MOCK: Optimizing Kernel Fuzzing Mutation with Context-aware Dependency

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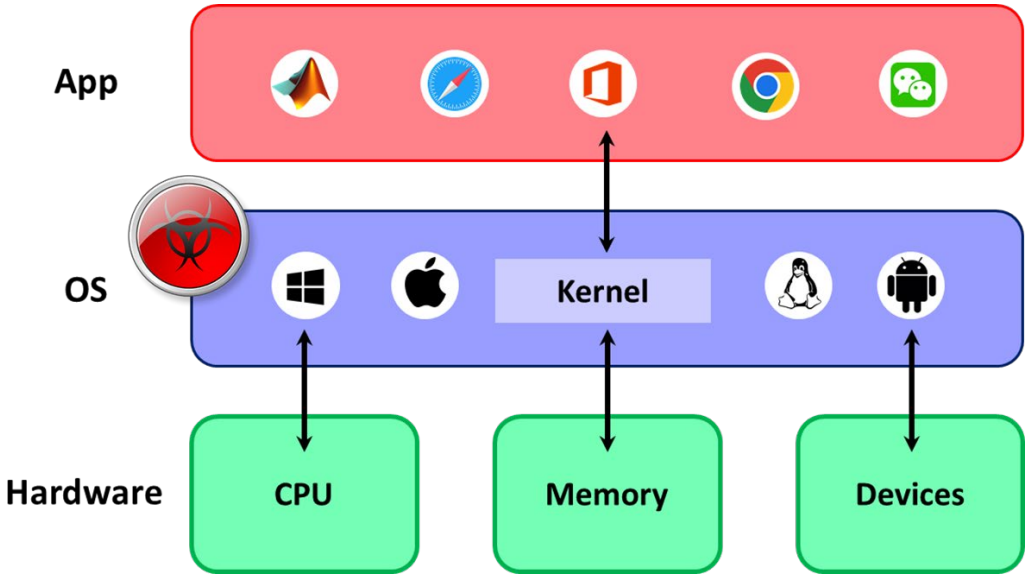
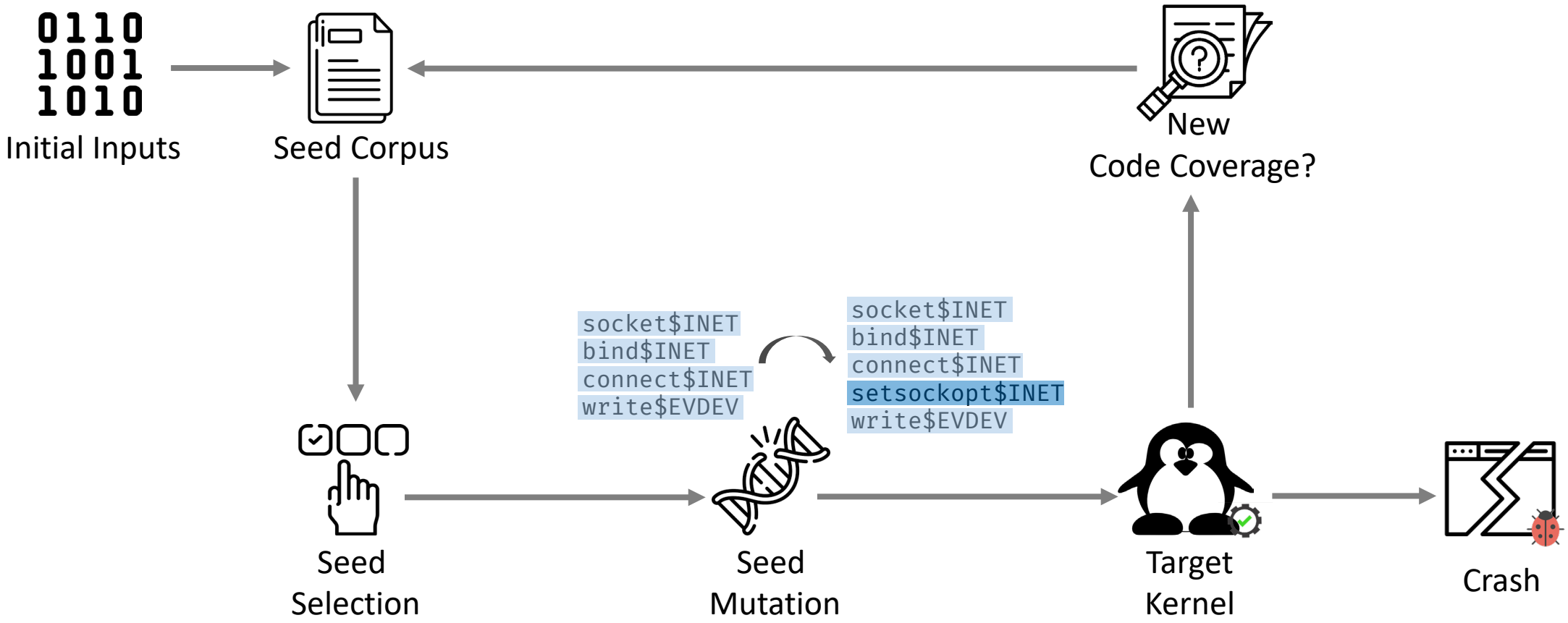
OS Kernel

OS kernel is ubiquitous and crucial, but also vulnerable.



