Automated Patching

Holistic Software Security

Aravind Machiry

Fixing code automatically!

```
else if(request_method == "POST") {
  buff=calloc(length, sizeof(char));
  rc=recv(socket,buff,length)
  buff[length]='\0';
}
```

```
  else if(request_method == "POST") {
+   if (length <= 0)
+       return null;
    buff=calloc(length, sizeof(char));
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```

What is it?

Patching a defect (bug or vulnerability) automatically, also known as Automated Program Repair:

- Where and how to fix?
- How to specify the defect?

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  - Alternatives:
    - On binaries by doing binary rewriting.
    - Runtime by avoiding error behavior (error recovery).
- How to specify the defect? => **Failing Test cases.**
  - Alternatives:
    - High level specification: All memory errors.

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    - Alternatives:
        - ~~On binaries by doing binary rewriting.~~
        - ~~Runtime by avoiding error behavior (error recovery).~~
- How to specify the defect? => **Failing Test cases.**
    - Alternatives:
        - ~~High level specification: All memory errors.~~

Not in this course.

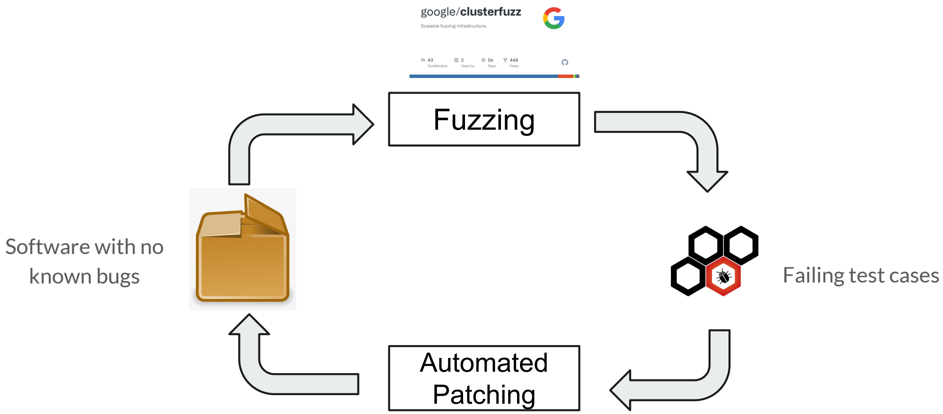
Clarifications

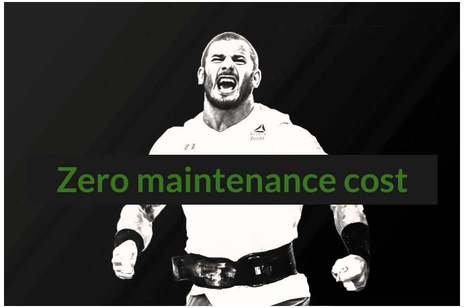
Bug => Root cause and Symptom.

- Root cause => Uninitialized variable, out of bounds access, etc.
  - Fixing Root cause => Program Repair or Automated Patching.

- Symptom => SIGSEGV, Failing test case, etc.
  - Fixing Symptom => Error recovery.

Why is it needed: Automated and continuous software maintenance.

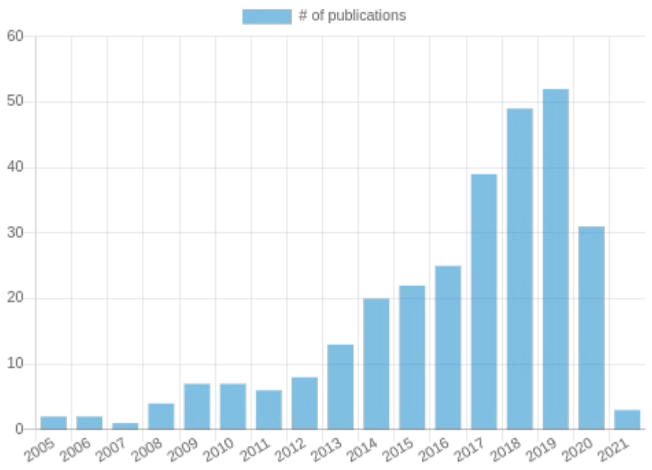


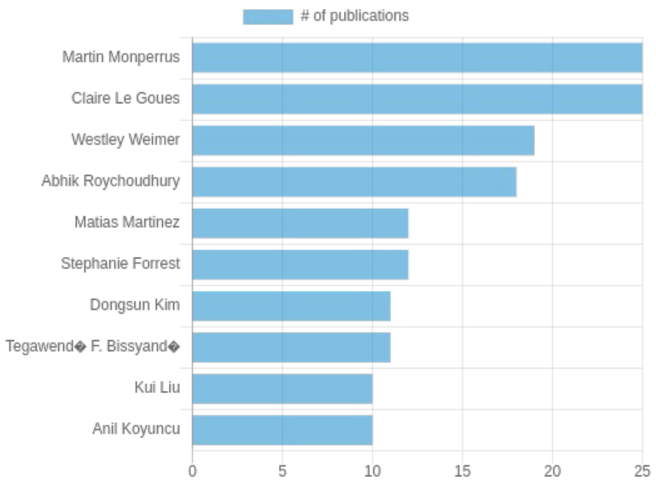


“What one would like ideally [...] is the automatic detection and correction of bugs” R. J. Abbott, 1990

Very active research area

Leaders





https://program-repair.org/index.html

Approaches: Overview

- Genetic Programming: GenProg and family.

