RUG: Turbo LLM for Rust Unit Test Generation

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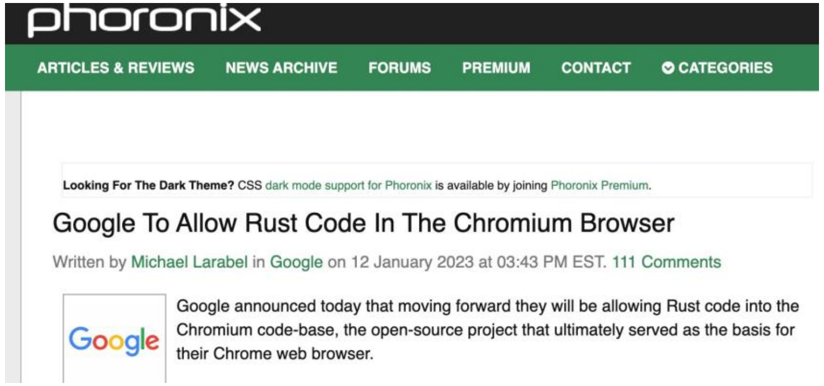
Content

- Motivating
- Challenge & Insights
- Solution
  - LLM
  - Fuzzing
- Evaluation

Rust's Adoption is very Fast

- From DARPA/Microsoft/Linux/Google: use Rust to ensure memory safety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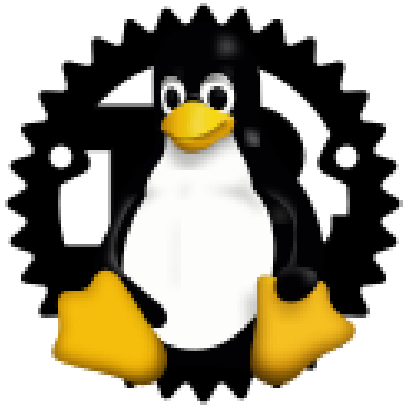
Google To Allow Rust Code In The Chromium Browser

Written by Michael Larabel in Google on 12 January 2023 at 03:43 PM EST. 111 Comments

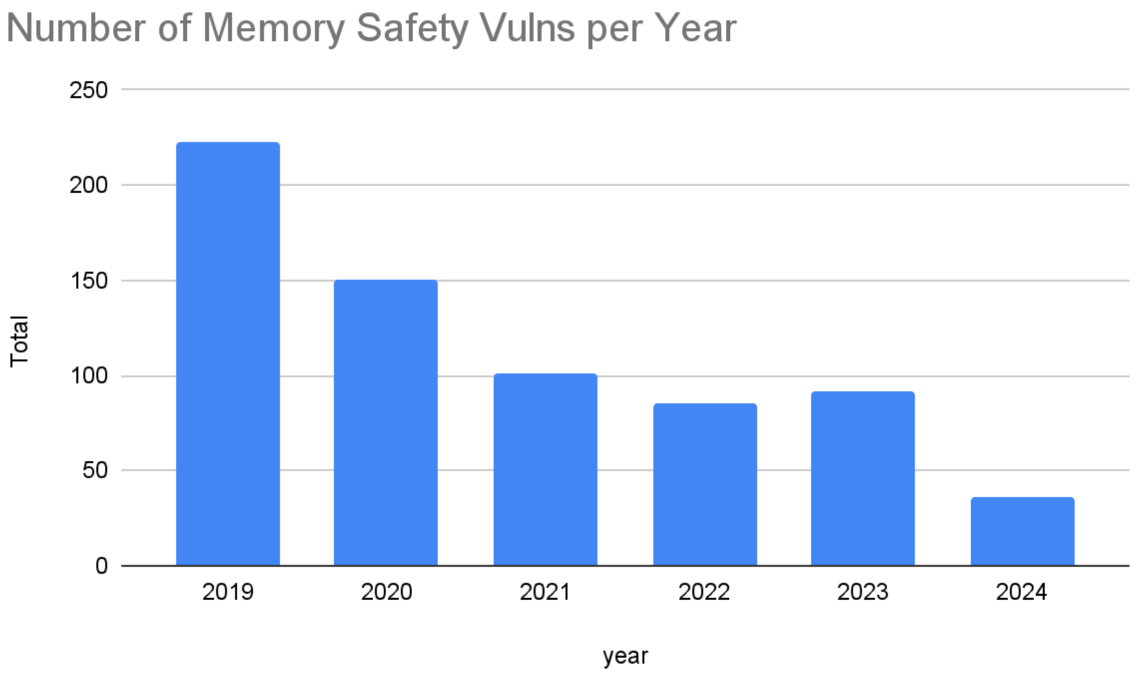
Google announced today that moving forward they will be allowing Rust code into the Chromium code-base, the open-source project that ultimately served as the basis for their Chrome web browser.

