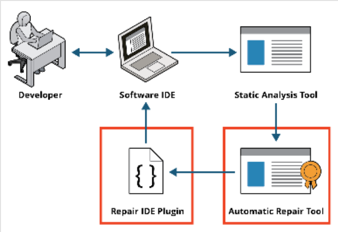
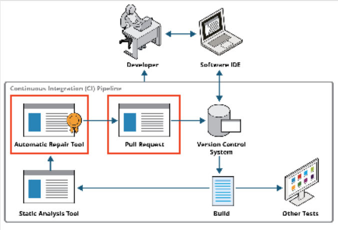
```diff
 void *zrealloc(void *ptr, size_t size) {
 #ifndef HAVE_MALLOC_SIZE
-    void *realptr;
+    void *realptr = NULL;
 #endif
-    size_t oldsize;
-    void *newptr;
+    size_t oldsize = 0;
+    void *newptr = NULL;

     if (ptr == NULL) return zmalloc(size);
```

via



or



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Static Analysis-Targeted Automated Repair to Secure Code and Reduce Effort

for NDIA's 27th Systems & Mission Engineering Conference

OCTOBER 2024

Lori Flynn, PhD
David Svoboda (PI)

Carnegie Mellon University Software Engineering Institute

Agenda

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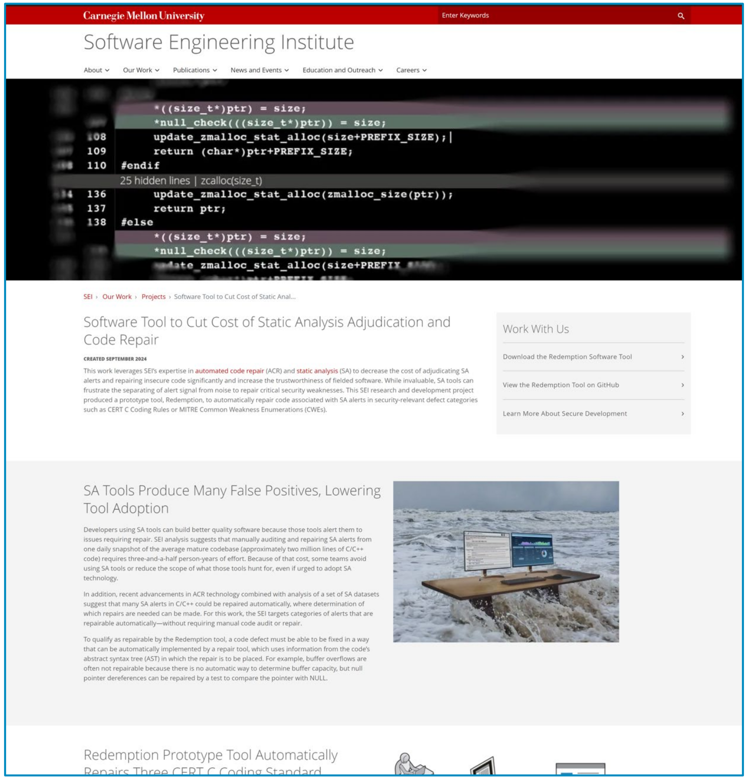
- Problem: static analysis (SA) alert deluge
- Our tool repairs source code associated with alerts
- Design choices
- Tool use during development, test, and evaluation
- Development methods
- Test results
- Demo
- How can this work be extended to help you?



Project page https://www.sei.cmu.edu/our-work/projects/display.cfm?customel_datapageid_4050=497941

Problem: static analysis (SA) alert deluge

Case study of 5 C/C++ audited codebases

- 239 kSLoC
- 364.5 alerts/kSLoC
- 85,268 SA alerts
- Repairs for 8 CERT rules would resolve 57,922 alerts (68%)

Average CERT-audited C/C++ program is 2 MSLoC

- 117 seconds to audit one alert*
- 15.5 person-years to audit all alerts
- If 32% of alerts are true and 117 seconds per repair → 5 person-years to fix all true alerts

* Ayewah, Nathaniel. & Pugh, William. The Google FindBugs fixit. Pages 241-252. In *Proceedings of the 19th International Symposium on Software Testing and Analysis*. July 2010. https://doi.org/10.1145/1831708.1831738

Does the DoD Require Use of Static-Analysis Tools?

- From the Application Security & Development (ASD) Security Technical Implementation Guide (STIG):
  - According to V-222624, *The ISSO must ensure active vulnerability testing is performed*, Use of automated scanning tools accompanied with manual testing/validation which confirms or expands on the automated test results is an accepted best practice when performing application security testing.
- The NIST Computer Security Resource Center (CSRC) documents recommendations for
  - RA-5: Vulnerability Monitoring and Scanning
  - SA-11: Developer Testing and Evaluation

Parasoft, Coverity, and Perforce all suggest that their SA tools help you achieve compliance with the Defense Information Systems Agency's (DISA's) ASD STIG.

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Collaborator Experience

Of the languages that our collaborator uses, they told us that C code tends to exhibit the most vulnerabilities.

One collaborator's process is

- Filter alerts based on a preset list of CWEs and (if time permits) analyze the *most critical* remaining alerts.
  - About 20% of (unfiltered) alerts are deemed to be true positives.
- Fix ~90% of the true positives.

C/C++ Automated Program Repair (APR) Tools

Template-based APR tools have a pre-set method to repair a defect

- **Visual Studio Code** has some APR for C/C++
- **Eclipse** IntRepair open-source APR tool for integer overflows, buffer overflows, and more (per research papers) is an extension to the C/C++ Development Tools (CDT) plugin
- **Automated Code Repair** (SEI's Dr. Will Klieber) APR for buffer overflows in C. It converts pointers to fat pointers, potential for changes throughout the codebase
- **clang-tidy** has recent APR fixes for many C/C++ checkers
- **Clang's** new JSON API outputs the AST in an easy-to-parse JSON file, useful for developing APRs

Rationale for project: 1. Significant DoD use of C code, 2. `clang`'s new JSON API, and 3. we did not find any OSS APR tool documentation that explicitly states a fix for "CERT C secure coding rule violations"

Learning-based APR tools use AI/ML/LLMs, past bugfixes, & more to make new patches

- Contact Lori lflynn@sei.cmu.edu about collaboration on APR research involving learning-based methods

Our tool repairs source code associated with alerts

Category	CERT Rule ID	CWE ID	Repair
Null Pointer Dereference	EXP34-C	CWE-476	Insert null check
Uninitialized Value Read	EXP33-C	CWE-908	Initialize variable at declaration
Ineffective Code	MSC12-C	CWE-561	Delete ineffective code

```
*((size_t*)ptr) = size;
*null_check(((size_t*)ptr)) = size;
update_zmalloc_stat_alloc(size+PREFIX_SIZE);
```