- Program Analysis: Senx, Talos, SAVER, SPR, etc.

- Machine Learning: Prophet, DeepFix, etc.

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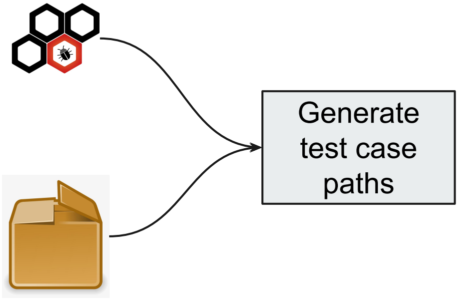
GenProg: Fixing by genetic programming

- Intuition: “The fix for a bug is most likely already present somewhere in the program.”

- The developer might have written mostly bug-free code except for a few cases where the bug might have crept in.

GenProg: Generate paths

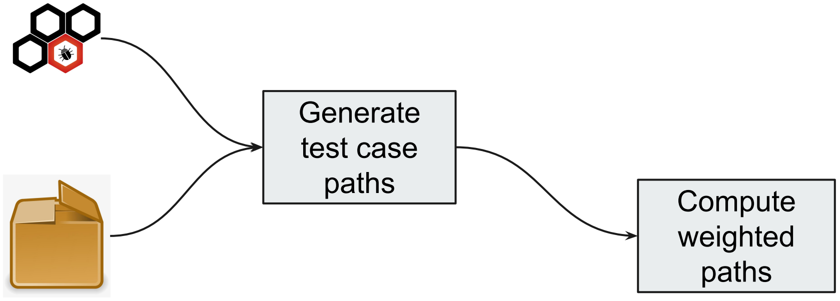


GenProg: Test case paths

For each test case:

- Get the path, i.e., sequence of statements executed.
- Remove duplicate statements, i.e., statements in loops.

GenProg: Weighted paths

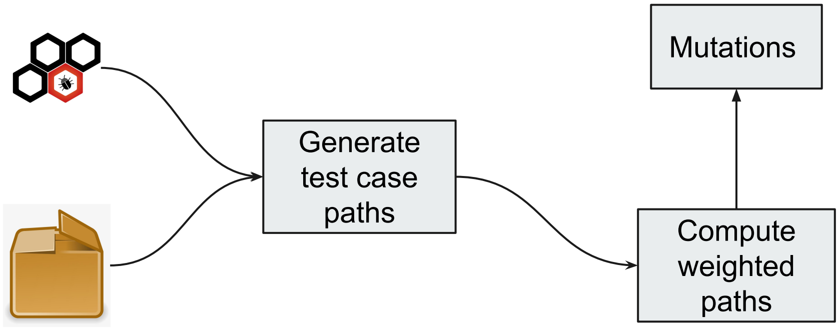


GenProg: Weighted paths

For each path:

- Assign a weight for each statement:
    - Statement executed only in failure test case, Weight = 1.