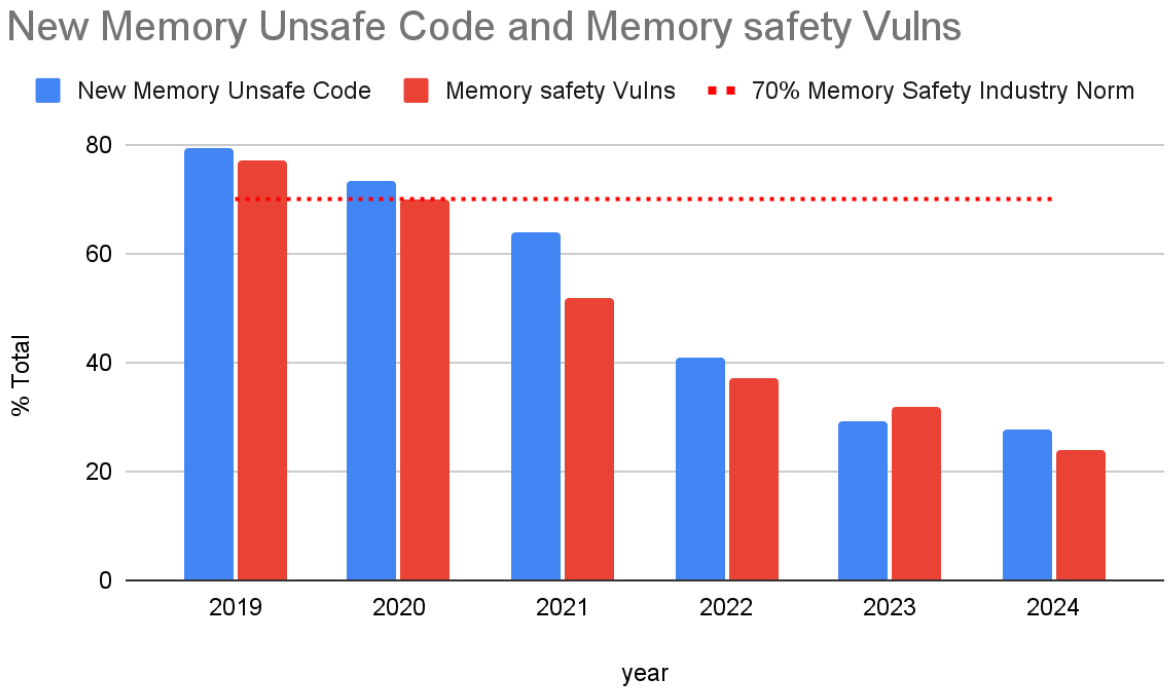


Picture: from chrome/windows/android/Rust-for-linux homepage

From Android's Practice

- AOSP starts to use Rust in 2019
- The total number of memory safety errors starts to drop even with unsafe Rust