Kernel Fuzzing

Syscall-based greybox fuzzing is a popular technique for finding vulnerabilities.



Kernel Fuzzing

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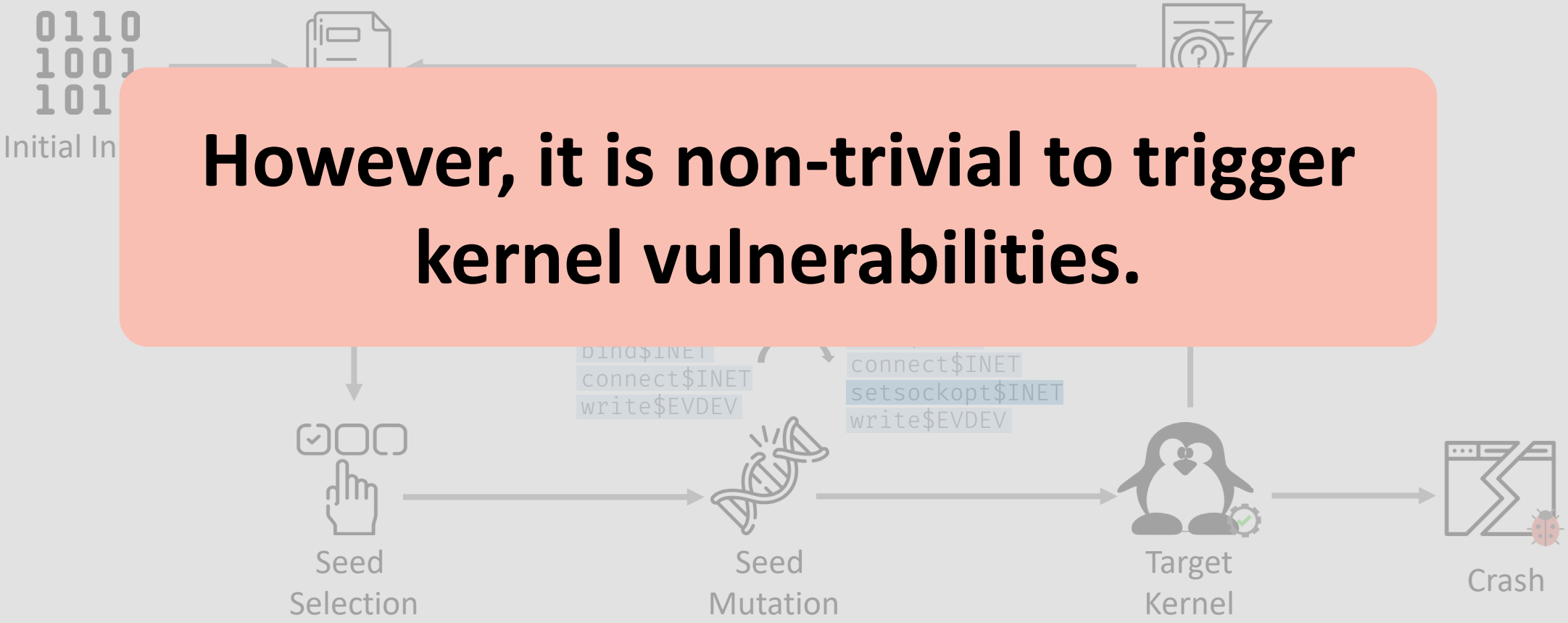
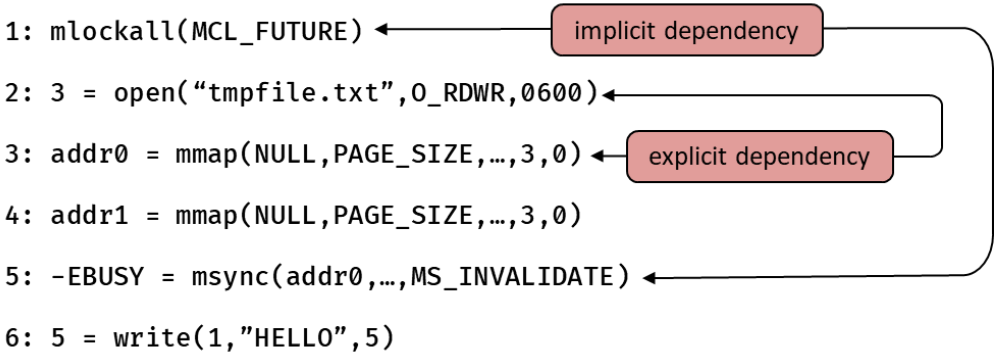


However, it is non-trivial to trigger kernel vulnerabilities.

