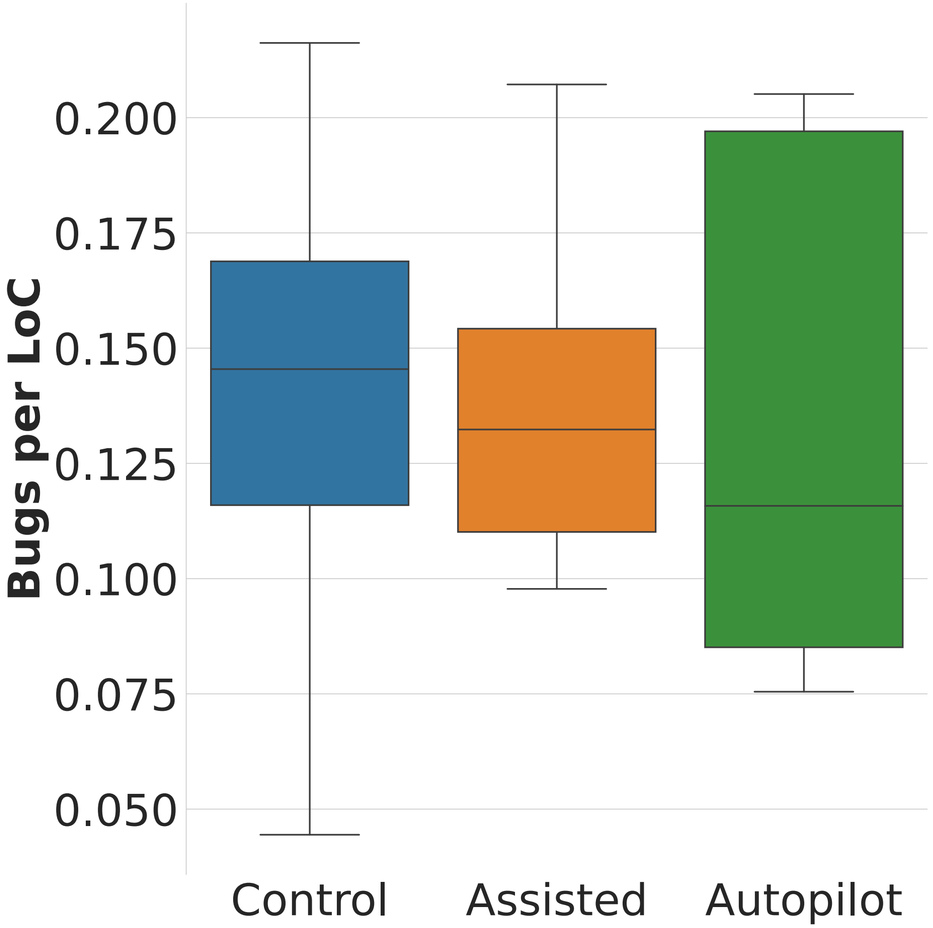


Measuring Security

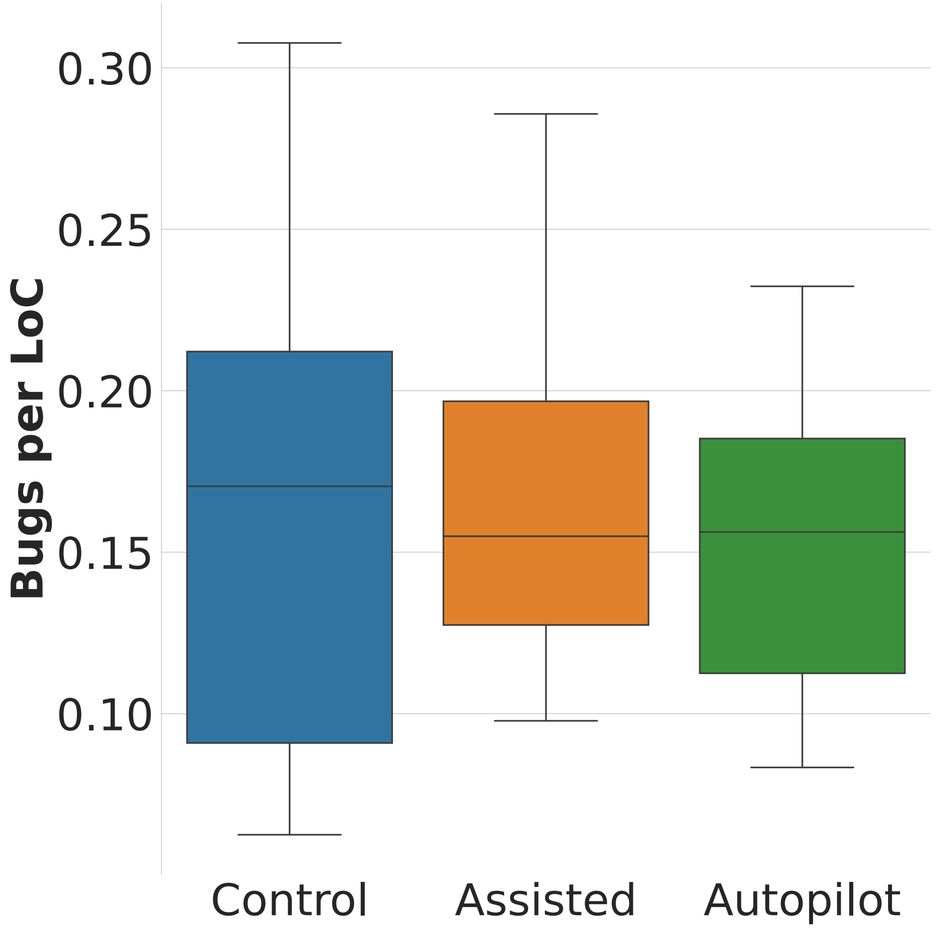
- Measuring security is **more difficult**
- CodeQL missed many issues, had false positives
- Fuzzing was attractive but many **duplicate** problems found
- We just bit the bullet and reviewed all code by hand
  - Three of us stared at each function and annotated with vulnerabilities categorized by MITRE's Common Weakness Enumeration
  - Also graded 5 of the Cushman Autopilot answers
  - 20 hours of my life I will never get back