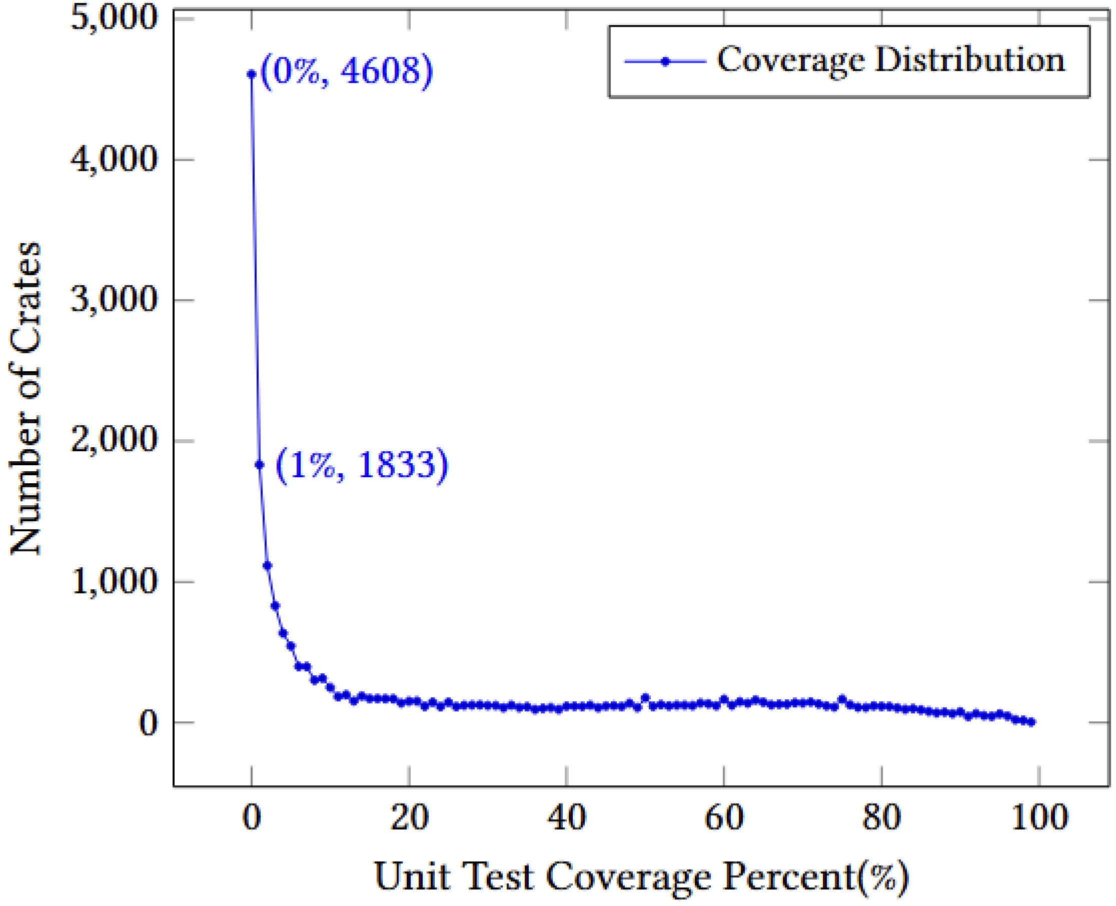
Picture: [Google Online Security Blog: Eliminating Memory Safety Vulnerabilities at the Source]

Rust Unit Testing

- Unit test is a type of software test that focuses on testing individual units or components of a program in isolation.
- Rust has a good support to unit test:
  - Annotations #[test] to mark a region as test
  - Temporally break encapsulation when testing in the same file
  - Provide driver build for all the tests:
    - cargo test – run all tests in the target repo

Unit testing status of Rust

- Crates.io is like npm/maven/pip, serves as the dependency manager in Rust
  - As of Dec 2024, serves 164k crates, and more than 96B downloads
- We evaluate the top 30K popular crates
  - 60% crates have less than 10% test coverage
  - 16% crates doesn't have any tests