Motivation

Input synthesis is one of bottlenecks.



- **Explicit/implicit dependency.**
- **Complex bug condition.**
- **Huge search space** $\sum_{k=8}^{32} \binom{4000}{k}$**.**

Motivation

Input synthesis is one of bottlenecks.

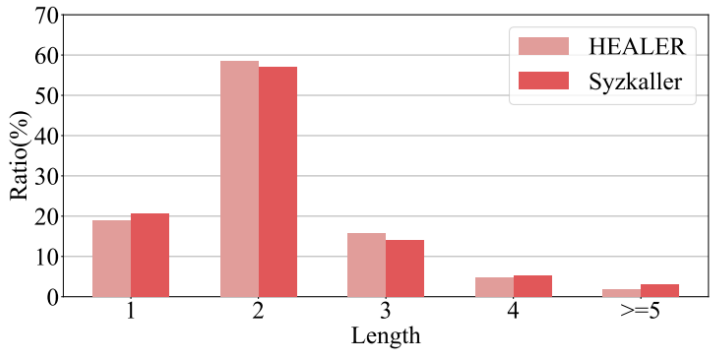
```
1: mlockall(MCL_FUTURE)
2: 3 = open("tmpfile.txt",O_RDWR,0600)
3: addr0 = mmap(NULL,PAGE_SIZE,…,3,0)
4: addr1 = mmap(NULL,PAGE_SIZE,…,3,0)
5: -EBUSY = msync(addr0,…,MS_INVALIDATE)
6: 5 = write(1,"HELLO",5)
```

implicit dependency

explicit dependency

- **Explicit/implicit dependency.**
- **Complex bug condition.**
- **Huge search space** $\sum_{k=8}^{32} \binom{4000}{k}$.

Existing works have limitations in modeling dependency.