Security Results

Number of vulnerabilities per line of code



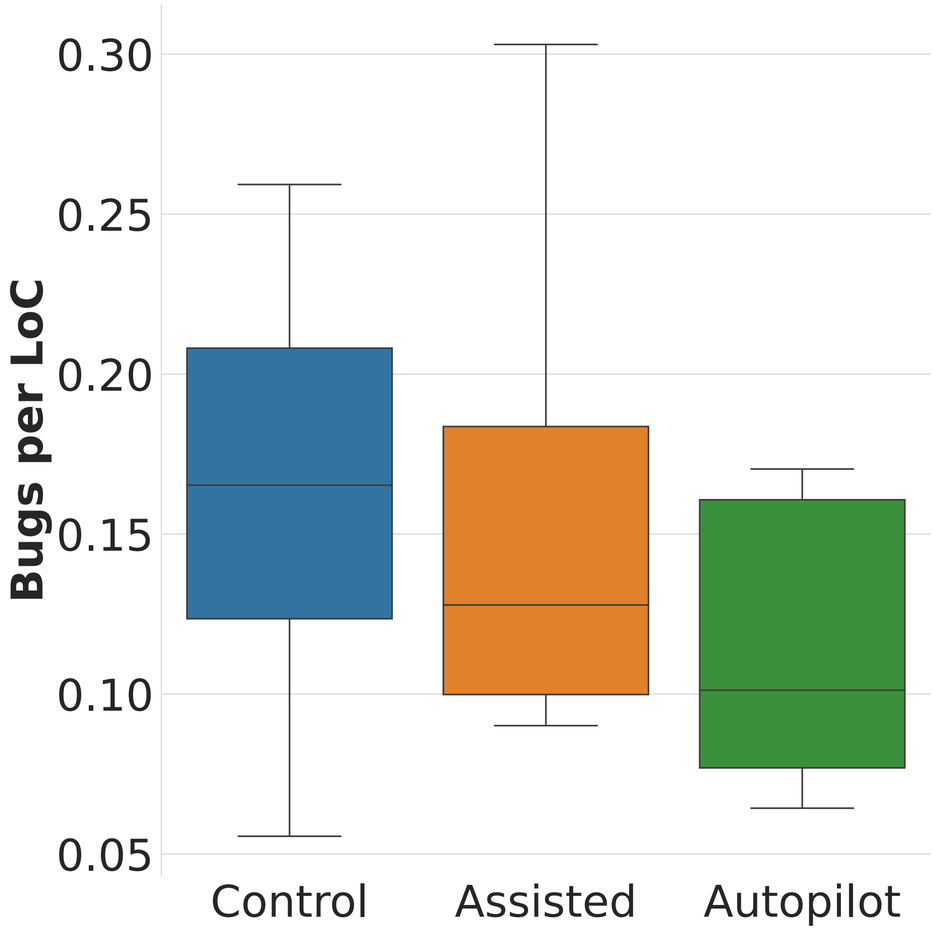
CWEs/LoC for *compiling* code



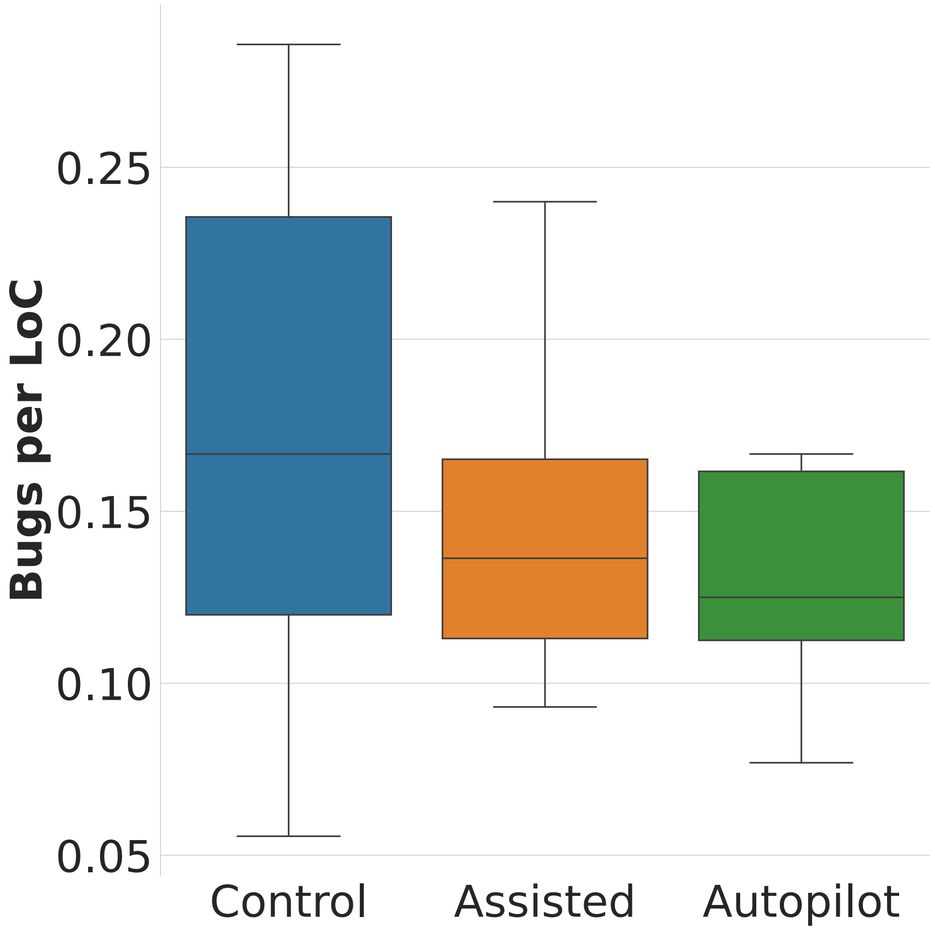
CWEs/LoC, code that *passes the basic unit test*