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Why unit test is difficult

- Unit test requires to build a minimal context to trigger the target function, it's not easy to implement in some cases
  - Rust is applied for low-level systems: embedding device, OS driver…
- Developers are tired of writing unit tests:
  - E.g. 3 conditions + 2 loops to test

```rust
pub fn unfill(text: &str) -> (String, Options<'_>) {
    let prefix_chars: &[_] = &[' ', '-', '+', '*', '>', '#', '/'];

    let mut options = Options::new(0);
    for (idx, line) in text.lines().enumerate() {
        options.width = std::cmp::max(options.width, display_width(line));
        let without_prefix = line.trim_start_matches(prefix_chars);
        let prefix = &line[..line.len() - without_prefix.len()];

        if idx == 0 {
            options.initial_indent = prefix;
        } else if idx == 1 {
            options.subsequent_indent = prefix;
        } else if idx > 1 {
            for ((idx, x), y) in prefix.char_indices().zip(options.subsequent_indent.chars()) {
                if x != y {
                    options.subsequent_indent = &prefix[..idx];
                    break;
                }
            }
            if prefix.len() < options.subsequent_indent.len() {
                options.subsequent_indent = prefix;
            }
        }
    }
```

Insight: LLM + Fuzzing

- Chain-of-thought is proven to be effective for LLM reasoning
  - => RUG uses type dependencies to automatically apply chain of thought
- The result of each subproblem needs to be verified, otherwise the error will accumulate
  - => RUG verifies the result for each subproblem, ensuring the final correctness
- The LLM isn’t good at exploring program paths
  - => RUG leverages fuzzing as post-processor to extend the testing coverage

Georgia Tech

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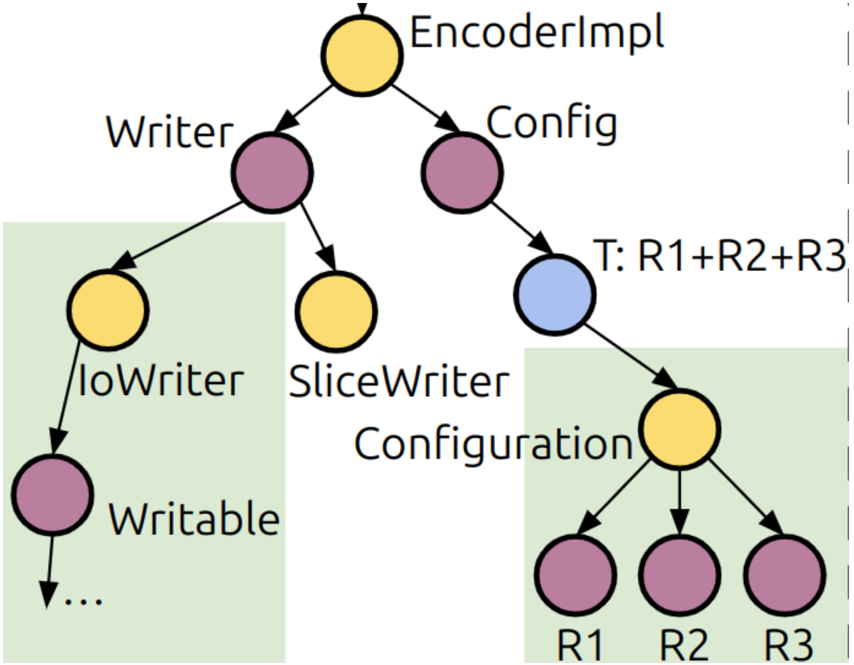
Semantic Aware Decomposition

- Challenge: to build the testing context, LLM is expected to correctly built all its necessary dependents in one shot, leading to errors
- Semantic aware decomposition: Type has dependencies, RUG automatically decomposes the context building into sub-problems

```
fn encode<E: Encoder> (&self :char, encoder: E)
    -> Result<EncodeError> // target testing function
// def for EncoderImpl
pub struct EncoderImpl<W, C: Config>
// impl for Encoder trait
impl<W: Writer, C: Config> Encoder for EncoderImpl
// impls for Writer Trait
impl Writer for SliceWriter
impl enc::write::Writer for IoWriter
// impls for Config Trait
pub trait Config: R1 + R2 + R3 {}
impl<T> Config for T where T: R1 + R2 + R3
// def for Configuration, impls R1, R2, R3
pub struct Configuration<A = R1, B = R2, C = R3>
```

```rust
fn encode<E: Encoder> (&self :char, encoder: E)
    -> Result<EncodeError> // target testing function
// def for EncoderImpl
pub struct EncoderImpl<W, C: Config>
// impl for Encoder trait
impl<W: Writer, C: Config> Encoder for EncoderImpl
// impls for Writer Trait
impl Writer for SliceWriter
impl enc::write::Writer for IoWriter
// impls for Config Trait
pub trait Config: R1 + R2 + R3 {}
impl<T> Config for T where T: R1 + R2 + R3
// def for Configuration, impls R1, R2, R3
pub struct Configuration<A = R1, B = R2, C = R3>
```