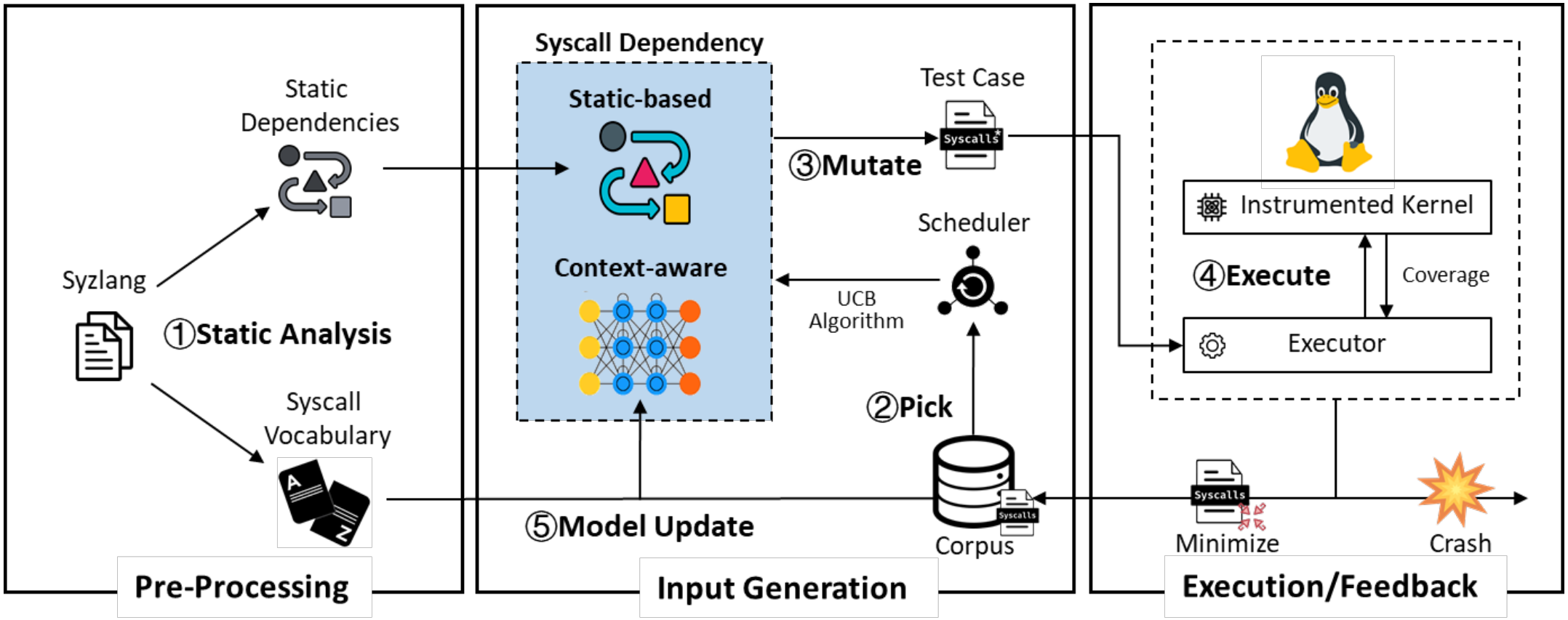


- **24-hour run: 8% of input has 3+ syscalls.**
- **Context-free dependency/mutation.**
- **Underrate the seed corpus.**

Context-aware dependency is desired.
But, how to automatically model and utilize context-aware dependency for better fuzzing?

Our Approach

MOCK: a prototype for context-aware kernel fuzzing.

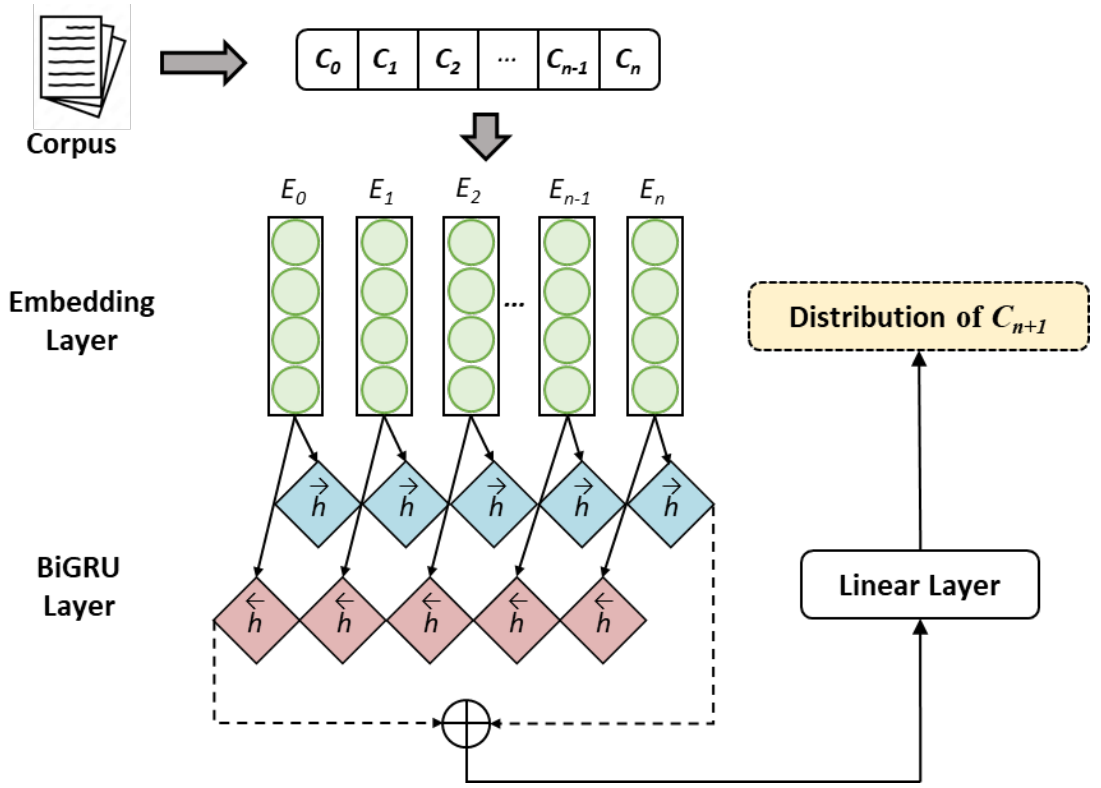


Context-aware Dependency Modeling

¤ **Infer context-aware dependency**
- **a conditional probability under various contexts.**
- **regarded as a NLP problem.**

¤ **Prepare trainingset.**
- **syscall sequences that achieve new code coverage.**
- **sequence minimization[1-2].**