    - Statement executed in successful test case, Weight = 0.01.

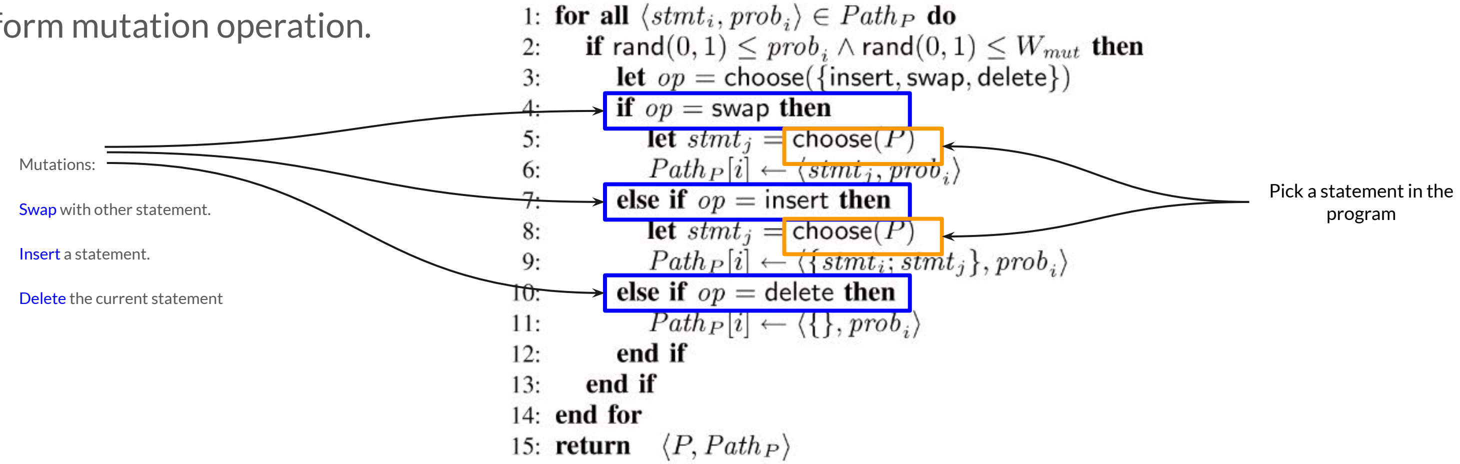
GenProg: Mutations



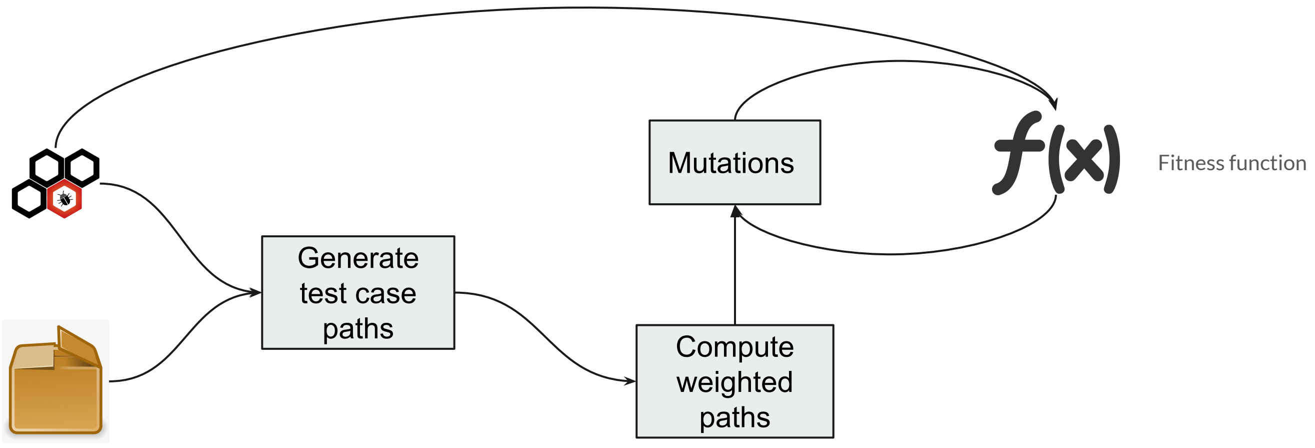
GenProg: Mutations

For each path:

- Pick a statement: Higher weight => Higher probability of picking.
- Perform mutation operation.



GenProg: Fitness function

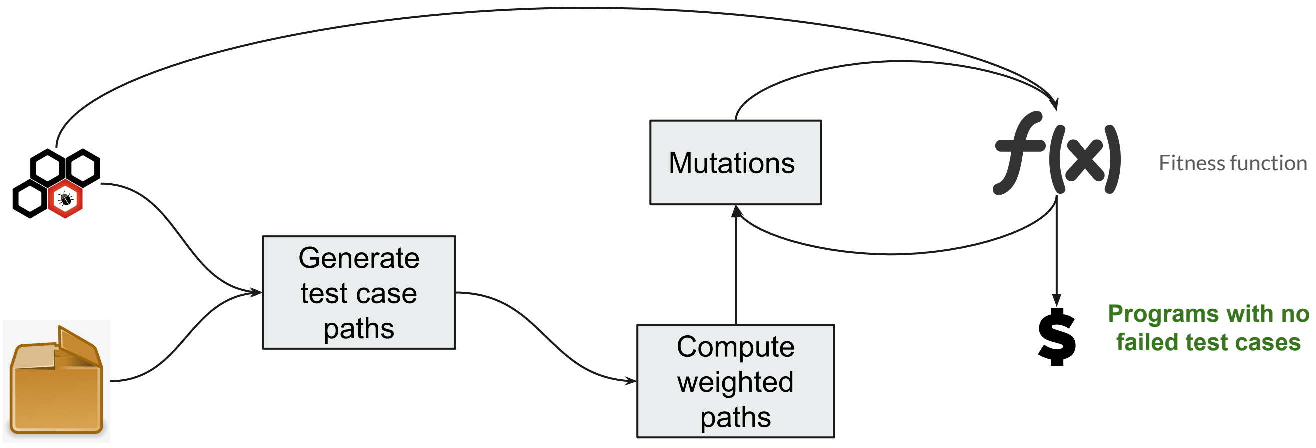


GenProg: Fitness function

Higher score => Passes most of the positive test cases and fails least of the test cases.

$$\begin{aligned}\text{fitness}(P) = {} & W_{PosT} \times |\{t \in PosT \mid P \text{ passes } t\}| \\ & + W_{NegT} \times |\{t \in NegT \mid P \text{ passes } t\}|.\end{aligned}$$

GenProg: Post processing



GenProg: Post processing

- Minimize the patched program:
  - Delta debugging : Iteratively remove statements unless there is a failed test case.