- Build type dependency graph as G = {E, V}, V denotes type entities and E denotes dependency relations, G is directed
- Divide the context generation into sub-problems and resolve them individually
- Rely on static analysis to guide and verify the LLM output

Pros and Corner Cases

- Semantic Aware Decomposition
  - We minimize the context for each iteration (only the direct dependent instances in the green square)
  - We verify the result of each iteration output to ensure the correctness
  - We memorize the result based on type and saves tokens in project scope
- Corner Cases:
  - Cycles: we will randomly decide the order and use natural language description of the dependencies as context
  - LLM failed in the middle: we will mark the node as unfinished and continue, using natural language description of dependencies
  - Candidate selection: our evaluation shows its influence is limited for different strategies

Fuzzing as post-processing

- Fuzzers are efficient to explore different paths in few seconds
- We build a harness transformation program based on Rustc to convert the generated tests into fuzzing harnesses
- To control the number of unit tests, we propose a greedy selection and ranking algorithm to select the fuzzing inputs

Evaluation

- How efficient is our approach compared with traditonal Rust/unit testing tools?
- How efficient is our problem division compared with other LLM based tools?
- How efficient is fuzzing?
- Can RUG be applied in real-world software development?

https://github.com/cxworks/rug

RUG vs Synthesizing Tools

- RustyUnit: SBST in Rust
- SyRust: SAT based Rust synthesizer
- RUG: using GPT-3.5

Crate	**Func**	**Region**	**Func**	**Region**
	RustyUnit		RUG	
gamie	55.54%	30.79%	68.67%	72.24%
humantime	45.55%	26.67%	50.33%	64.92%
lsd	32.58%	40.23%	37.66%	43.98%
quick-xml	17.38%	24.61%	54.5%	62.76%
tight	24.70%	30.27%	32.24%	36.90%
time	75.26%	70.78%	68.13%	56.94%
mean	**37.23%**	**34.70%**	**49.96%**	**54.84%**
	SyRust		RUG	
data-structure	26.11%	31.19%	52.10%	56.03%
encoding	30.69%	28.51%	55.47%	48.54%
mean	**28.40%**	**30.65%**	**53.79%**	**52.28%**

RUG vs Synthesizing Tools

- RustyUnit: SBST in Rust
- SyRust: SAT based Rust synthesizer
- RUG: using GPT-3.5
- RUG out-performs both tools for 20.14% and 21.63%

