Cracking Sendmail crackaddr

Still a challenge for automated program analysis?

Name Lastname < *name@mail.org* > ()()()()()()()()()() . . . ()()()

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Sendmail crackaddr Bug

Discovered 2003 by Mark Dowd

Buffer overflow in an email address parsing function of Sendmail. Consists of a parsing loop using a state machine. ~500 LOC

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∼50 LOC

Since then . . .

Various talks at security conferences and a paper presenting a static analysis of the example. The solutions however required manual specification of the loop invariant.

Backstory

Halvar likes to challenge people!

Halvar gave us the challenge some years ago:
“The tool should automatically (i.e. without hints provided by the user) show that the vulnerable version has a bug and the fixed version is safe.”

We were sure our analyzer could not yet handle it so did not look into it.

Last year we gave it a try and it suddenly worked :).

Sendmail Bug (simplified)

Let's see the bug details ...

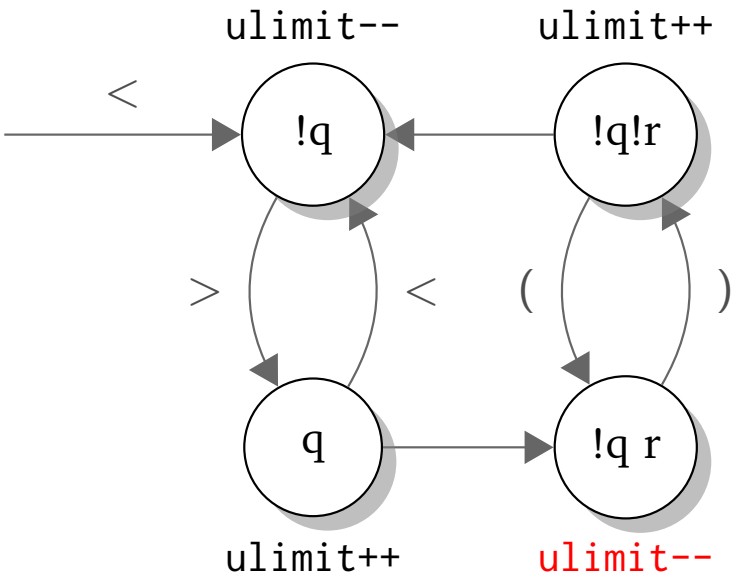
Sendmail Bug Code

```
1  #define BUFFERSIZE 200
2  #define TRUE 1
3  #define FALSE 0
4  int copy_it (char *input, unsigned int length) {
5      char c, localbuf[BUFFERSIZE];
6      unsigned int upperlimit = BUFFERSIZE - 10;
7      unsigned int quotation = roundquote = FALSE;
8      unsigned int inputIndex = outputIndex = 0;
9      while (inputIndex < length) {
10         c = input[inputIndex++];
11         if ((c == '<') && (!quotation)) {
12             quotation = TRUE; upperlimit--;
13         }
14         if ((c == '>') && (quotation)) {
15             quotation = FALSE; upperlimit++;
16         }
17         if ((c == '(') && (!quotation) && !roundquote) {
18             roundquote = TRUE; upperlimit--; // decrementation was missing in bug
19         }
20         if ((c == ')') && (!quotation) && roundquote) {
21             roundquote = FALSE; upperlimit++;
22         }
23         // If there is sufficient space in the buffer, write the character.
24         if (outputIndex < upperlimit) {
25             localbuf[outputIndex] = c;
26             outputIndex++;
27         }
28     }
29     if (roundquote) {
30         localbuf[outputIndex] = ')'; outputIndex++; }
31     if (quotation) {
32         localbuf[outputIndex] = '>'; outputIndex++; }
33 }
```