GenProg: Results

```
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}
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```
  else if(request_method == "POST") {
+   if (length <= 0)
+       return null;
    buff=calloc(length, sizeof(char));
    rc=recv(socket,buff,length)
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  }
```

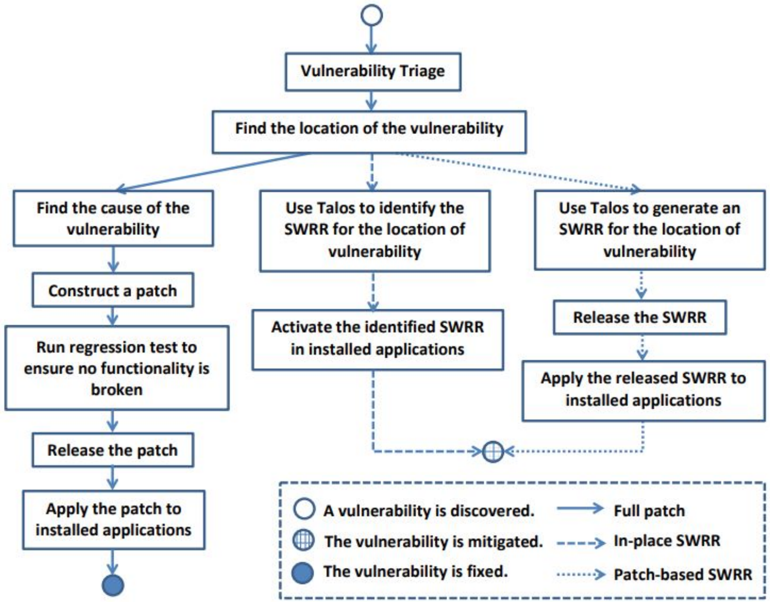
GenProg: Improvements

- Improved search: Randomized Search

Defect Specific Techniques

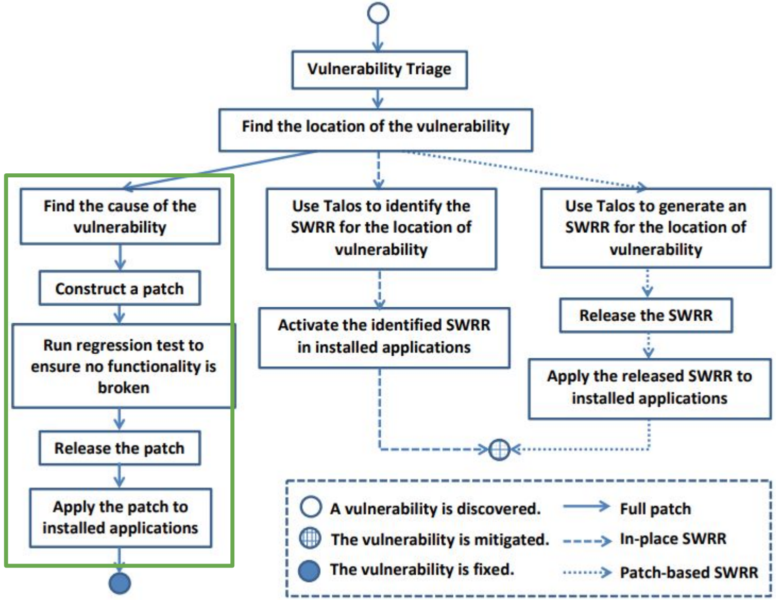
- Workarounds => Talos: Instead of fixing, avoid the bug
- Buffer overflow, Integer overflow, Bad casts => Senx
- Temporal heap errors => SAVER

Security Workarounds

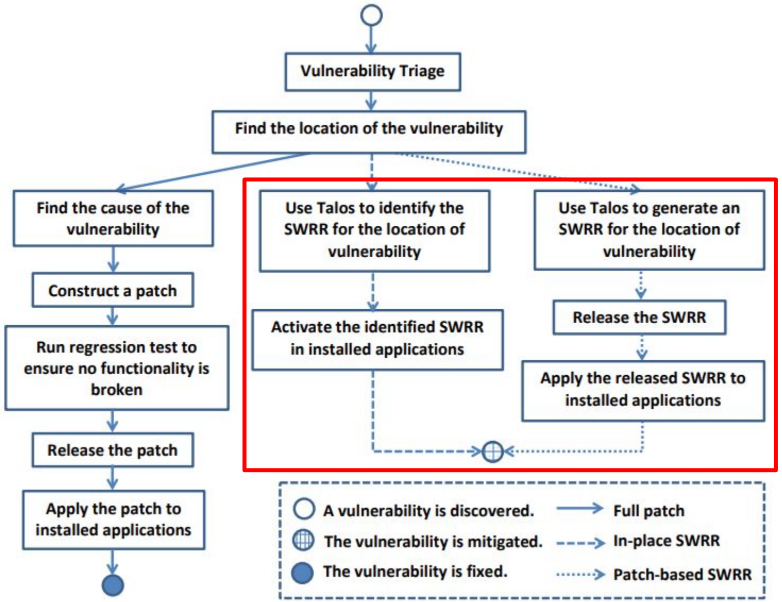


Security Workarounds

Regular flow:
Patching vulnerability



Security Workarounds



Vulnerability Mitigation:
Security Workarounds

Talos: Security Workarounds

Basic Idea: Selectively disable execution of certain (i.e., vulnerable) functions.

Instrument appropriate functions and disable execution of those functions.

Novelty: Correctly disabling functions without affecting "major" functionality of the application.

Talos: Disabling functions

Find error handling behavior of each function:

- `return error_code/NULL.`
- `log error message.`
- `Other heuristics.`

Instrument function to have error handling behavior.

Talos: Disabling functions

```
int example_function(...) {
  /* SWRR inserted at top of function */
  if (SWRR_enabled(<SWRR_option>))
    return <error_code>;

  /* original function body */
  ...
}
```

Talos: Disabling functions

```
int example_function(...) {
  /* SWRR inserted at top of function */
    return <error_code>;

  /* original function body */
  ...