Design choices

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Design choices

1. Make cheap, local fixes.
2. Only fix code associated with an SA alert.
3. Goal: Fixes are sound and do not change the behavior of good code.
   - A repair should not break the code, even if the alert was a false positive.
4. The tool should be *idempotent* (i.e., the tool will not modify code it already repaired).

```c
char *f(int a, int b) {
  int x;
  int sum = a + b;
  /* ... */
```

If the mathematical value of **a+b** cannot be stored in an **int**, the behavior is undefined.

```c
char *f(int a, int b) {
  int x;
  int sum;
  if (((b > 0) && (a > (INT_MAX - b)))
||
      ((b < 0) && (a < (INT_MIN - b))))
  {
    /* Handle error */
  }
  sum = a + b;
  /* ... */
```

Design choices

1. Make cheap, local fixes.
2. Only fix code associated with an SA alert.
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4. The tool should be *idempotent* (i.e., the tool will not modify code it already repaired).

```
char *f(int a, int b) {
  int x;
  int sum = a + b;
  /* ... */
```

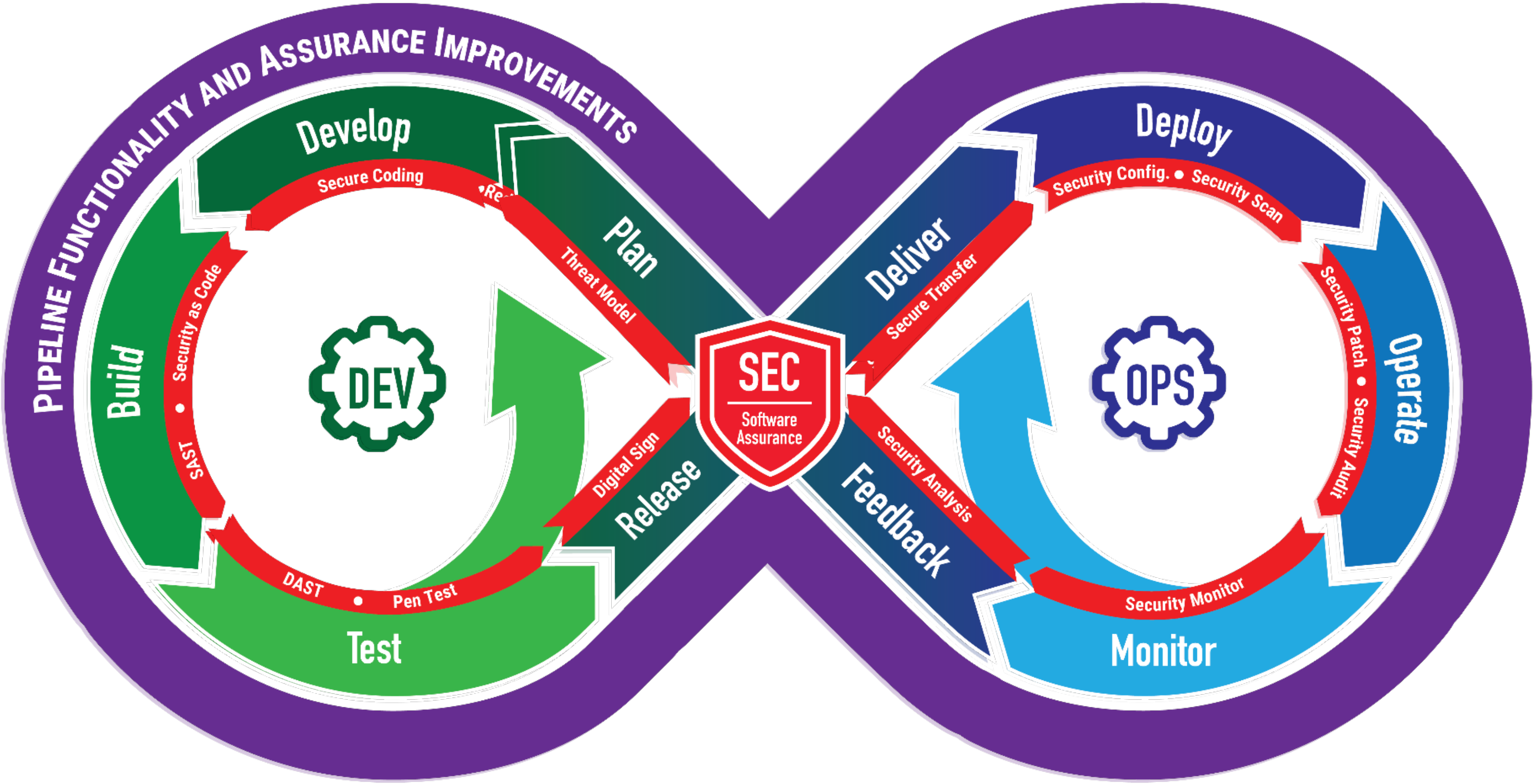
Possible integer overflow?

```
char *f(int a, int b) {
  int x;
  int sum = SAFE_ADD(a, b,
    /* Handle error */
  );
/* ... */
```

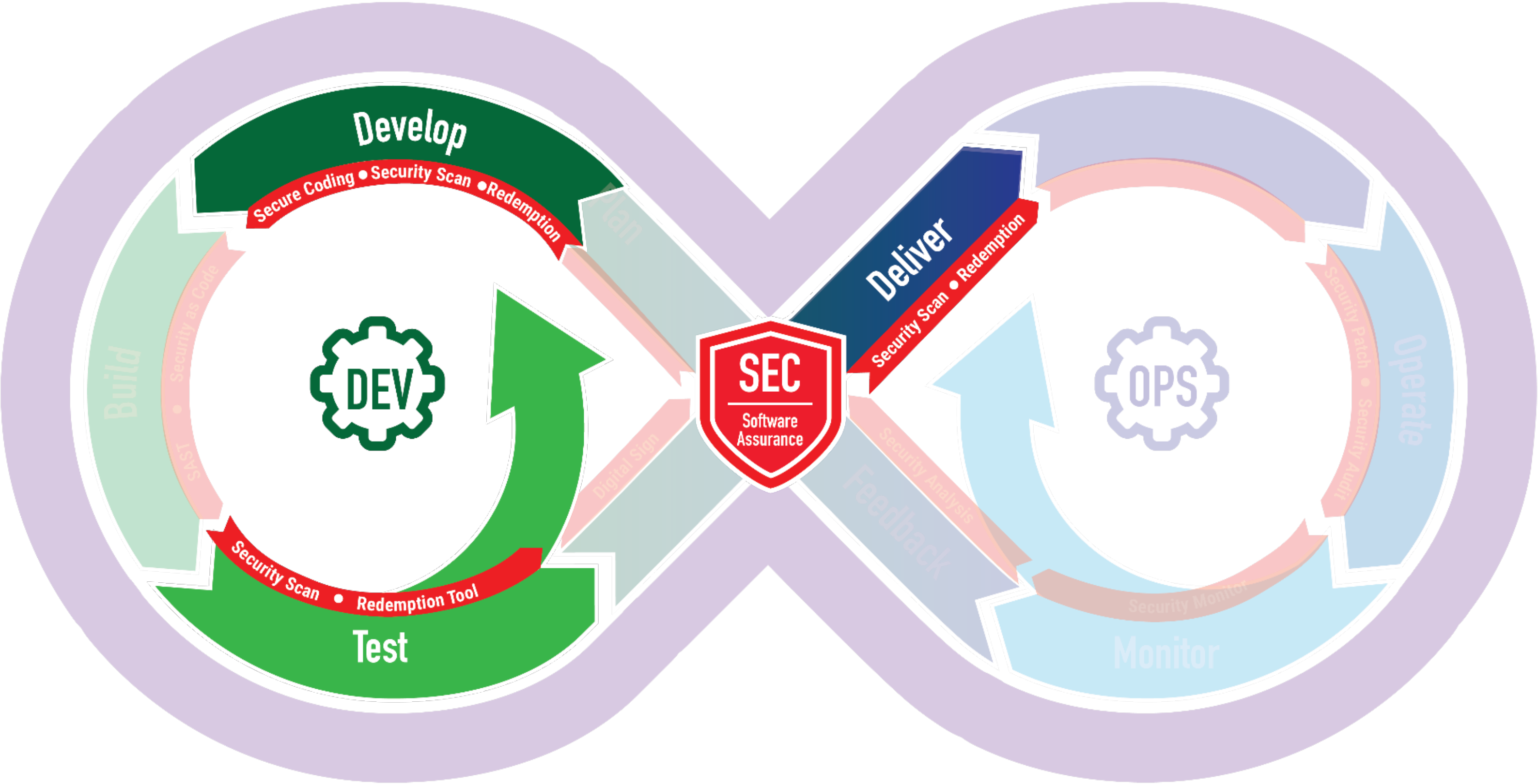
Static Analysis-Targeted Automated Repair to Secure Code and Reduce Effort