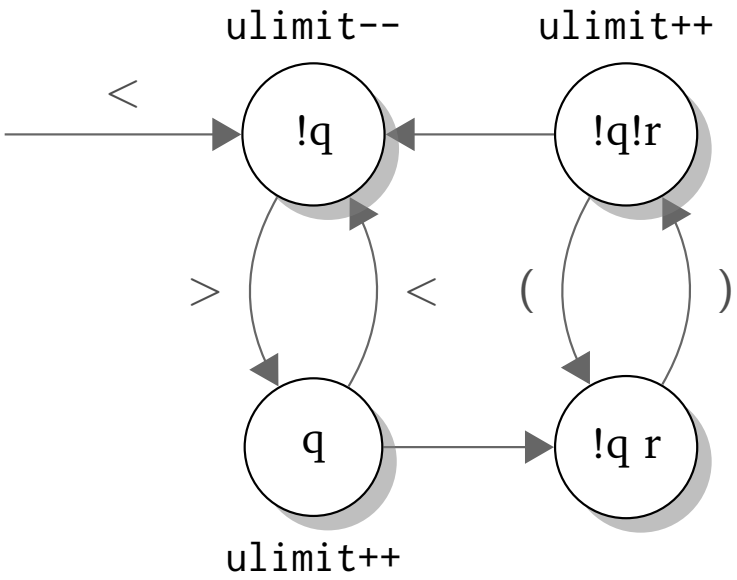
State Machine of Parser

We need to verify that `outputIndex < upperlimit < BUFFERSIZE` always holds in the good version.

Good:



Bad:



In the bad version `upperlimit` can be steadily incremented and a write outside of the stack allocated buffer can be triggered.

Sendmail Bug Analysis

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- a naïve state space exploration in worst case would need to visit around $2 * 5^{201} \approx 2^{664}$ paths to find the bug!

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- a naïve state space exploration in worst case would need to visit around $2 * 5^{201} \approx 2^{664}$ paths to find the bug!
- to naïvely prove the absence of the bug we would need to test all the possible input strings
  e.g. with lengths from 0 to 65535 = UINT_MAX
  $\rightsquigarrow$ around $10^{65535} \approx 2^{217702}$ paths that need to be tested!

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- abstraction might introduce imprecision and false positives

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On the other hand . . . !

- finding the bug requires just finding 1 of the faulty paths!
- smarter tools combine many paths together and reason about all of them at once (abstraction)!

But unfortunately

- abstraction might introduce imprecision and false positives
- $\leadsto$ the non-vulnerable version is flagged as vulnerable, too, by an imprecise analyzer

Abstraction Techniques

Let's introduce one abstraction technique in more detail ...

Abstract Interpretation Primer

Static program analysis using abstract interpretation

- use abstract domains to over-approximate concrete states
- abstract transformers simulate the concrete program semantics on the abstract state
- perform a fixpoint computation to infer invariants for each program point
- merge over all paths over-approximates all possible program executions (soundness)
- precision depends on the abstraction (completeness)
- for termination widening is necessary (introduces imprecision)

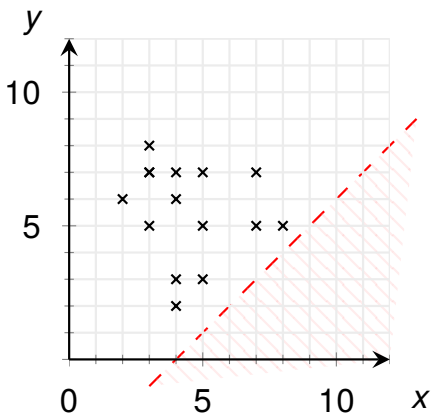
Abstraction Examples

Some examples of concrete values and their abstractions ...