Security Results

Number of *severe* (MITRE Top 25) vulnerabilities per line of code

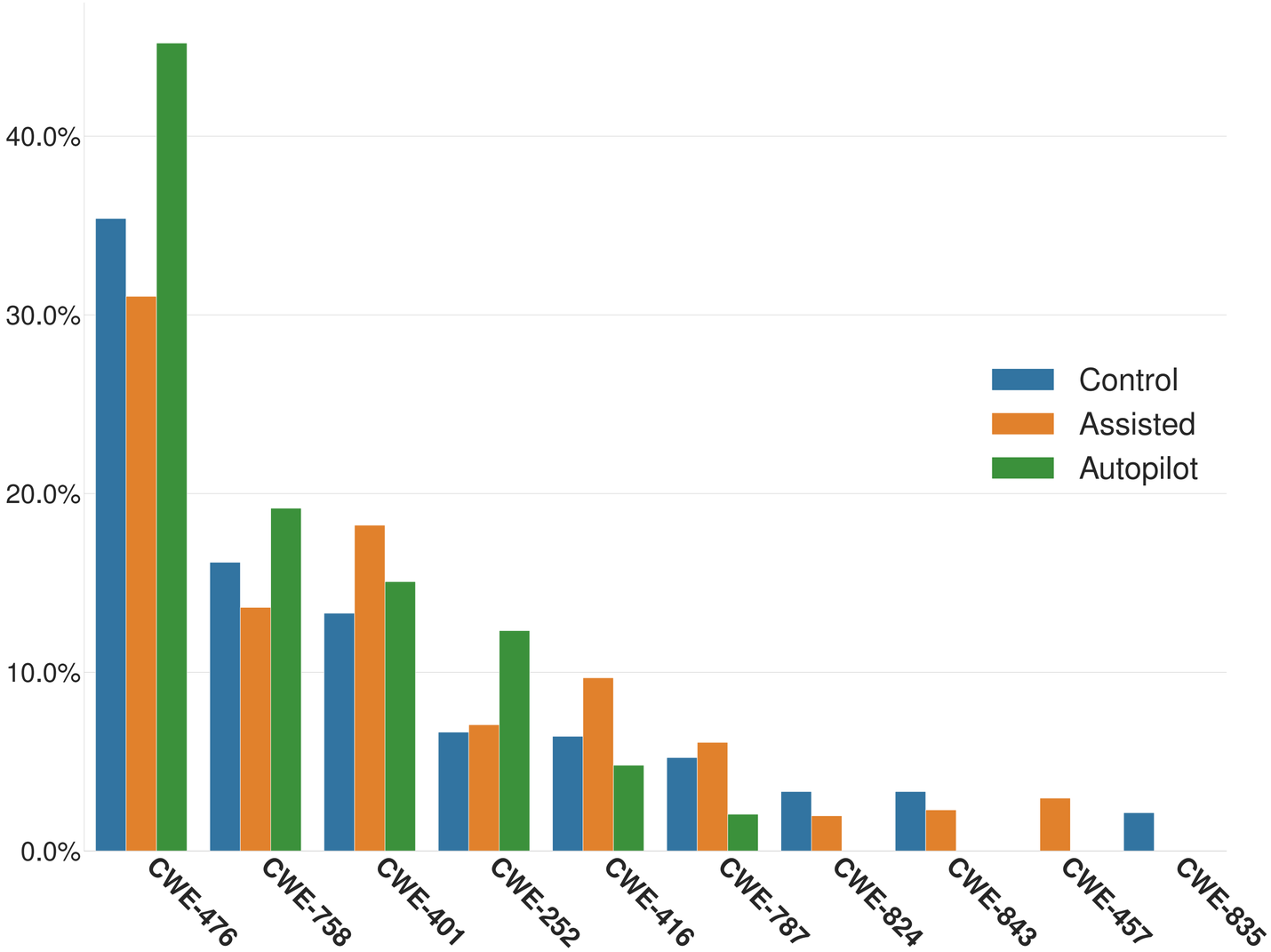


Severe CWEs/LoC for *compiling* code



Severe CWEs/LoC, code that *passes the basic unit test*

Security Results: CWEs



CWE-476 NULL Pointer Dereference

CWE-758 Reliance on Undefined, Unspecified, or Implementation-Defined Behavior

CWE-401 Missing Release of Memory after Effective Lifetime

CWE-252 Unchecked Return Value

CWE-416 Use After Free

CWE-787 Out-of-bounds Write

CWE-457 Use of Uninitialized Variable

CWE-843 Access of Resource Using Incompatible Type ('Type Confusion')