Tool use during development, test, and evaluation

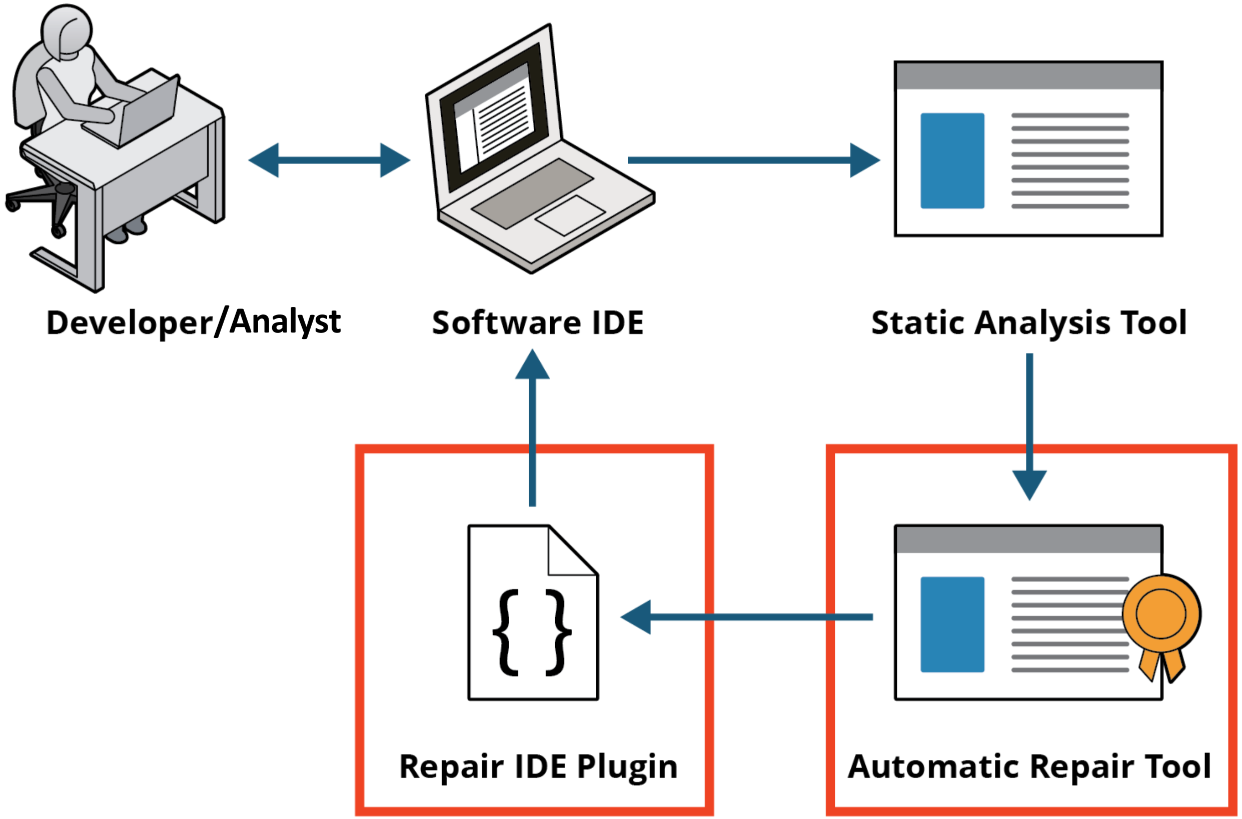
Where to use Redemption in DevSecOps



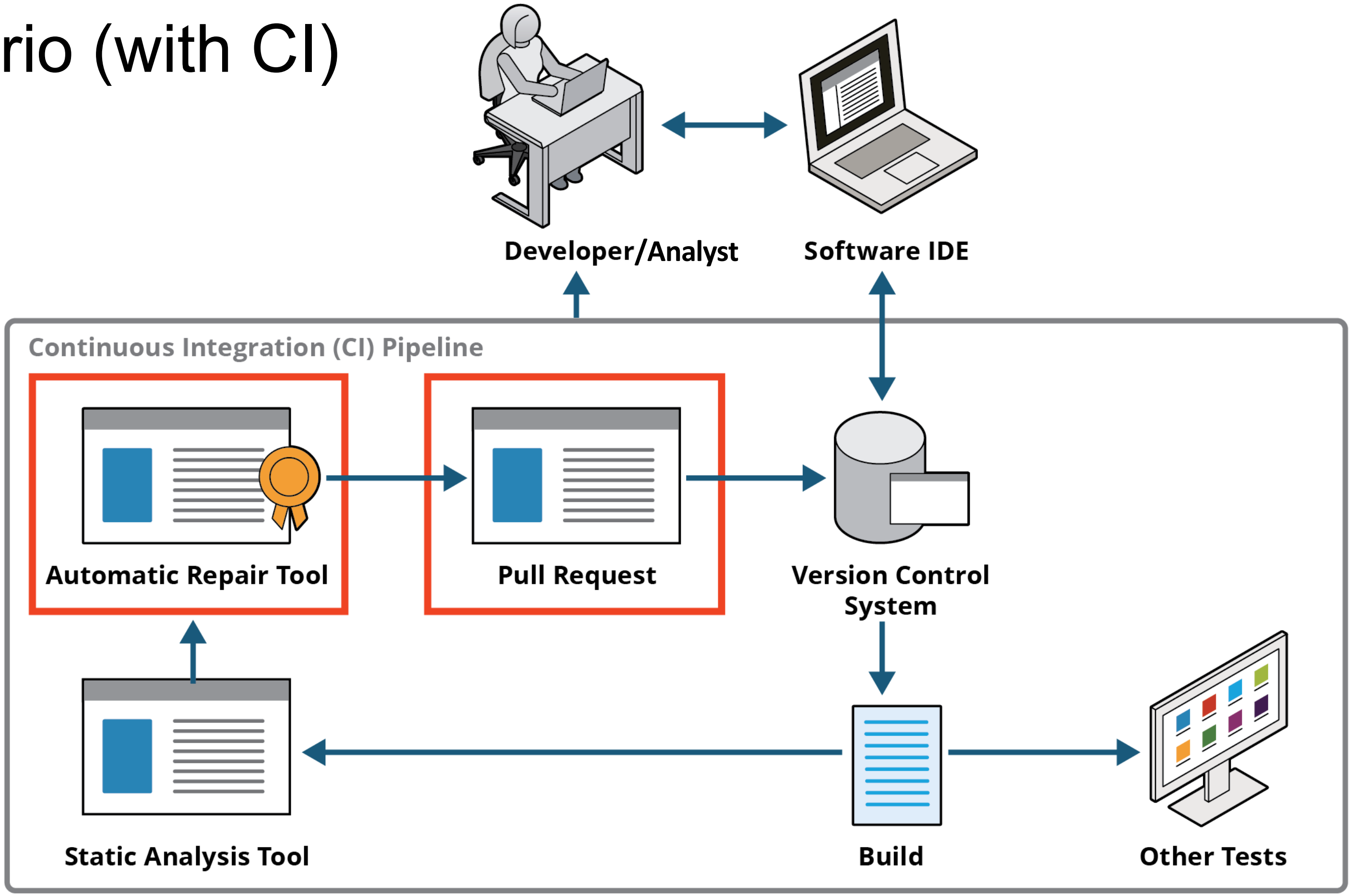
Where to use Redemption in DevSecOps



Usage Dataflow Scenario (Without CI)