Sets of Concrete Values and their Abstractions

Concrete Points

$\pm x = c$

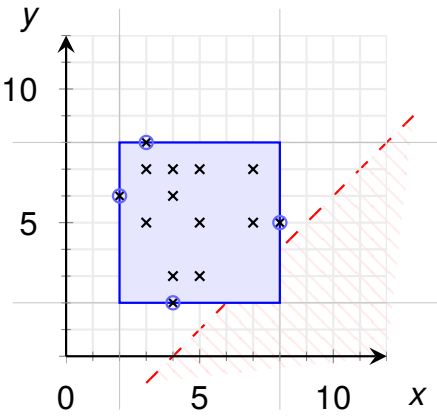


Constraints:

$$\begin{array}{l} x = 2 \wedge y = 6 \\ \vee\, x = 3 \wedge y = 5 \\ \vee\, x = 3 \wedge y = 7 \\ \vee\, x = 3 \wedge y = 8 \\ \vee\ \ldots \end{array}$$

Intervals

$\pm x \leq c$

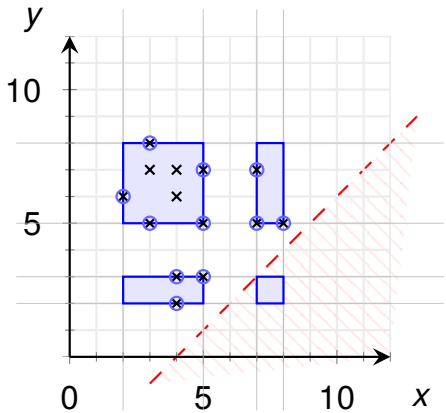


Constraints:

$$\begin{array}{l} 2 \leq x \wedge x \leq 8 \\ \wedge\, 2 \leq y \wedge y \leq 8 \end{array}$$

Interval Sets

$\bigvee_i (l_i \leq x \wedge x \leq u_i)$

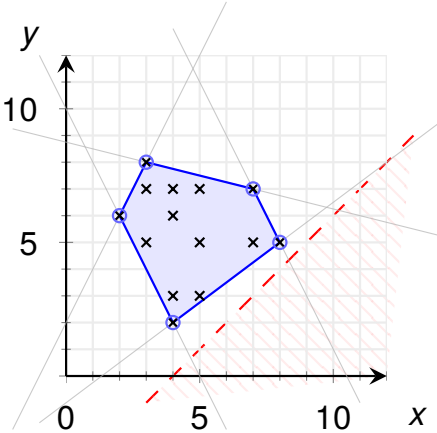


Constraints:

$$\begin{array}{l} 2 \leq x \wedge x \leq 5 \\ \vee\, 7 \leq x \wedge x \leq 8 \\ \vee\, 2 \leq y \wedge y \leq 3 \\ \vee\, 5 \leq y \wedge y \leq 8 \end{array}$$

Polyhedra

$\sum_i a_i x_i \leq c$



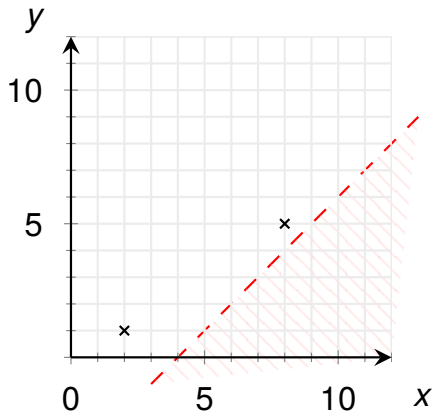
Constraints:

$$\begin{array}{l} 2x - y \leq -2 \\ \wedge\ -2x - y \leq -10 \\ \wedge\, 2x + y \leq -21 \\ \wedge\, 3x + 4y \leq 4 \\ \wedge\, x + 4y \leq 35 \end{array}$$

Sets of Concrete Values and their Abstractions

Concrete Points

$\pm x = c$

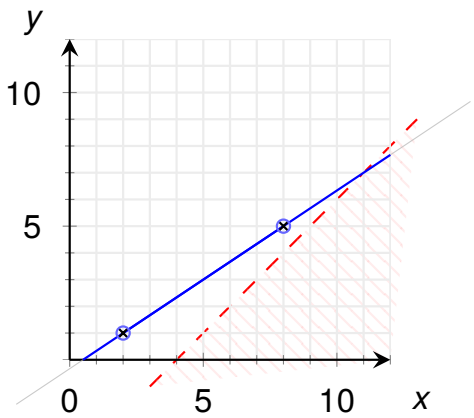


Constraints:

$x = 2 \wedge y = 1$
$\vee\, x = 8 \wedge y = 5$

Affine Equalities

$\sum_i a_i x_i = c$

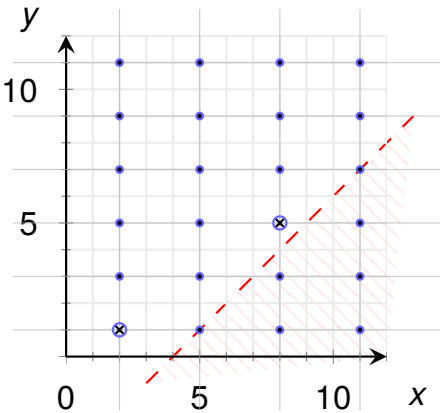


Constraints:

$2x - 3y = 3$

Congruences

$x \equiv b \pmod{a}$



Constraints:

$x \equiv 2 \pmod 3$
$\wedge\, y \equiv 1 \pmod 2$

Operations on Abstractions

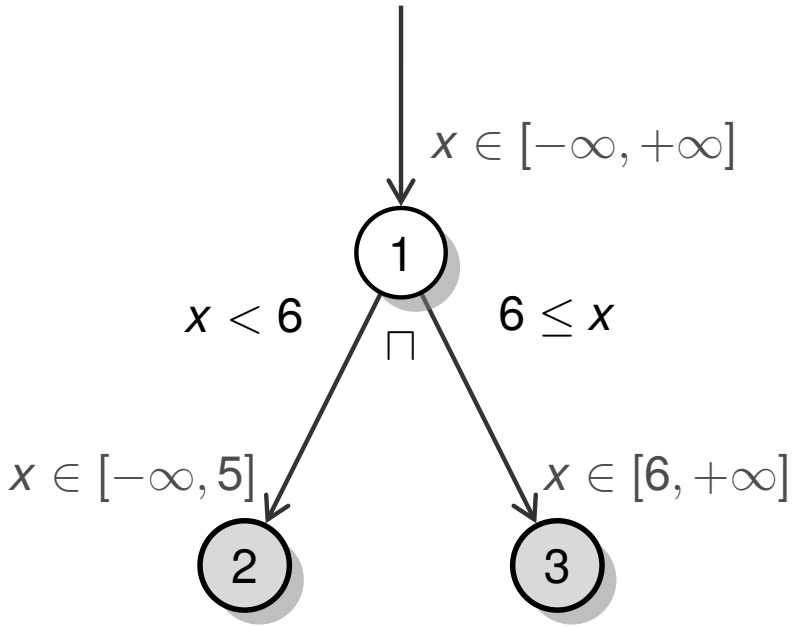
Some examples of operations on abstractions ...

Some Operations on Intervals

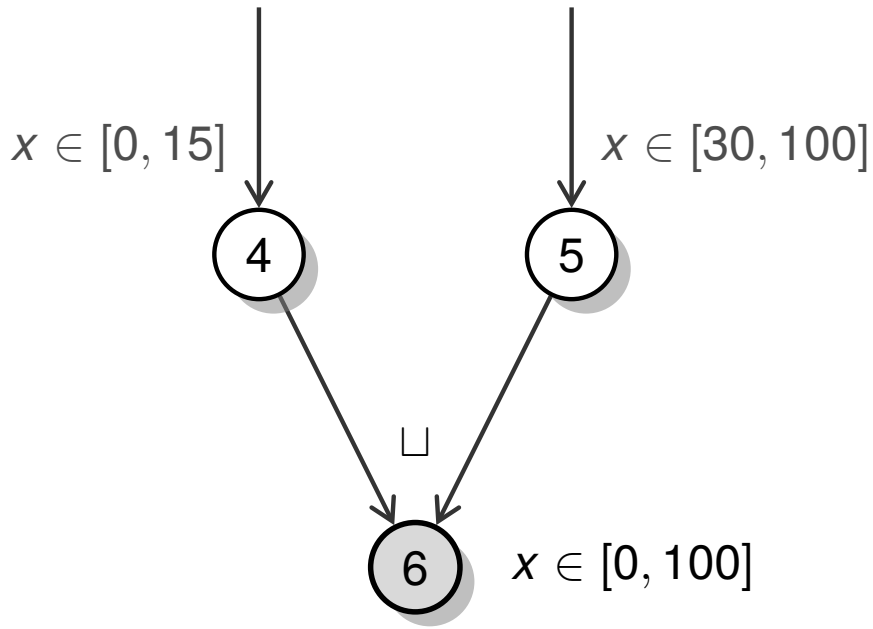
Arithmetics:

$$[0, 100] + [1, 2] = [1, 102]$$
$$[0, 100] - [1, 2] = [-2, 99]$$

Tests or Assumptions, Meet $\sqcap$



Merge of paths, Join $\sqcup$



Operations on Abstractions

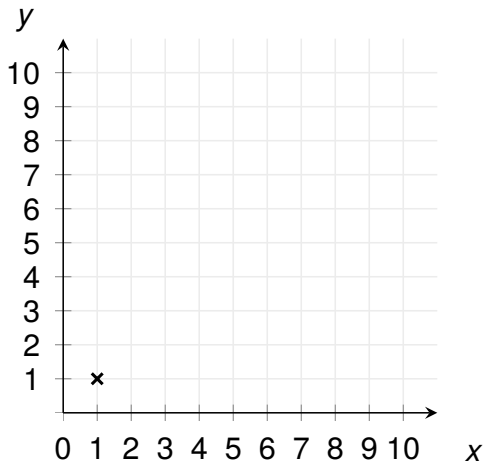
Widening and Narrowing

To analyze loops in less steps than the real iterations count ...
and especially always analyze loops in finitely many steps.

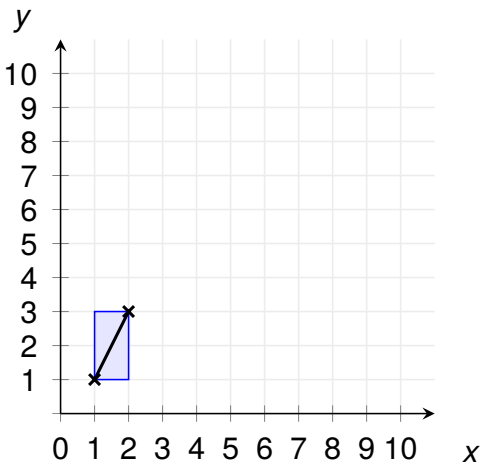
Termination of Analysis!

Widening and Narrowing on Intervals

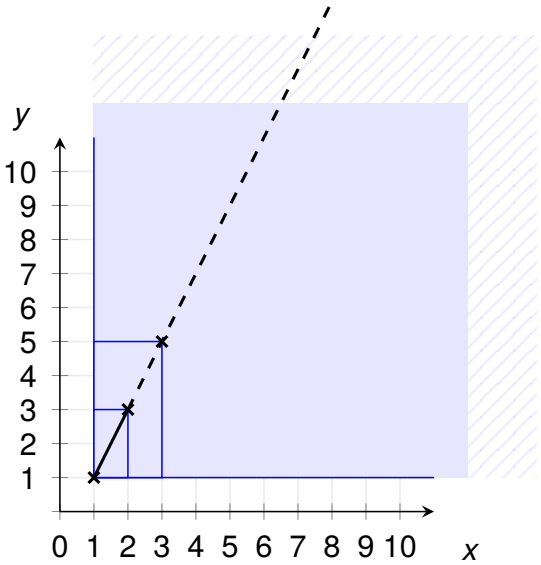
```
int x = 1;
int y = 1;
// shown x, y values
// are at loop head
while (x <= 6) {
  x = x + 1;
  y = y + 2;
}
```