}
```

If the vulnerability is known then just disable the function.

Talos: Results

App.	CVE ID	Heuristics	Security?	Unobtrusive?
lighttpd	CVE-2011-4362	NULL Return	Yes	Yes
lighttpd	CVE-2012-5533	Indirect	Yes	No
lighttpd	CVE-2014-2323	Error-Propagation	Yes	No
apache	CVE-2014-0226	Error-Logging	Yes	Yes
squid	CVE-2009-0478	Indirect	Yes	No
squid	CVE-2014-3609	Error-Logging	Yes	Yes
sqlite	CVE-2015-3414	Error-Propagation	Yes	Yes
sqlite	OSVDB-119730	Error-Logging	Yes	Yes
proftpd	OSVDB-69562	Error-Propagation	Yes	Yes
proftpd	CVE-2010-3867	Error-Logging	Yes	Yes
proftpd	CVE-2015-3306	Error-Logging	Yes	Yes

Affected major functionality of the application

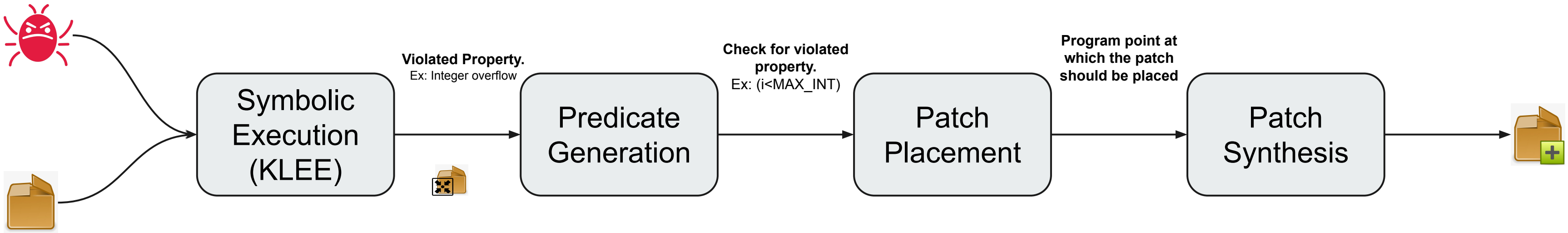
Senx: Vulnerability Specific Patches

Given a vulnerability triggering input => Create a patch that avoids the vulnerability.

Vulnerability types:

- Buffer overflow.
- Bad-cast.
- Integer overflow.

Senx: Overview



Senx: Symbolic Execution

Given program and vulnerability triggering input:

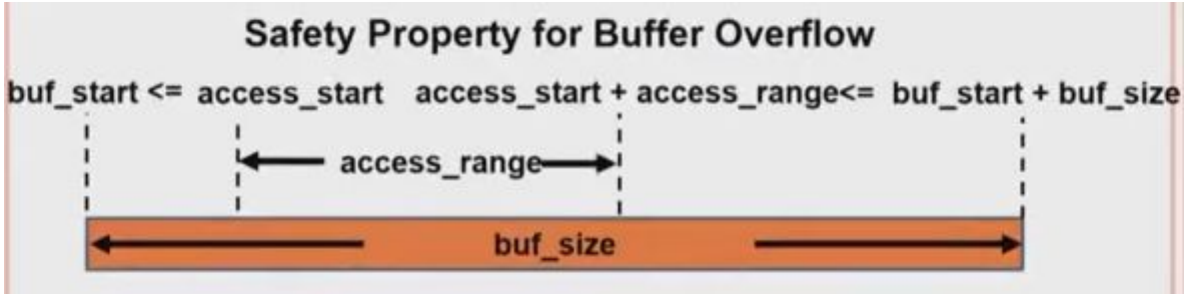
Symbolically trace the program with pre-constraining the input.

At each program point, check for vulnerability condition:

- Out of memory access.
- Integer overflow
- Bad casts.