Usage Dataflow Scenario (with CI)



Development methods

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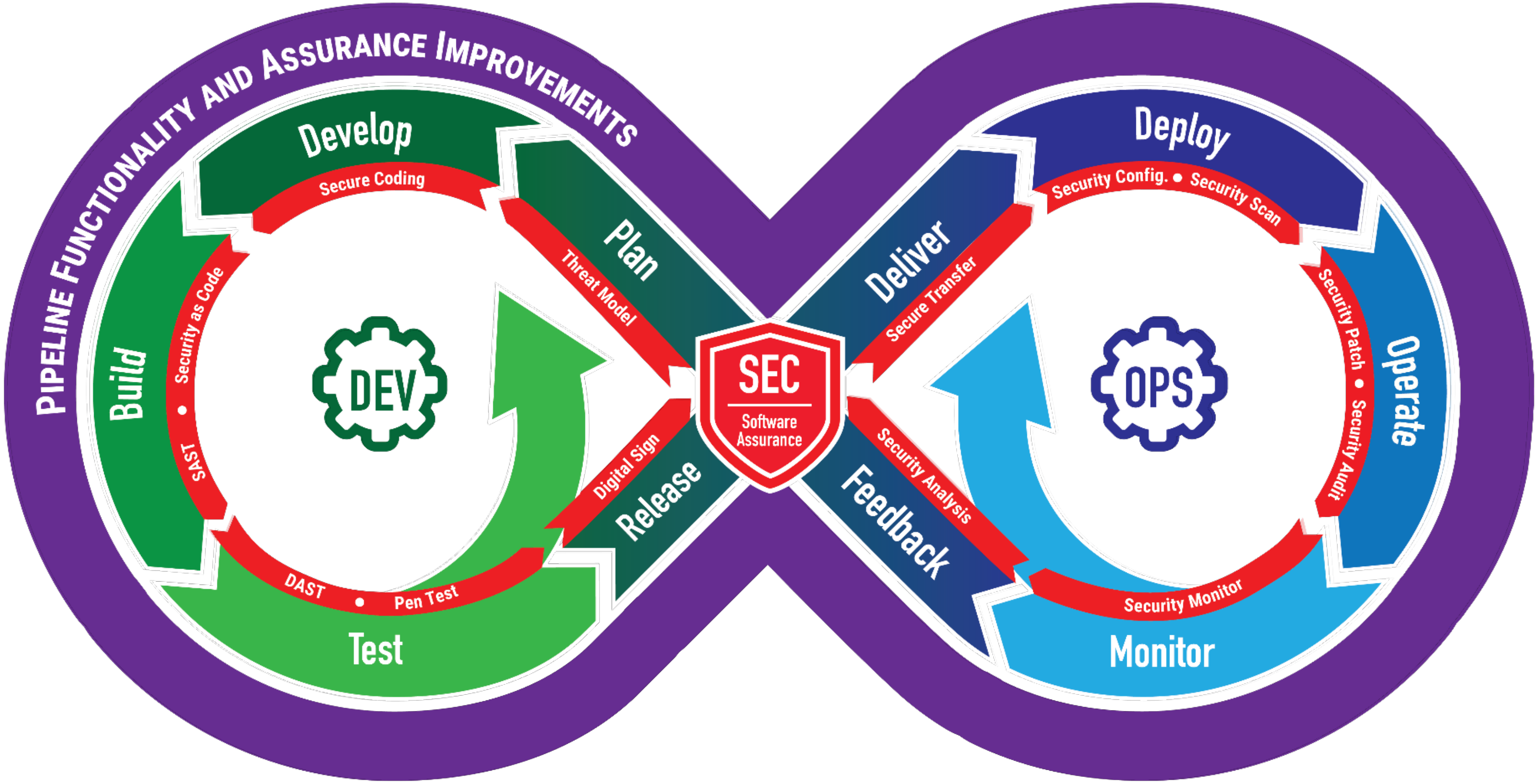
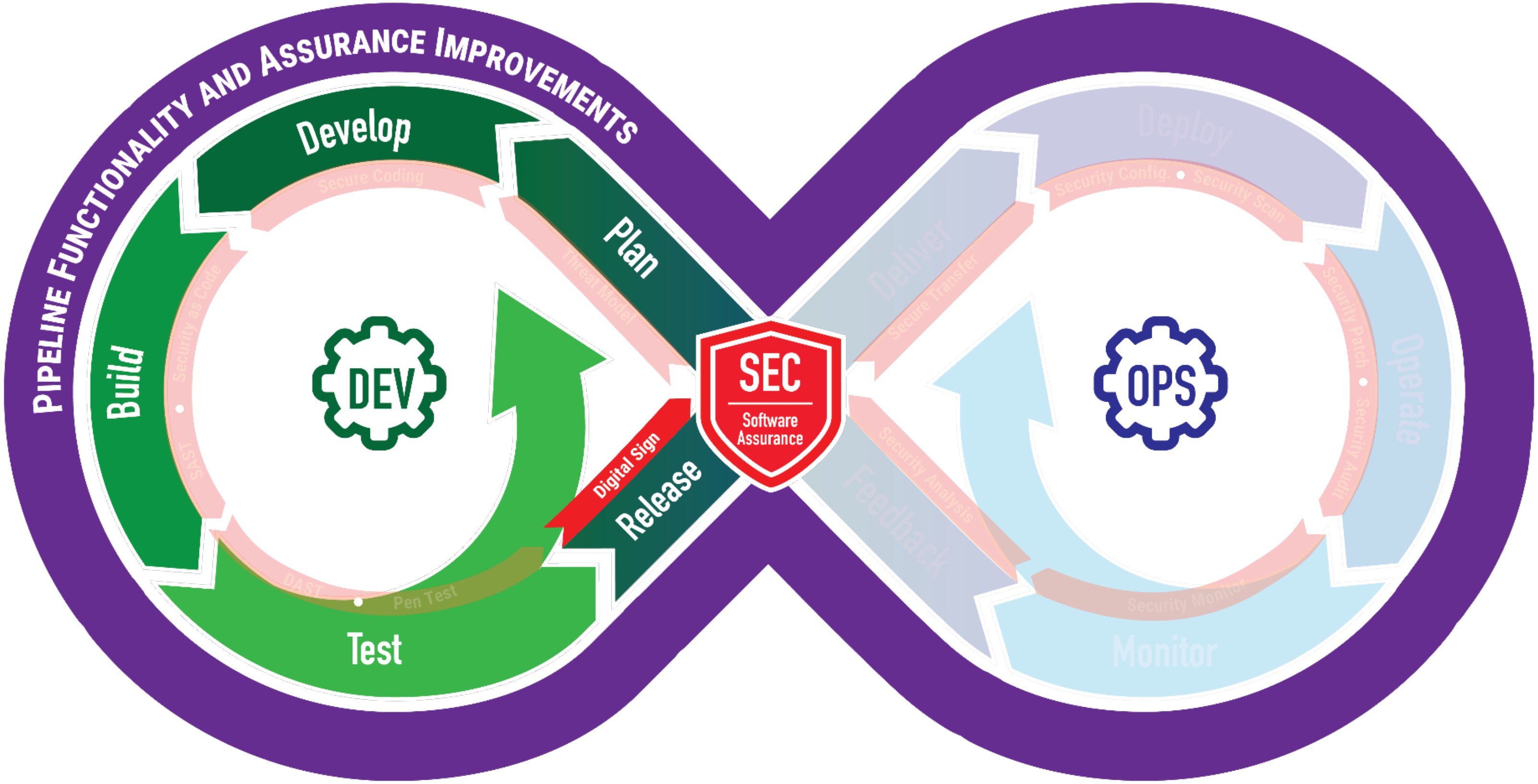
Existing Redemption capabilities that help extending it