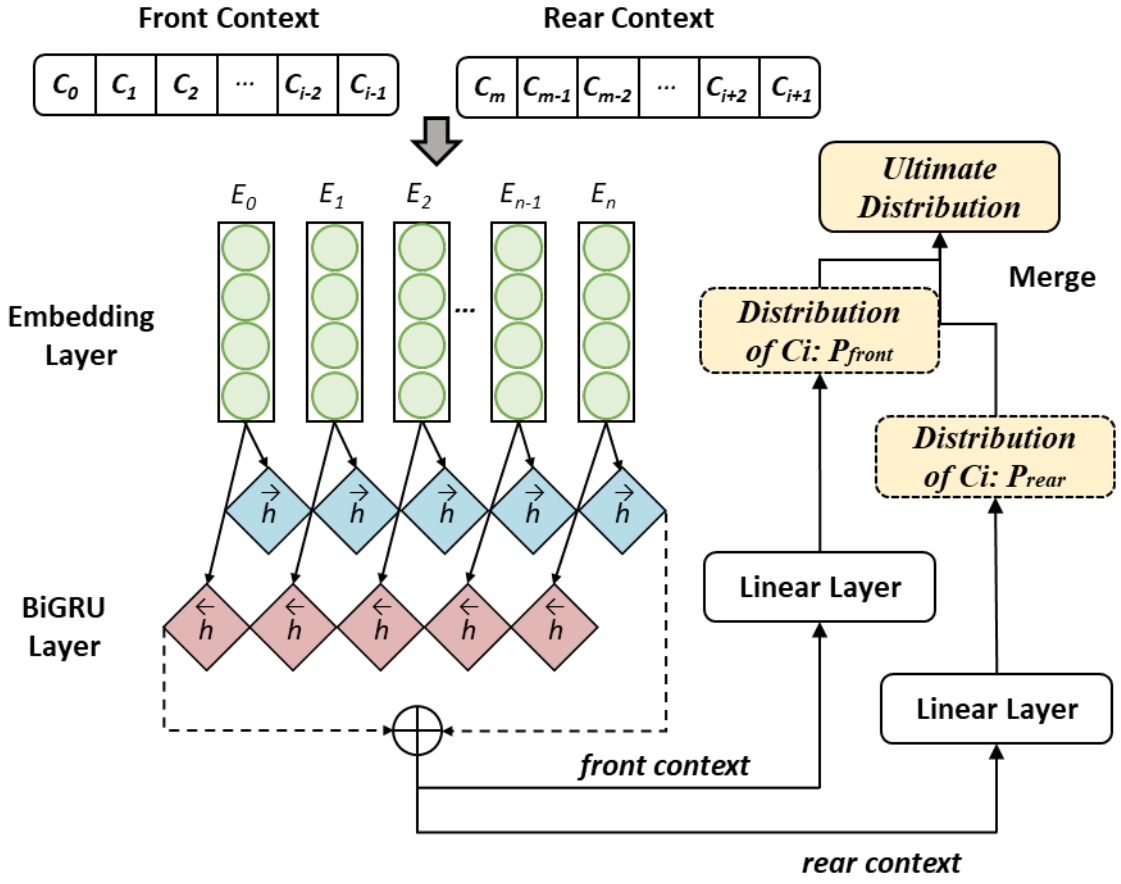
¤ **Employ language model**
- **Bi-LSTM model that detects both front and rear contexts.**



[1] Syzkaller, https://github.com/google/syzkaller
[2]Sun, Hao, et al. "Healer: Relation learning guided kernel fuzzing." SOSP'21.

Context-aware Mutation

- **Extract context**
  - decide a mutation position.
  - extract front and rear contexts.
- **Candidate suggestion**
  - feed front and rear context into the model, respectively.
  - predict candidate syscalls with two probabilities P_{front} and P_{rear}.
- **Syscall selection**
  - merge P_{front} and P_{rear} as the ultimate distribution P_i.
  - random choose a candidate by weight P_i.