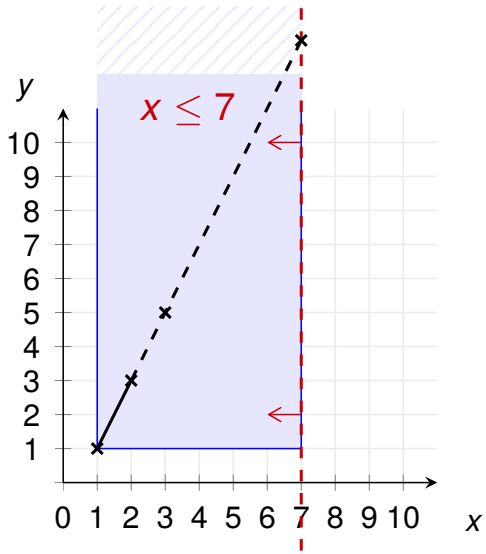
1^{st} Iteration



2^{nd} Iteration: $\sqcup$ join



3^{rd} Iteration: ∇ widening



4^{th} Iteration: Δ narrowing

Abstract Interpretation

Good introduction and overview material:

- A gentle Introduction to Formal Verification of Computer Systems by Abstract Interpretation, P. Cousot and R. Cousot, 2010
- Abstract Interpretation Based Formal Methods and Future Challenges, P. Cousot, 2001
- Abstract Interpretation: Past, Present and Future, P. Cousot and R. Cousot, 2014

Static Binary Analyzer

Now to our Analyzer “Bindead” ...

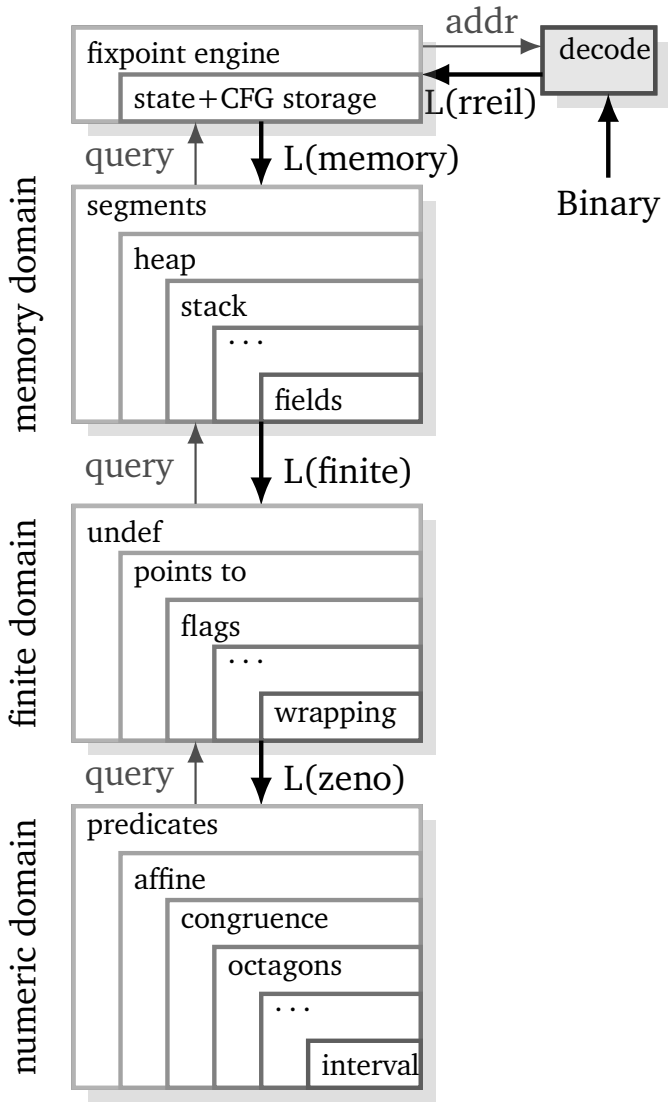
Analyzer Features

Analysis of binaries using abstract interpretation

- analyze machine code from disassembled executables
- translate machine code to intermediate language (RREIL)
- abstract transformers for instruction semantics of RREIL
- perform a reachability analysis to infer jump targets and
- use abstract domains to infer memory bounds and flag out-of-bounds accesses