- Docker containerized
- Tests (unit, integration, performance, etc.)
- Modular code
- Documentation
- Demos
- Test code + static analysis alerts

Existing Redemption capabilities that help extending it



- Docker containerized
- Tests (unit, integration, performance, etc.)
- Modular code
- Documentation
- Demos
- Test code + static analysis alerts

How to Develop New Repairs

1. Choose code flaw to repair
2. Find or create test cases that need repair
3. Develop repair:
   a. Determine repair site of flawed code using AST (`.json`) and LLVM IR (`.ll`) code
   b. Implement “template” repair algorithm to repair the code
4. Run tests (unit, integration, performance etc.)
5. Iteratively address any bugs
6. Document repair method in `README.md`

Testing & test results

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Verification Theory: Undefined Behavior

Typically, code that violates a CERT rule causes undefined behavior (UB).

- EXP33-C: Reading an uninitialized variable — Read garbage value
- EXP34-C: Dereferencing a null pointer — Crash

Platforms may define platform-specific behaviors.

ISO C only constrains programs without UB.

- UB means the platform may do anything.

International Organization for Standardization, Public domain, via Wikimedia Commons

Compilers may assume UB cannot happen.

- This makes subsequent behavior unpredictable.

Verification

Our repair algorithms do the following:

- Replace code with UB with error-handling code (e.g., termination).
- Possibly run additional operations or checks on code with no UB.
  - These operations or checks must **NOT** change the behavior.

Limitation: Cannot reliably repair code that depends on

- Undefined behavior (UB)
- Performance or timing issues

Components for Testing

SA alerts were produced by running SA tools over the following OSS codebases:

- git (v2.39.0, C)
  Has internal test systems with good test coverage.
  - All tests pass.
- zeek (v5.1.1, C++)
  Has internal test systems with good test coverage.
  - Many tests currently fail (without repair).

We address these CERT guidelines:

- EXP34-C Dereferencing a null pointer
- EXP33-C Reading an uninitialized variable
- MSC12-C Code that is never executed

To test the repair tool, we produced >15,000 SA alerts using the following SA tools:

- cppcheck (v2.9)
- clang-tidy (v15.0.7)
- CERT Rosecheckers

We use an internal CI system to catch regressions.

Tests & Experiments

Regression Testing ← All these tests currently pass

Verifies that each improvement to the tool does not cause bugs or failures to previously-working code.

"Stumble-Through" Tests

Verifies that the repair tool does not crash or hang

- Test the repair tool on all alerts in all codebases.
- The test fails if the tool crashes, hangs, or throws exceptions.

For this test, it does not matter whether the tool correctly repairs any alerts.

Sample Alert Experiments ← Next slide

Ensures repairs are correct

BUT with >15,000 alerts to repair, we cannot test all of them!

For each tool/guideline/codebase,

- Pick N random alerts; N=5 for now. For each alert,
  - Manually check if APR did the right thing:
    - Repaired correctly or correctly refused to repair.
  - Until APR does the Right Thing on >=80% of alerts, Fix APR bugs and re-run experiment.

Integration Experiments ← All these tests currently pass

Verifies that repairs did not change the behavior of code

- Run the repair tool on all codebases.
- Compile the codebases, run their internal testing mechanisms.

The experiment is successful if all codebase-specific internal tests pass.

Performance Experiments ← All timing tests pass for git and zeek*.

Confirms that repairs do not significantly impede performance

- Compile original codebases; run their internal testing mechanism.
  - Measure the time and memory usage of the testing mechanisms.
- Run the repair tool on all codebases.
- Compile the codebases; run their internal testing mechanisms.
  - Measure the time and usage of the testing mechanisms.

Time should be <5% slower. Memory usage should be equivalent.