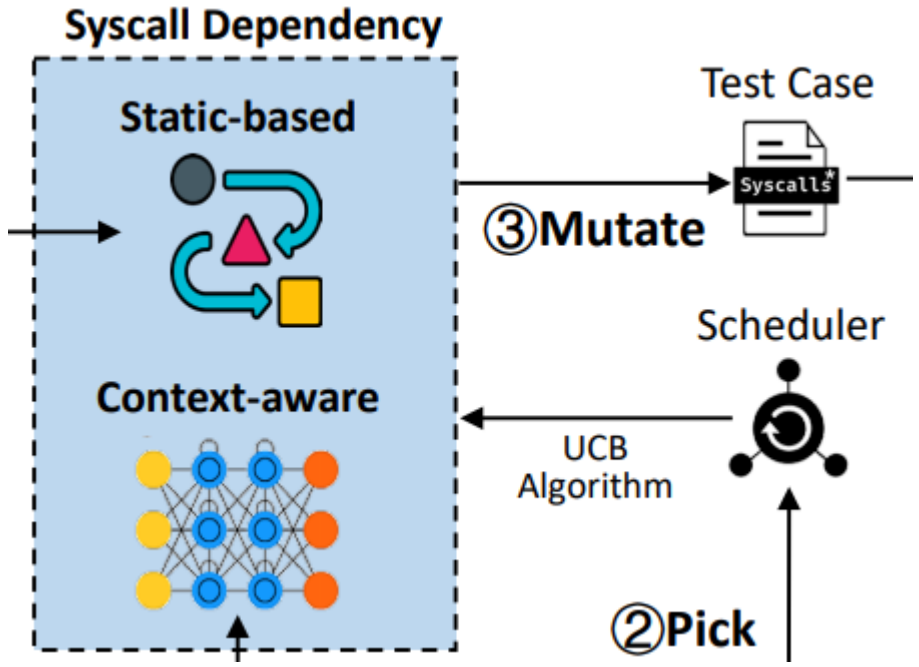
Task Scheduling

¤ **Why scheduling**

- **over-reliance is harmful.**
- **lack of diversity.**
- **limited mutation candidates.**

¤ **Multi-armed bandit**

- **static dependency & context-aware dependency.**
- **UCB-1 algorithm.**
- **coverage-oriented rewards.**
- **the task that discovers more new code coverage is preferred.**



Evaluation

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- **RQ1: How does MOCK perform in code coverage?**
- **RQ2: How effective is context-aware dependency compared to context-free dependency?**
- **RQ3: Do various setups (e.g. initial seeds, pre-trained models) reduce warmup time and boost fuzzing performance?**
- **RQ4: How does MOCK perform in vulnerability detection?**
- **RQ5: Can MOCK discover new vulnerabilities in real-world kernels?**
- **RQ6: How is the significance and overhead of key components in MOCK?**

Experiment Setup

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- Target kernel: Linux-5.4, 5.10, 5.15.
- The same configuration of kernels and resources.
- Baseline: Syzkaller, HEALER, SyzVegas.
- Fuzzing time budget: 144 hours.
- No initial seeds.

Evaluation (1/6)

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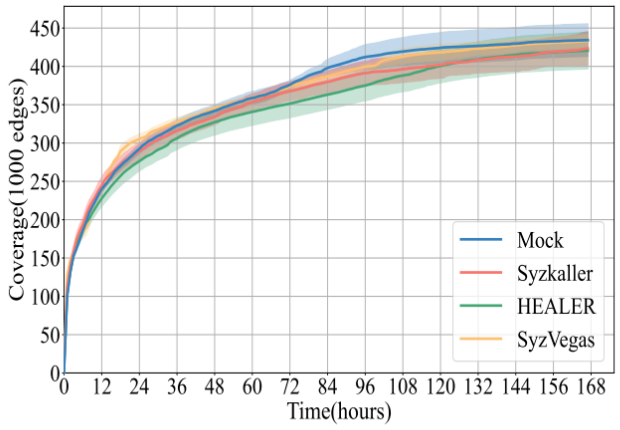
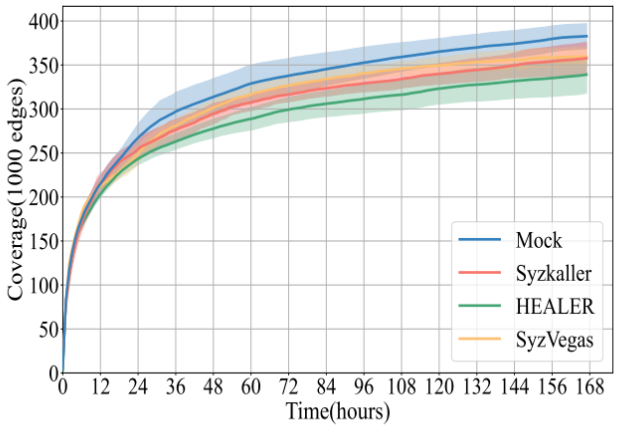
¤ Coverage Performance

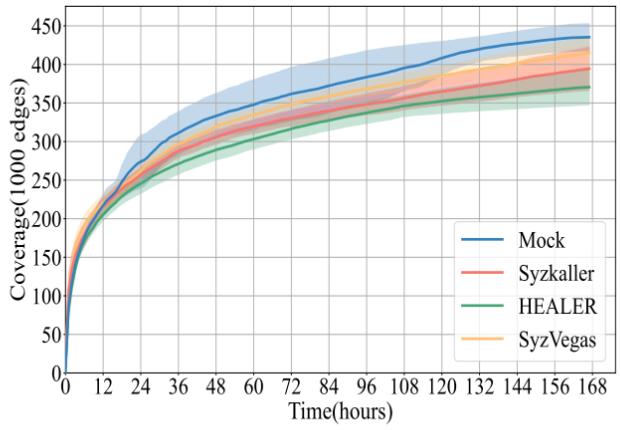
- code coverage: MOCK achieves a **7%** increase compared to SOTAs on average.
- speed-up: MOCK achieves a **1.71x** acceleration compared to SOTAs on average.