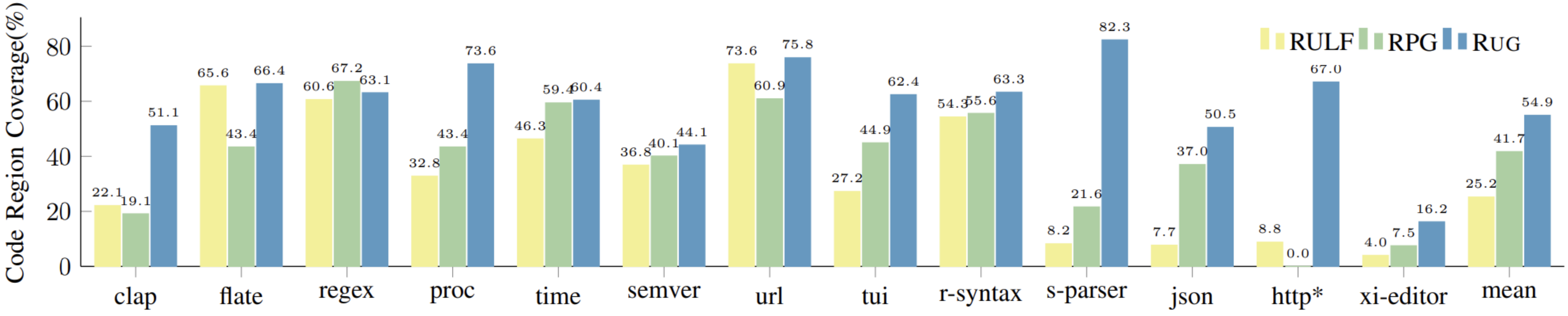
Crate	Func	Region	Func	Region
	RustyUnit		RUG	
gamie	55.54%	30.79%	68.67%	72.24%
humantime	45.	[illegible]	[illegible]	%
lsd	32.	[illegible]	[illegible]	%
quick-xml	17.	[illegible]	[illegible]	%
tight	24.	[illegible]	[illegible]	%
time	75.2	[illegible]	[illegible]	4%
mean	**37.23%**	**34.70%**	**49.96%**	**54.84%**
	SyRust		RUG	
data-structure	26.1	[illegible]	[illegible]	3%
encoding	30.	[illegible]	[illegible]	%
mean	**28.**	[illegible]	[illegible]	**%**

RUG improves RustyUnit coverage by 20.14%

RUG improves SyRust coverage by 21.63%

RUG vs Fuzzing based Testing

- RULF: type dependency based fuzzing harness generator for Rust
- RPG: improved RULF with harness selection algorithm
- RUG achieves 54.9% code coverage, while RULF as 25.2% and RPG has 41.7%



RUG vs Fuzzing based Testing

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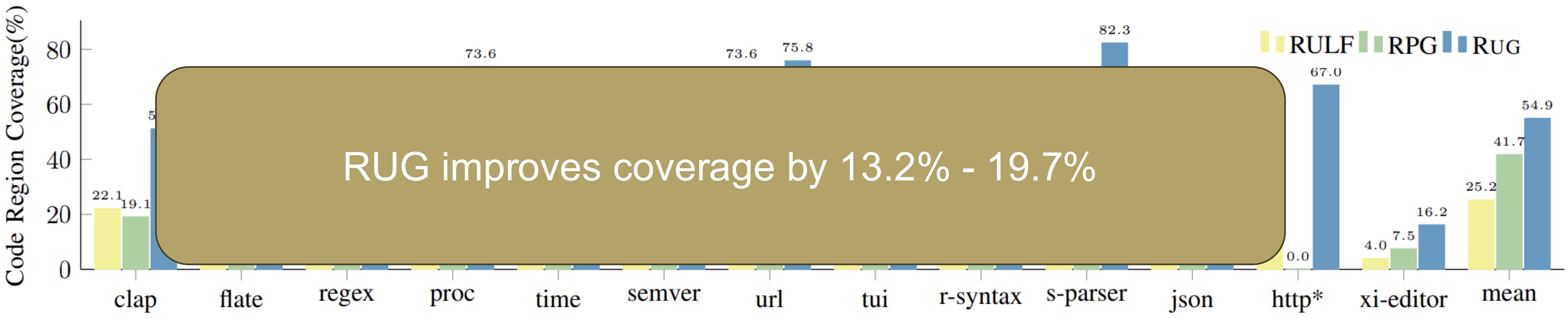

RUG vs LLM Approach

- Base: RUG improves baseline for 21.81% in GPT-3.5 and 10.20% in GPT-4
- Sensitivity test of RUG for: GPT model/fuzzing/problem decomposition