Recurrence Experiments ← All these tests currently pass

Verifies that repaired alerts are not reported or re-repaired

- Run the repair tool on all codebases.
- Re-run SA tools on all codebases, and compare alerts generated with original alerts.
- The experiment is successful if repaired alerts are no longer reported by an SA tool.
- Re-run the APR tool on the repaired codebase's new alerts.
- Ideally, the APR tool should do nothing since what remains are only the alerts it could not repair.
- If a repaired alert recurs, the APR tool should report it as a false positive.

Test Results for Sample Alert Experiments

	git	git	git	zeek	zeek	zeek
	clang-tidy	cppcheck	rosecheckers	clang-tidy	cppcheck	rosecheckers
EXP33-C	9157	1		5225	29	
EXP34-C	77	20		44	53	14
MSC12-C		25	721		131	480

	git	git	git	zeek	zeek	zeek
	clang-tidy	cppcheck	rosecheckers	clang-tidy	cppcheck	rosecheckers
EXP33-C	100.0% (5/5) [0,0,5,0,0,0,0]	100.0% (1/1) [0,0,1,0,0,0,0]		100.0% (5/5) [1,0,4,0,0,0,0]	100.0% (5/5) [2,0,3,0,0,0,0]	
EXP34-C	100.0% (5/5) [4,0,1,0,0,0,0]	100.0% (5/5) [1,2,2,0,0,0,0]		100.0% (5/5) [4,2,0,0,0,0,0]	100.0% (5/5) [2,2,1,0,0,0,0]	100.0% (5/5) [5,0,0,0,0,0,0]
MSC12-C		20.0% (1/5) [1,0,0,4,0,0,0]			40.0% (2/5) [2,0,0,2,1,0,0]	

Testing Result States for Sample Alert Experiments

Is_satisfactory	Is_repaired	Adjudication	Label
Satisfactory	Repaired	True/suspicious	A
Satisfactory	Repaired	False positive	C
Satisfactory	Not repaired	True/suspicious	None
Satisfactory	Not repaired	False positive	B
Unsatisfactory	Repaired	True/suspicious	F
Unsatisfactory	Repaired	False positive	G
Unsatisfactory	Not repaired	True/suspicious	D
Unsatisfactory	Not repaired	False positive	E

A+B+C = 100%
of all alerts, for 2 rules

G = 0%

Don't break code!

Some repairs require human supervision (accept/reject)

Some repair types are expected correct; others require human supervision

Not always a good idea to make the MSC12-C changes.

- MSC12-C (“Ineffective Code”) is a recommendation, not a rule in the CERT coding standard
- Repairs would not necessarily improve the code.

MSC12-C alerts are flagged for many reasons. For example:

- A label is never accessed via `goto`. Often generated by tools like `yacc(1)`.
  - Removing the label may not change code behavior.
  - The label makes the code simpler. It might represent a node in a state diagram or DFA.

MSC12-C repairs are disabled by default (enabled via environment variable)

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Demo

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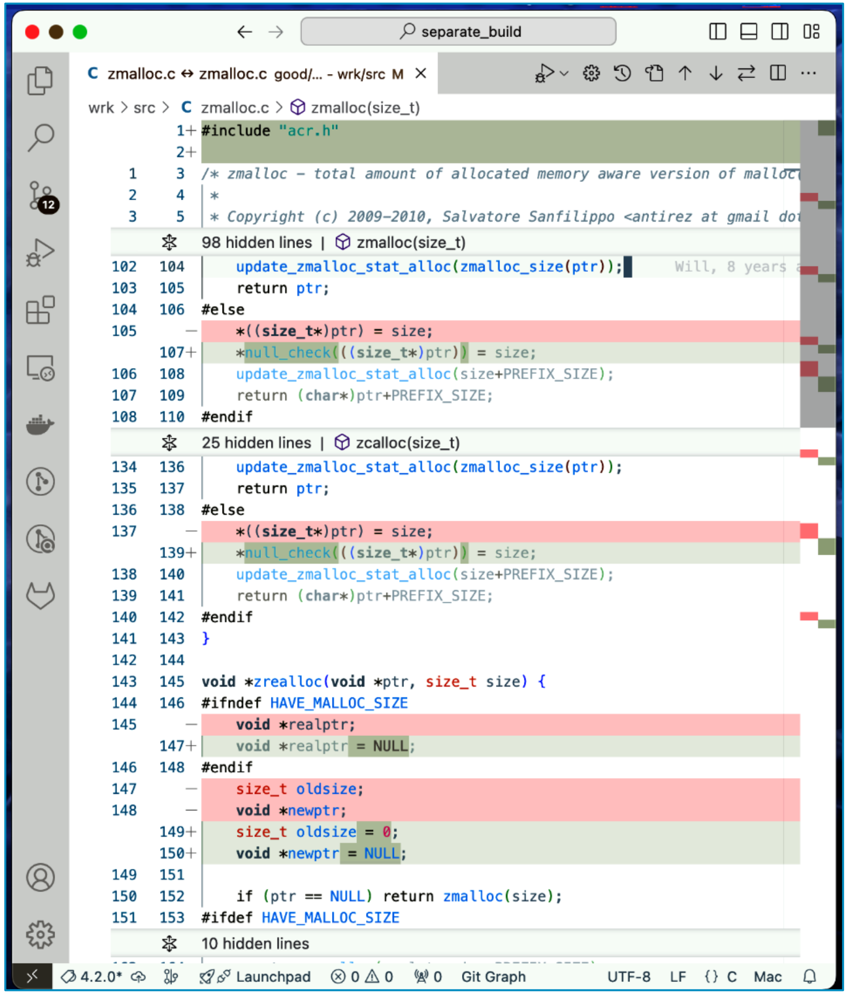
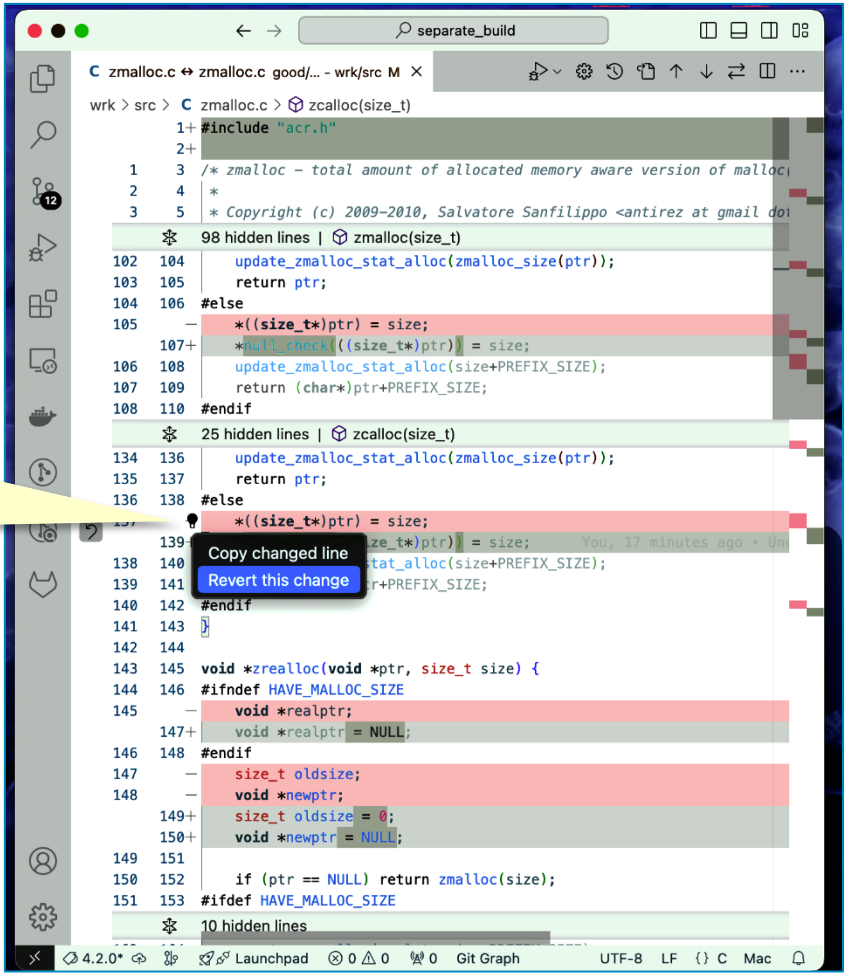
Merging repaired code with original code (1/3)