(a) Linux-5.4



(b) Linux-5.10

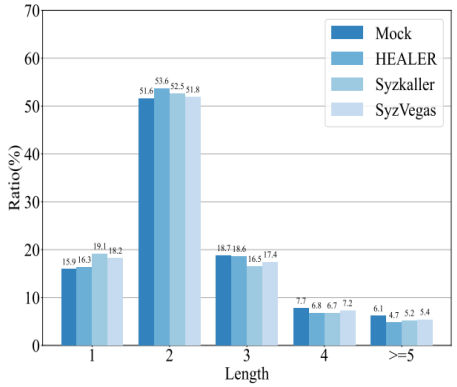


(c) Linux-5.15

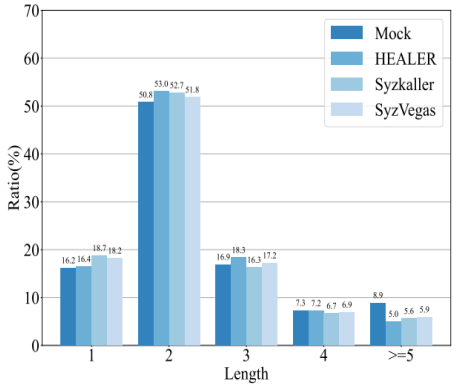
Evaluation (2/6)

¤ Effectiveness of Context-aware Dependency

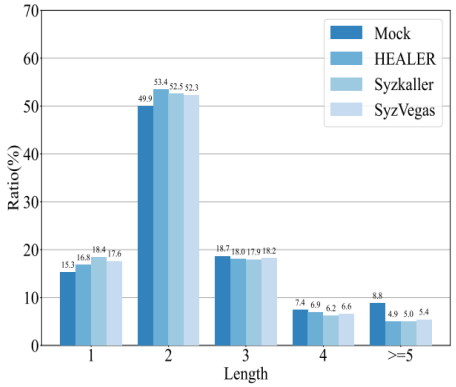
- testcase analysis: MOCK can produce **50%** more interrelated syscall sequences.
- contextual mutation analysis: context-aware dependency facilitates more interrelated input synthesis while marginally deficient in a simple context.



(a) Linux-5.4



(b) Linux-5.10



(c) Linux-5.15

Dependency Model	Context Size 1	2	3	4	>=5
No. of test cases that trigger new coverage					
context-free	4,381	8,275	3,966	1,846	1,921
context-aware	5,488	10,199	4,906	2,308	2,374
Improvement (%)	25	25	24	25	24
No. of test cases that increase the length of syscall sequences					
context-free	604	701	183	68	84
context-aware	533	940	270	81	104
Improvement (%)	-13	34	48	19	24

Evaluation (3/6)

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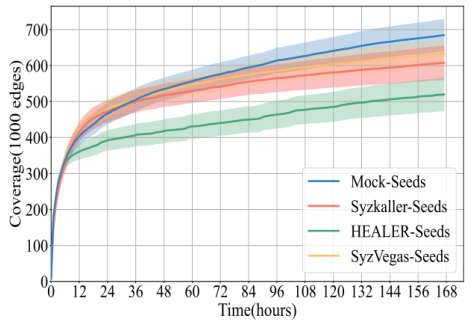
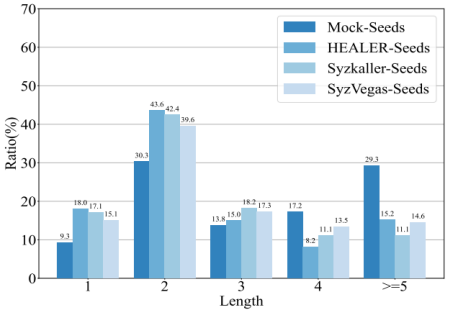
¤ Various setups

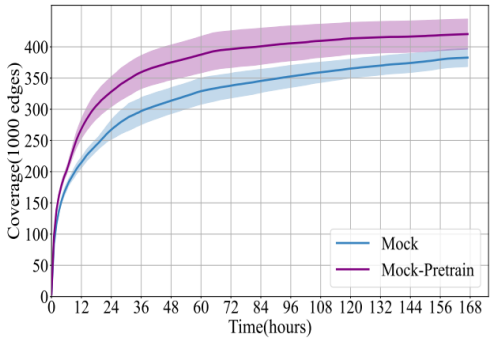
- fuzzing with initial seeds: more coverage growth (21%), higher speed-up (2.58x) and more interrelated sequences.
- Pre-trained model
  - corpus source: syzbot, previous runs.
  - MOCK-Pretrain earns advantages soon after startup.
- both setups reduce the warmup time and boost the fuzzing performance.