Crate Name (Downloads)	Tests ac/rej	GPT-3.5				GPT-4					Human Test Coverage
		Base		RUG		Base		RUG		Newly API Cov Rate	
		w/o	w. fuzzing	w/o	w. fuzzing	w/o	w. fuzzing	w/o	w. fuzzing		
bincode(49M)	4/0	1.57%	1.57%	22.92%	23.91%	16.63%	18.79%	44.67%	47.91%	74.11%	**64.58%**
chrono(128M)	22/13	37.88%	44.07%	47.2%	58.29%	54.04%	59.24%	56.90%	62.67%	73.05%	**76.66%**
hashes(266M)	**P**(7)	43.84%	43.84%	68.28%	68.28%	57.71%	57.71%	68.96%	**85.16%**	61.41%	**85.17%**
humantime(98M)	**P**(5)	63.09%	64.40%	67.02%	75.39%	74.08%	75.92%	74.61%	**80.37%**	40.00%	79.32%
itoa(221M)	1/0	26.00%	26.00%	82.00%	96.00%	96.00%	98.00%	100.00%	**100.00%**	83.33%	86.00%
json(203M)	-	28.10%	35.69%	44.60%	52.07%	62.26%	67.00%	70.25%	70.49%	47.33%	**72.36%**
mio(145M)	-	20.47%	20.47%	25.20%	25.20%	26.77%	26.77%	33.86%	**33.86%**	38.89%	24.19%
nom(114M)	6/1/**P**(14)	25.81%	25.81%	39.93%	40.04%	51.13%	51.17%	53.84%	53.87%	28.64%	**76.20%**
num-traits(185M)	-	36.02%	36.47%	43.20%	43.95%	46.94%	46.94%	47.23%	47.98%	90.36%	**50.58%**
demangle(93M)	**P**(14)	21.32%	21.62%	21.83%	65.99%	20.00%	74.82%	26.60%	**76.55%**	18.75%	72.25%
crc32fast(104M)	-	62.35%	64.71%	70.59%	71.76%	87.06%	88.24%	87.06%	**88.24%**	92.86%	68.24%
ryu(185M)	0/3	52.51%	95.28%	61.65%	97.64%	76.40%	99.42%	81.72%	**99.42%**	100.00%	87.85%
semver(168M)	18/0	61.40%	62.96%	62.54%	73.36%	72.36%	74.64%	74.22%	76.50%	95.24%	**84.33%**
textwrap(134M)	1/0	88.84%	92.56%	90.15%	94.31%	92.78%	94.75%	92.56%	**94.97%**	83.34%	87.53%
time(200M)	**P**(3)	33.08%	35.06%	48.98%	51.72%	55.34%	55.34%	79.89%	79.89%	66.06%	**96.48%**
toml(125M)	-	32.43%	37.06%	47.28%	49.02%	59.58%	64.40%	38.90%	38.90%	25.14%	**70.81%**
uuid(108M)	1/0	58.66%	64.44%	69.30%	77.20%	73.86%	75.08%	75.68%	**76.60%**	88.89%	61.40%
mean	-	40.79%	45.41%	53.69%	62.60%	60.17%	66.37%	65.11%	71.37%	65.14%	**73.18%**
Identifier	P	A	B	C	D	E	F	G	H	I	J

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chrono(128M)	22/13	37.88%	44.07%	47.2%	58.29%	54.04%	59.24%	56.90%	62.67%	73.05%	**76.66%**
hashes(266M)	**P**(7)									61.41%	**85.17%**
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demangle(93M)	**P**(14)									18.75%	72.25%
crc32fast(104M)	-	62.35%	64.71%	70.59%	71.76%	87.06%	88.24%	87.06%	**88.24%**	92.86%	68.24%
ryu(185M)	0/3	52.51%	95.28%	61.65%	97.64%	76.40%	99.42%	81.72%	**99.42%**	100.00%	87.85%
semver(168M)	18/0	61.40%	62.96%	62.54%	73.36%	72.36%	74.64%	74.22%	76.50%	95.24%	**84.33%**
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toml(125M)	-	32.43%	37.06%	47.28%	49.02%	59.58%	64.40%	38.90%	38.90%	25.14%	**70.81%**
uuid(108M)	1/0	58.66%	64.44%	69.30%	77.20%	73.86%	75.08%	75.68%	**76.60%**	88.89%	61.40%
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RUG improves baseline for 10.2%-21.8%