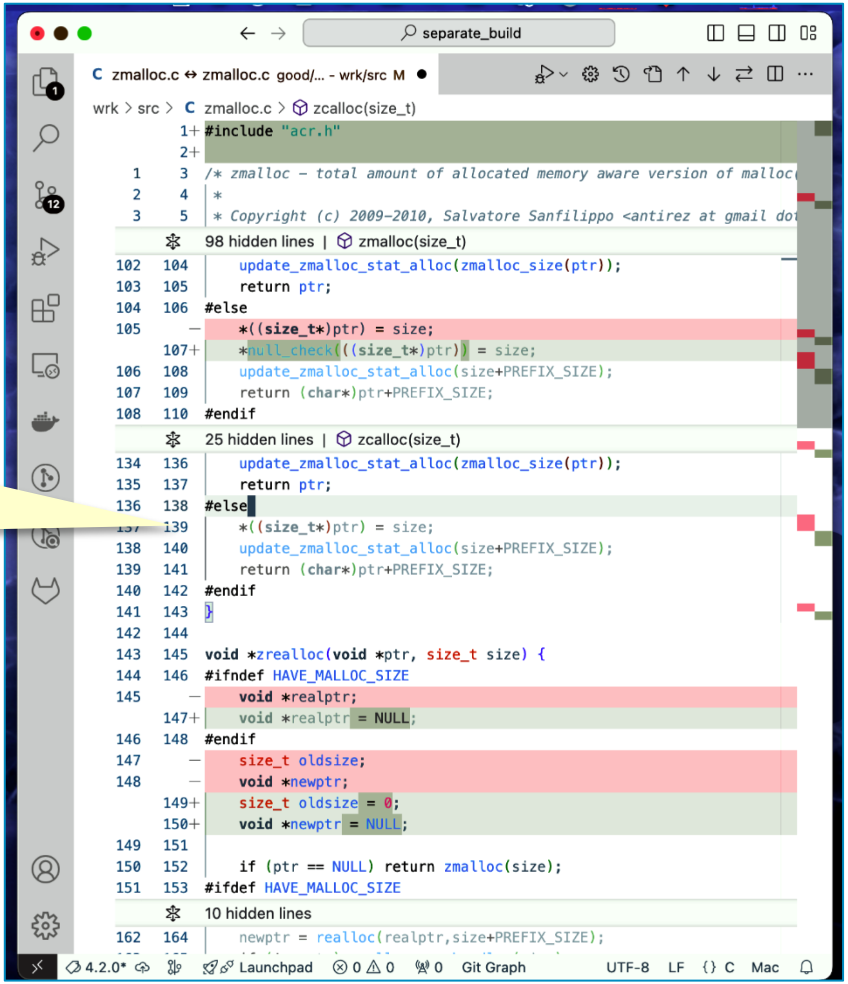


Merging repaired code with original code (2/3)



If you dislike a repair, you can click on a line of code…

Merging repaired code with original code (3/3)



…and revert it!

How can this work be extended to help you?

The Automated Repair Team

Carnegie Mellon University Software Engineering Institute

David Svoboda
Senior Software Security Engineer
Principal Investigator

Will Klieber
Software Security Engineer

Lori Flynn
Senior Software Security Researcher

Joseph Sible
Associate Software Engineer

Michael Duggan
Reverse Engineer

Nicholas H. Reimer
Engineer

Ebonie McNeil
Technical Engagement Lead

Robert Schiela
CSF Deputy Director

Timothy Chick
Technical Manager

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How can this work be extended to help you?

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Potential extensions

1. Add support for more static analysis tools
2. Repairs for more categories of SA alerts
3. Enhance Redemption's capability to work on MS Windows programs
4. Integrate more workforce tools, including IDEs and CI pipelines

Related APR proposal

1. Lori is **looking for DoD/govt. collaborators** on her research project proposal involving **learning-based APR** (proposal due 11/11)
2. What APR feature(s) would make your organization likely to use it?
3. What are barriers to APR use at your org?

Contact
David Svoboda svoboda@sei.cmu.edu
Lori Flynn lflynn@sei.cmu.edu

Achievements highlights

- Developed APR tool that repairs 3 CERT coding rules and 3 mapped CWEs
- Tested tool on OSS codebases and collaborator code, with successful repairs
- Published code, OSS test results, use documentation, demo videos, presentations
- Published dataset for APR research & testing
- Research paper (pending acceptance)
- Redemption project page (links to tool, dataset, presentations, videos, paper, etc.)
- Redemption tool on GitHub

Static Analysis-Targeted Automated Repair to Secure Code and Reduce Effort

BACKUP SLIDES

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Command Line Tool – Source Codebase