(a) Branch coverage



(b) Length distribution of corpus



Evaluation (4/6)

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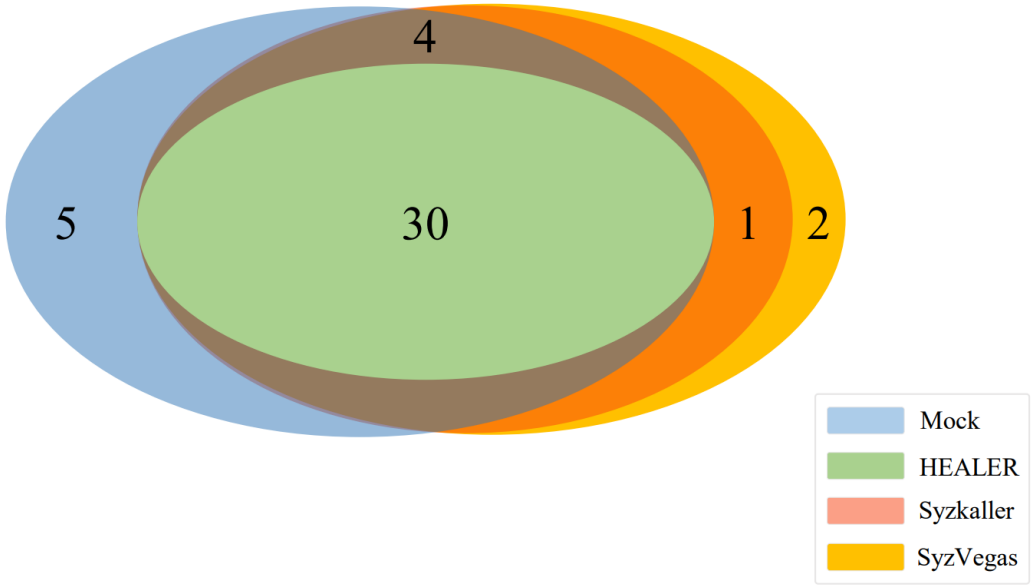
¤ Vulnerability Detection Ability

- **MOCK finds 15% more vulnerabilities than SOTAs.**
- **MOCK outperforms in finding vulnerabilities whose triggering requires more interrelated syscall sequences.**



Evaluation (5-6/6)

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¤ Real-World Vulnerabilities Discovery

- MOCK found 15 unique vulnerabilities, of which four are confirmed and four are fixed.
- we also received two CVEs.

Subsystem	Crash Type	Operation	Kernel	Status
filesystem	use-after-free	nilfs_mdt_destro[C]	4.14	Fixed
filesystem	kernel bug	btrfs_init_reloc_root	5.10	Reported
filesystem	kernel bug	__btrfs_drop_extents	5.10	Reported
filesystem	null-ptr-deref	io_req_track_inflight[C]	5.15	Fixed
filesystem	use-after-free	ntfs_are_names_equal	5.15	Fixed
filesystem	deadlock	io_poll_double_wake	5.15	Reported
filesystem	kernel bug	ntfs_readpage[*]	5.15	Reported
filesystem	kernel bug	ntfs_read_folio[*]	5.19	Reported
drivers	warning	md_probe	5.19	Reported
drivers	deadlock	sch_direct_xmit	5.19	Reported
drivers	deadlock	rfcomm_sk_state_change[*]	5.19	Confirmed
network	refcount	bpf_exec_tx_verdict	5.19	Fixed
network	use-after-free	__fib6_clean_all[×]	6.0	Reported
network	use-after-free	nexthop_flush_dev[×]	6.0	Reported

[*]: Also reported by Syzkaller or HEALER.
[×]: Without syz repro. [C]: Received CVE ID.

¤ Further analysis

- every component in MOCK has a crucial role to play.
- our designs introduce negligible overhead.

	B	B+M	B+M+S
design	-	context-aware dependency	task scheduling
branch coverage	286k	335k	383k
overhead	-	<7%	<1%

Future Work

- Incorporate various model structure and extra features (e.g. parameter types, direction) to augment dependency model.
- Extend dependency inference to syscalls in a concurrency space.

Conclusion

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- A new fuzzing solution MOCK to enhance input synthesis.
- MOCK infers dependency using data-driven approaches and conducts context-aware mutation with the dependency.
- Comprehensive evaluation shows MOCK outperforms the SOTA fuzzers in fuzzing Linux kernels.

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