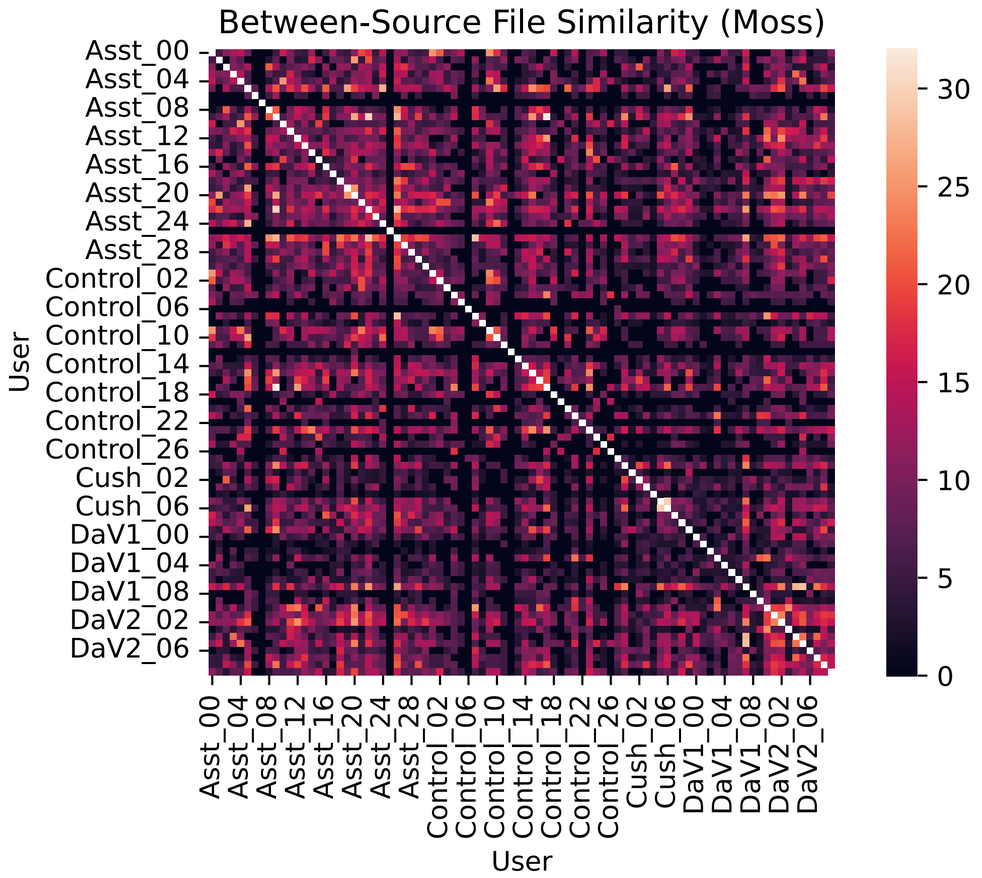
CWE-824 Access of Uninitialized Pointer

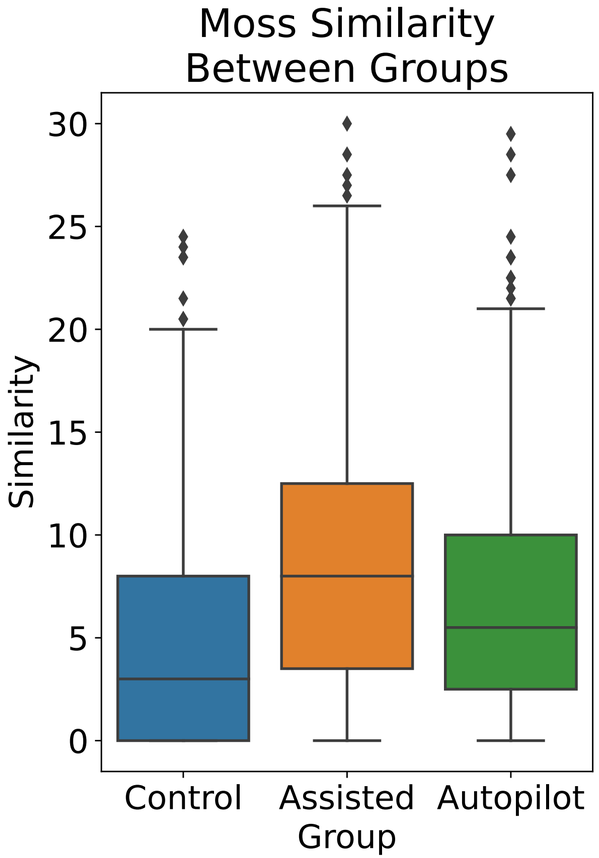
CWE-835 Loop with Unreachable Exit Condition ('Infinite Loop')

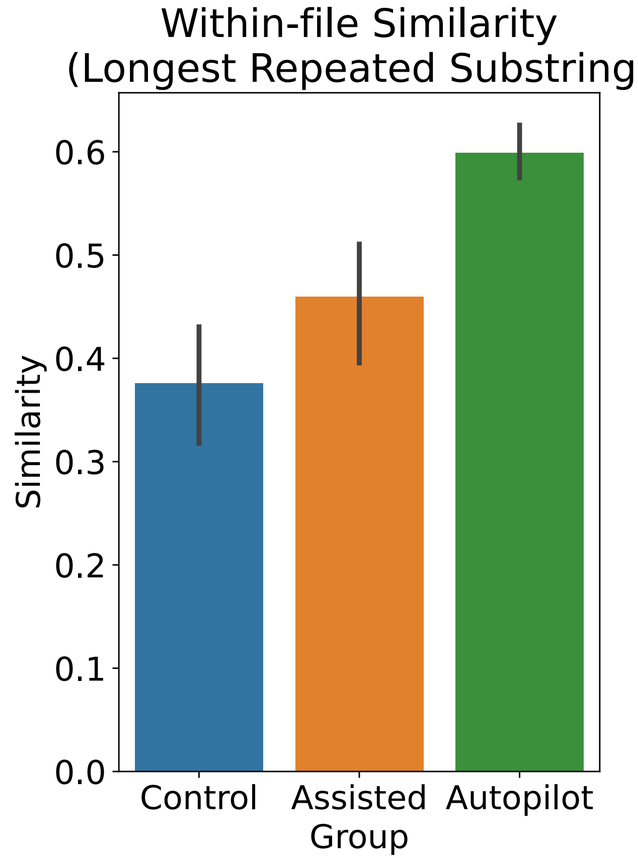
Measuring Style

- We wanted to check if there were difference in style between human and AI-assisted users
  - Can we tell if someone is using Copilot?
- We used two measures:
  - The Moss plagiarism detection tool to measure similarity between users
  - The quantity of *repeated substrings* in the file to measure similarity *within* an individual user's submission