RUG vs LLM Approach(cont'd)

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nom(114M)	6/1/**P**(14)	25.81%	25.81%	39.93%	40.04%	51.13%	51.17%	[illegible]	[illegible]	[illegible]	[illegible]
num-traits(185M)	-	36.02%	36.47%	43.20%	43.95%	46.94%	46.94%	[illegible]	[illegible]	[illegible]	[illegible]
demangle(93M)	**P**(14)	21.32%	21.62%	21.83%	65.99%	20.00%	74.82%	[illegible]	[illegible]	[illegible]	[illegible]
crc32fast(104M)	-	62.35%	64.71%	70.59%	71.76%	87.06%	88.24%	[illegible]	[illegible]	[illegible]	[illegible]
ryu(185M)	0/3	52.51%	95.28%	61.65%	97.64%	76.40%	99.42%	[illegible]	[illegible]	[illegible]	[illegible]
semver(168M)	18/0	61.40%	62.96%	62.54%	73.36%	72.36%	74.64%	[illegible]	[illegible]	[illegible]	[illegible]
textwrap(134M)	1/0	88.84%	92.56%	90.15%	94.31%	92.78%	94.75%	[illegible]	[illegible]	[illegible]	[illegible]
time(200M)	**P**(3)	33.08%	35.06%	48.98%	51.72%	55.34%	55.34%	[illegible]	[illegible]	[illegible]	[illegible]
toml(125M)	-	32.43%	37.06%	47.28%	49.02%	59.58%	64.40%	38.90%	38.90%	25.14%	**70.81%**
uuid(108M)	1/0	58.66%	64.44%	69.30%	77.20%	73.86%	75.08%	75.68%	**76.60%**	88.89%	61.40%
mean	-	40.79%	45.41%	53.69%	62.60%	60.17%	66.37%	65.11%	71.37%	65.14%	**73.18%**
Identifier	P	A	B	C	D	E	F	G	H	I	J

RUG with GPT-4 generates comparable tests to human developers

Evaluation on real world development

- We run the project's original test and compare with RUG, find the coverage differences
- For the untested regions, we submit RUG's tests as Pull Request to the project
  - 113 tests submitted: 53 merged/17 rejected/43 pending for response

```rust
#[test]
fn test_unfill_consecutive_different_prefix() {
let (text, options) = unfill("foo\n*\n/");
assert_eq!(text, "foo * /");
...
}
```

```rust
pub fn unfill(text: &str) -> (String, Options<'_>) {
    let prefix_chars: &[_] = &[' ', '-', '+', '*', '>', '#', '/'];

    let mut options = Options::new(0);
    for (idx, line) in text.lines().enumerate() {
        options.width = std::cmp::max(options.width, display_width(line));
        let without_prefix = line.trim_start_matches(prefix_chars);
        let prefix = &line[..line.len() - without_prefix.len()];

        if idx == 0 {
            options.initial_indent = prefix;
        } else if idx == 1 {
            options.subsequent_indent = prefix;
        } else if idx > 1 {
            for ((idx, x), y) in prefix.char_indices().zip(options.subsequent_indent.chars()) {
                if x != y {
                    options.subsequent_indent = &prefix[..idx];
                    break;
                }
            }
            if prefix.len() < options.subsequent_indent.len() {
                options.subsequent_indent = prefix;
            }
```

Evaluation on real world development

- We run the project’s original test and compare with RUG, find the coverage differences
- For the untested regions, we submit RUG’s tests as Pull Request to the project
  - 113 tests submitted: 53 merged/17 rejected/43 pending for response
- RUG received positive feedback

“The PR looks good, great job at finding a test case to improve the coverage like this.”

RUG can help developer in submit missed unit tests with 53/70 accepted cases

Conclusion

- RUG leverages program analysis to guide LLM for Rust unit test generation and address the concerns of compiling errors
- RUG can help developers to build uncovered tests and achieves a coverage comparable with experienced human efforts

Thanks for listening

Paper

Code, AE