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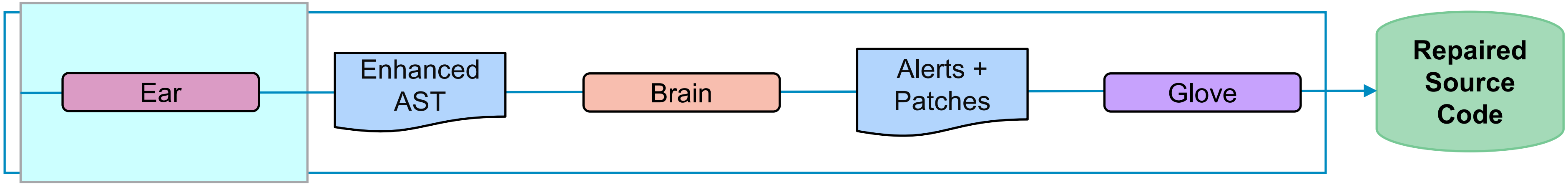
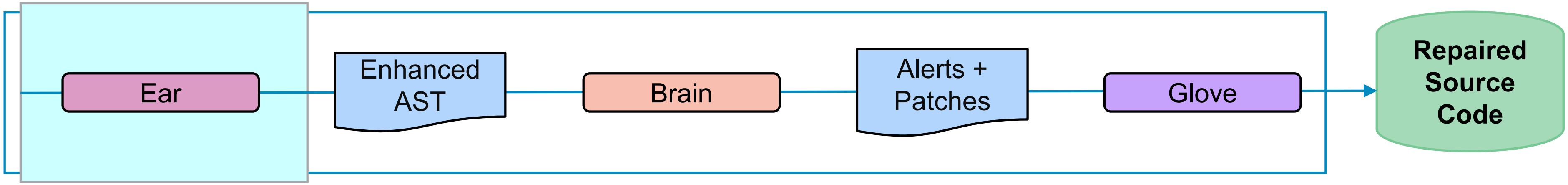


Inputs

C/C++ source file(s) in codebase

```

int flag = 0;

#define NULL 0

/* Should return 0 upon error */
unsigned int foo1(int* p) {
    if (flag) {
      return 0;
    }
    return *p;
}

/* Should return -1 upon error */
int foo2(int* p) {
    if (flag) {
      return -1;
    }
    return *p;
}

/* Should return NULL upon error */
```

Command Line Tool – Build Commands



Build Commands

Each command includes -D/-U macro definitions and other switches to let Clang parse each source code file.

```
cc -DDEBUG=0 -I/usr/local/include  -O2 -Wall  -c pgm.c -o pgm.o
```

Command Line Tool – Static Analysis Alerts

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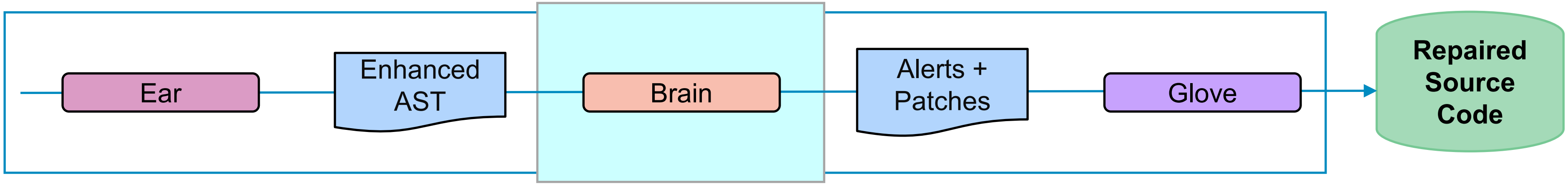

Next input: distinct SA Tool Alerts

Each alert contains the following:

- CERT rule
- Location where rule is being violated (e.g., source code path, line number, column number, end-line number, end column number)
- Message


```xml
<?xml version="1.0" encoding="UTF-8"?>
<results version="2">
    <cppcheck version="2.9"/>
    <errors>
        <error id="unreadVariable" severity="style" msg="Variable &apos;InF&apos; is assigned a
            <location file="/datasets/dos2unix/common.c" line="1331" column="12"/>
            <symbol>InF</symbol>
        </error>
        <error id="unreadVariable" severity="style" msg="Variable &apos;InF&apos; is assigned a
            <location file="/datasets/dos2unix/common.c" line="1373" column="12"/>
            <symbol>InF</symbol>
        </error>
        <error id="unreadVariable" severity="style" msg="Variable &apos;conversion_error&apos;
            <location file="/datasets/dos2unix/common.c" line="2549" column="28"/>
            <symbol>conversion_error</symbol>
        </error>
        <error id="uninitvar" severity="error" msg="Uninitialized variable: lpMsgBuf" verbose="
            <location file="/datasets/dos2unix/common.c" line="117" column="19"/>
            <symbol>lpMsgBuf</symbol>
        </error>
        <error id="ConfigurationNotChecked" severity="information" msg="Skipping configuration &
```

Command Line Tool – Repaired Source Code

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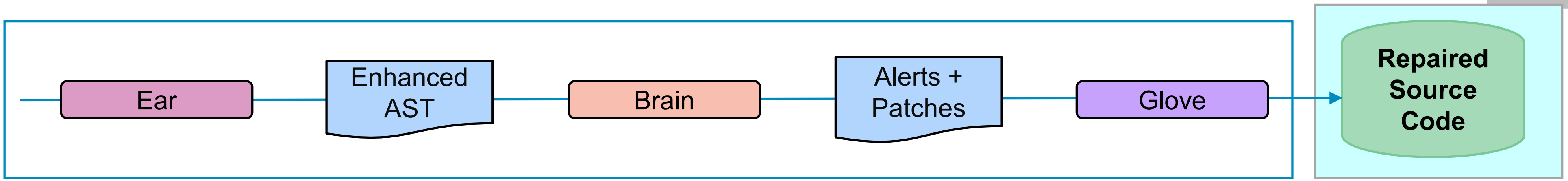


Outputs

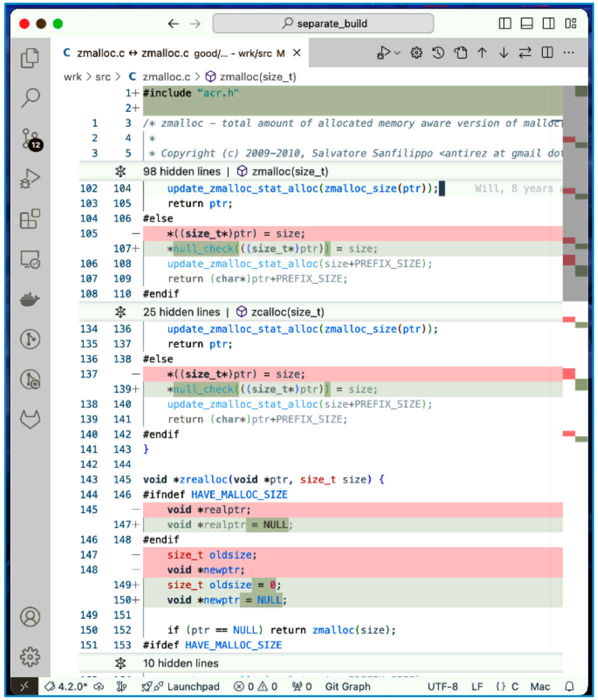
For each SA alert from input

- Patch to repair the alert.

  OR

- Explain in a text message why it cannot be repaired.

All patches should be independent (i.e., they repair distinct regions of code)



Handling Errors

What should our tool instruct the program to do when it discovers an error (e.g., integer overflow) and `/* Handle error */` is not sufficient?

Some choices include

- `return;`
- `return NULL;  /* or EOF */`
- `abort();`
- `signal(SIGINT, handler);`

The right choice depends on the code. How does the function currently handle other errors?