Style Results







On the Origin of Bugs

git blame codex

- Using the data from the IDE, can we identify where vulnerabilities were introduced into the user's code?
  - In particular, did they come from **Codex suggestions** or were they written by **humans**?
- **Idea**:
  - Find an automated way to check for some common vulnerability
  - Use our document snapshots and suggestion data to see if it first appeared in a **document** (human-written) or **suggestion** (introduced by Codex)

Bug Origins: Missing `strdup`

- We picked one bug for this that we could identify with just a regular expression
  - Vulnerability failing to make a copy of the `item_name` provided by the caller (e.g. using strdup) before storing it in the node
  - Can lead to **CWE-416: Use-After-Free** because the list library has no control over when the user-provided string will be freed
  - We can identify it by just looking for direct assignments to `node->item_name` with no strdup/strcpy/malloc

Bug Origins: Results

- This vulnerability was introduced by Codex more often than not
- But some users introduced it themselves, and did not accept further buggy suggestions
- Some users got a **lot** of buggy suggestions (69 in one case!)
- Weak trend: more bug suggestions => more bugs in final file

Participant ID	First location of bug (document / suggestion)	# Bug suggestions	# Bug suggestions accepted	# Bugs in final file
0640	Suggestion	5	3	3
1f1c	Document	5	0	2
2125	Document	0	0	3
26a4	Suggestion	3	1	2
3533	Suggestion	2	1	1
36de	Suggestion	69	5	4
3cff	Suggestion	2	2	2
514e	Document	1	1	1
7193	Suggestion	13	1	2
74bd	Suggestion	4	2	2
925c	Suggestion	8	2	1
a3ed	Suggestion	10	2	2
a4b3	Suggestion	11	5	4
a5ba	Document	0	0	1
a80d	Document	6	3	3
a974	Suggestion	12	5	3
b59f	Suggestion	8	2	2
be6f	Suggestion	4	1	2
c23b	Suggestion	20	10	5
dac3	Document	10	2	2
dc47	Suggestion	1	0	2
ddac	Suggestion	13	1	1
ec83	Document	11	3	2
fd62	Suggestion	12	1	1

Bonus Qualitative Content

Not everyone enjoyed the AI's help

```
// was fighting the language model whenever I was trying
// to do anything and I ended up giving up, because whenever
// I would start with an idea, it would suggest something that
// looked good at first sight, I would add it to my own code
// and then I would spend time debugging some of its code rather
// than develop my ideas

// for the other functions where it gave me the answer straight
// up and it just worked, I felt like I just cheated and got
// someone else to do the work for me

// I ended up not having too much time to finish and the couple
// hours I spent on this was mostly just fighting with the robot
```

Limitations

Learning to live with small N

- Biggest limitation: due to small sample size, most of our results are **not statistically significant** (particularly for security)
  - But *probably* we can rule out really big effects
- Participants were all university students; we can't generalize to professional developers
  - Hopefully they can write better C code?
- Likewise, this is just one task (linked list) and one language (C)
  - Maybe other tasks and languages would give different results?

Conclusions

Check out the paper! https://arxiv.org/abs/2208.09727

- Significant differences in functionality between groups on **functionality**
- Surprisingly, **no discernible difference** on security
  - Limited by small sample size
  - *Maybe* a slight trend in favor of Codex
- Potentially found a signal we can use to distinguish **Copilot/Codex** written code from human-written code (repetition)
  - Has implications for stylometry, confirms that tendency toward repetition may *amplify* the existing vulnerabilities in the code