Vulnerability point: Program point at which the vulnerability condition (security property violation) occurs

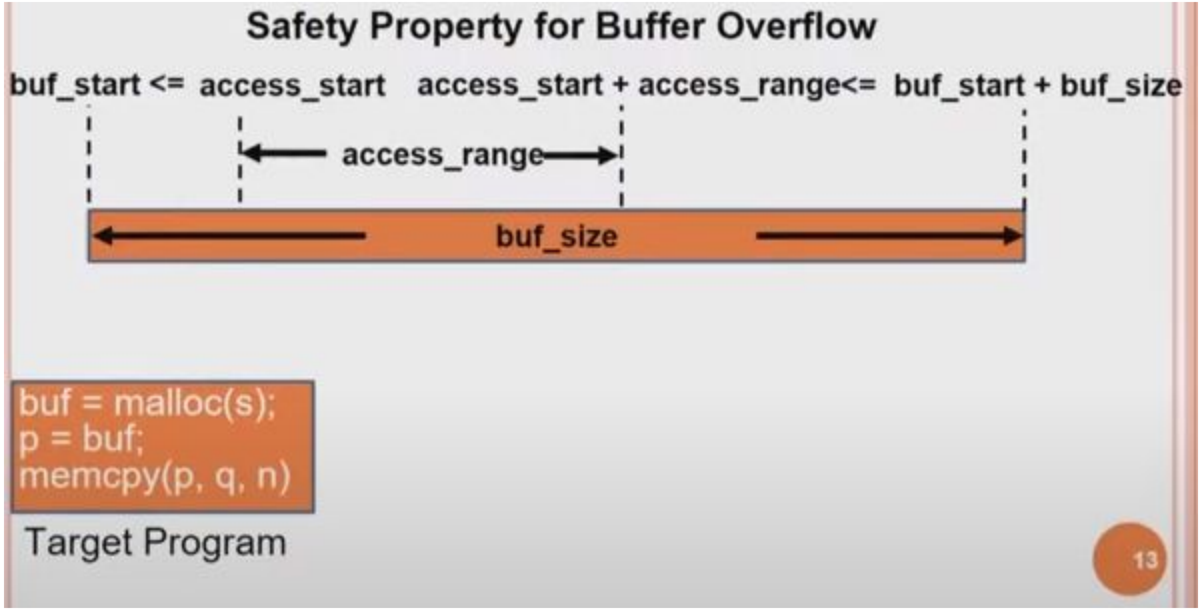
Senx: Safety property



Senx: Predicate Generation

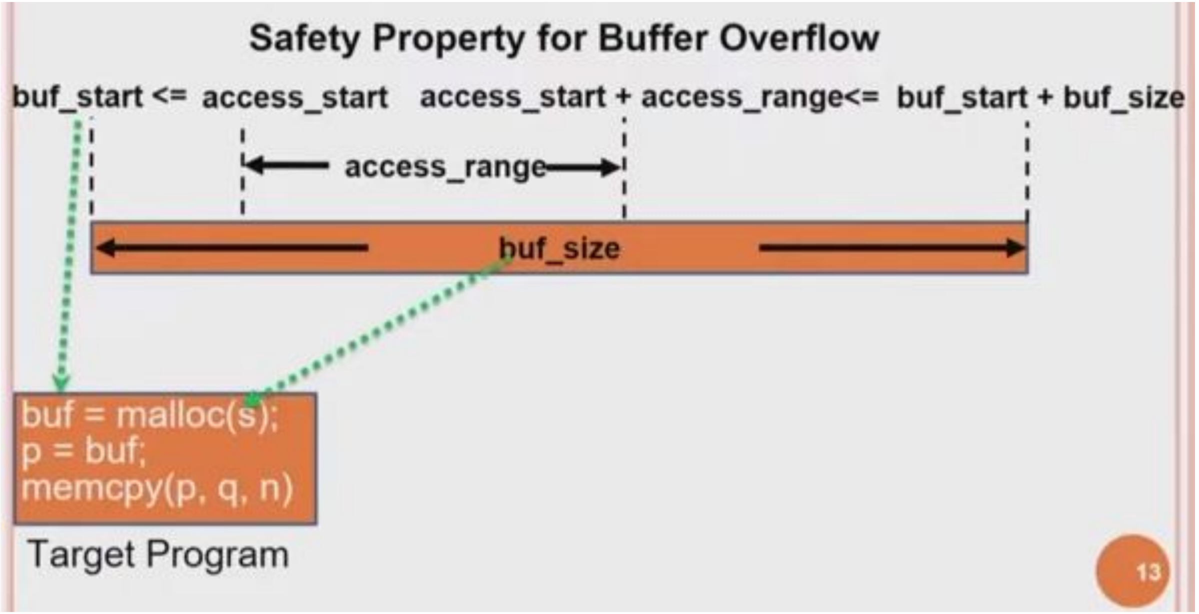
Generate a condition that prevents the vulnerable condition.

Senx: Predicate Generation



https://www.youtube.com/watch?v=rHf_teG6iQc

Senx: Predicate Generation



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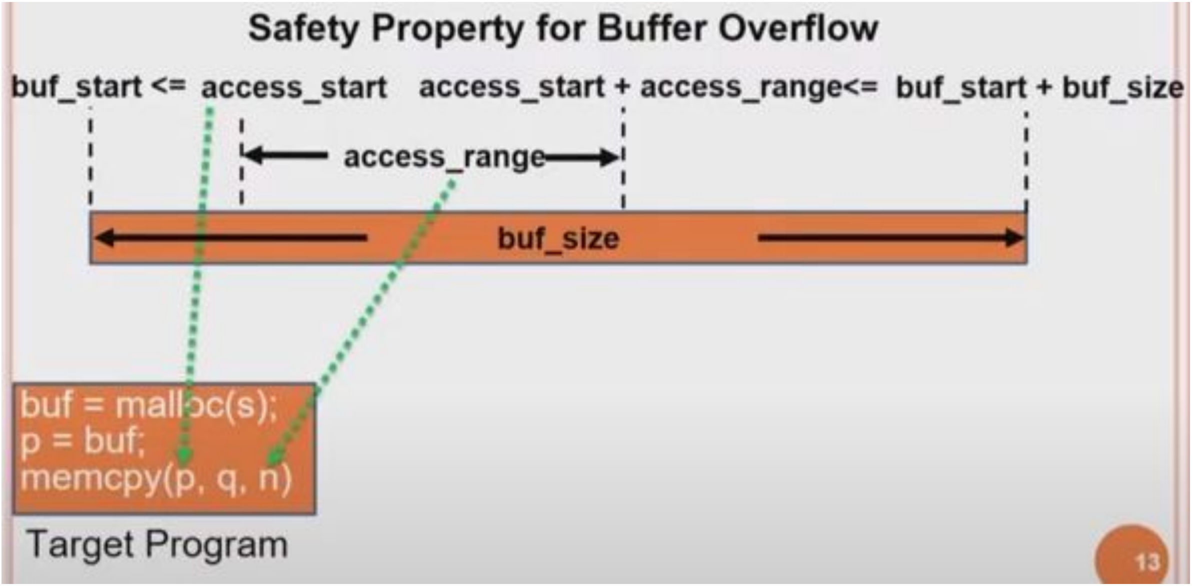

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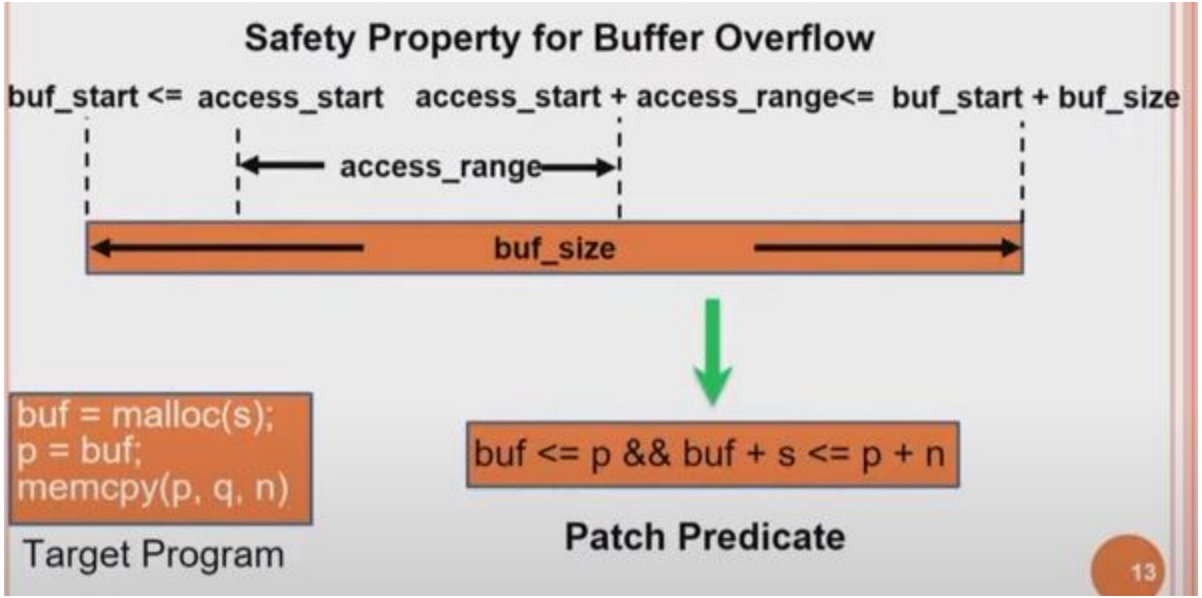

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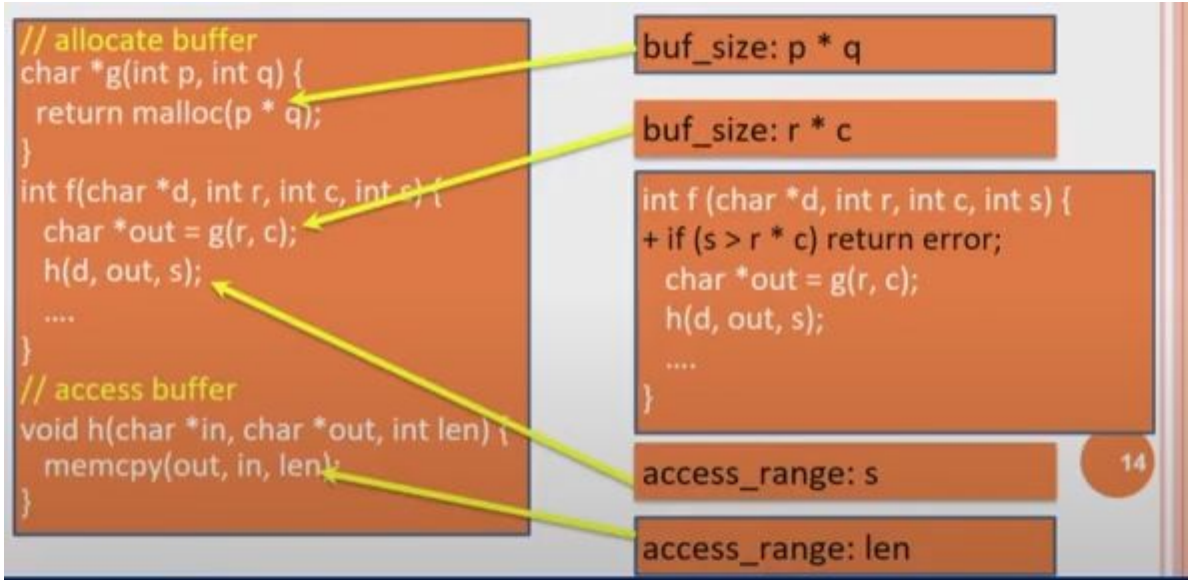
Senx: Patch Placement

Place the patch at the **highest point in the call-graph** where all the **variables needed for the predicate are available**.

Senx: Patch Placement



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SAVER: Memory Error Repair

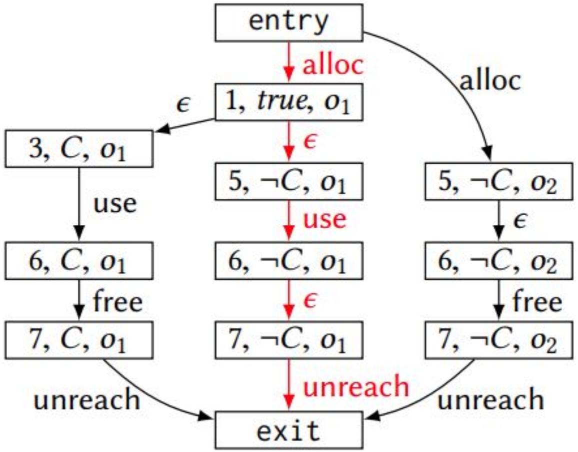
Fixes temporal memory errors using static analysis warning.

Run Infer (static analysis tool) to find temporal memory errors, i.e., use-after-free, memory leak, double free.

SAVER: Object flow graph

Construct Object flow graph from Infer warning: “*Object allocated at 1 is unreachable at 7*”

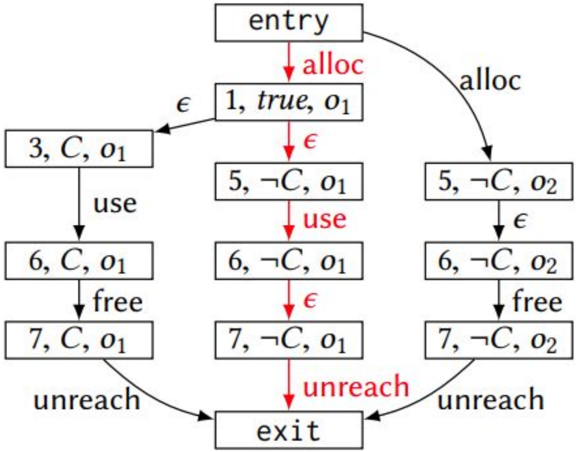
```
1  p = malloc(1); //o1
2  if (C)
3    q = p;
4  else
5    q = malloc(1); //o2
6  *p = 1;
7  free(q);
```



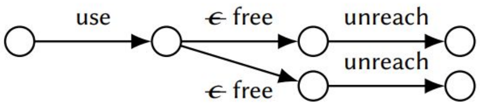
SAVER: Buggy Paths

We need to fix paths containing invalid event sequences by inserting appropriate memory allocation/deallocation operations.

$$\text{alloc} \cdot \epsilon \cdot \text{use} \cdot \epsilon \cdot \text{unreach}$$

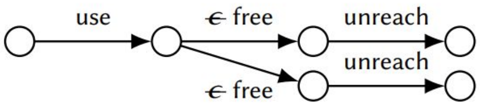


SAVER: Fixing strategies



(a) Inserting free

SAVER: Fixing strategies



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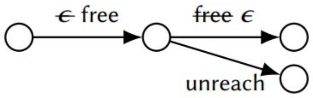
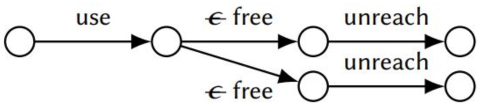


(b) Relocating free

SAVER: Fixing strategies



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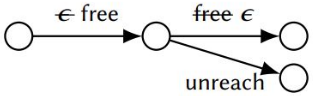

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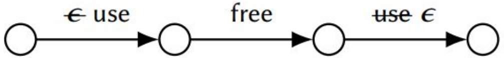
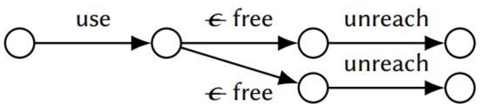


(c) Relocating use (dereference)

SAVER: Fixing strategies



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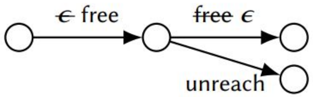

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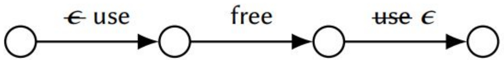

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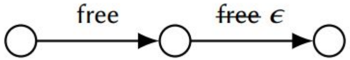

(d) Deleting free

SAVER: Results

```
int append_data (Node *node, int *ndata) {
    if (!(Node *n = malloc(sizeof(Node)))
        return -1; // failed to be appended
    n->data = ndata;
    n->next = node->next; node->next = n;
    return 0; // successfully appended
}

Node *lx = ... // a linked list
Node *ly = ... // a linked list
for (Node *node = lx; node != NULL; node = node->next) {
    int *dptr = malloc(sizeof(int));
    if (!dptr) return;
    *dptr = *(node->data);
(-) append_data(ly, dptr); // potential memory-leak
(+) if ((append_data(ly, dptr)) == -1) free(dptr);
}
```

Automated Patching: Final Thoughts

- Defect specific techniques and ML techniques are on rise.
- Should explore interactive patching strategies => Active learning for patching strategies!!?
- Can we ask developer for some input that would make the patching easier and more precise!?
- Keep an eye on: https://program-repair.org/index.html