Project page: https://bitbucket.org/mihaila/bindead

Analyzer Overview



- disassembler frontend produces RREIL for the analysis
- RREIL gets transformed to simpler languages for the abstract domains
- fixpoint and disassembly process are intertwined
- modular construction using co-fibered abstract domains
- domains stack is a partially reduced product of domains
- for interprocedural analysis we use either call-string or a summarization approach

Sendmail Problem for Abstract Interpretation

... and what is needed to solve the Sendmail Example

Sendmail Code Revisited (Problems and Ideas)

```
#define BUFFERSIZE 200
#define TRUE 1
#define FALSE 0     prove memory correctnes for all possible concrete inputs!
int copy_it (char *input, unsigned int length) { *input[i] ∈ [−∞, +∞], length ∈ [0, +∞]
    char c, localbuf[BUFFERSIZE];
    unsigned int upperlimit = BUFFERSIZE - 10;
    unsigned int quotation = roundquote = FALSE;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) {
        c = input[inputIndex++];
        if ((c == '<') && (!quotation)) {
            quotation = TRUE; upperlimit--;
        }
        if ((c == '>') && (quotation)) {
            quotation = FALSE; upperlimit++;
        }
        if ((c == '(') && (!quotation) && !roundquote) {
            roundquote = TRUE; upperlimit--; // decrementation was missing in bug
        }
        if ((c == ')') && (!quotation) && roundquote) {
            roundquote = FALSE; upperlimit++;
        }
        // If there is sufficient space in the buffer, write the character.
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c; prove that outputIndex < BUFFERSIZE holds
            outputIndex++;
        }
    }
    if (roundquote) { prove that invariant outputIndex < BUFFERSIZE holds
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (quotation) { prove that invariant outputIndex < BUFFERSIZE holds
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

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#define BUFFERSIZE 200
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    char c, localbuf[BUFFERSIZE];
    unsigned int upperlimit = BUFFERSIZE - 10;
    unsigned int quotation = roundquote = FALSE;
    unsigned int inputIndex = outputIndex = 0;   inputIndex ∈ [0, 0], outputIndex ∈ [0, 0]
    while (inputIndex < length) {
        c = input[inputIndex++];    inputIndex ∈ [1, 1]
        if ((c == '<') && (!quotation)) {
            quotation = TRUE; upperlimit--;
        }
        if ((c == '>') && (quotation)) {
            quotation = FALSE; upperlimit++;
        }
        if ((c == '(') && (!quotation) && !roundquote) {
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            roundquote = FALSE; upperlimit++;
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        // If there is sufficient space in the buffer, write the character.
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c; prove that outputIndex < BUFFERSIZE holds
            outputIndex++;   outputIndex ∈ [1, 1]
        }    ⊔ : outputIndex ∈ [0, 1]
    }
    if (roundquote) { prove that invariant outputIndex < BUFFERSIZE holds
        localbuf[outputIndex] = ')'; outputIndex++; }
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    unsigned int upperlimit = BUFFERSIZE - 10;
    unsigned int quotation = roundquote = FALSE;
    unsigned int inputIndex = outputIndex = 0;   inputIndex ∈ [0, 0], outputIndex ∈ [0, 0]
    while (inputIndex < length) { widening ∇: inputIndex ∈ [0, +∞], outputIndex ∈ [0, +∞]
        c = input[inputIndex++];    inputIndex ∈ [1, 1]
        if ((c == '<') && (!quotation)) {
            quotation = TRUE; upperlimit--;
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        // If there is sufficient space in the buffer, write the character.
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c; prove that outputIndex < BUFFERSIZE holds
            outputIndex++;   outputIndex ∈ [1, 1]
        }    ⊔ : outputIndex ∈ [0, 1]
    }
    if (roundquote) { prove that invariant outputIndex < BUFFERSIZE holds
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}
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Sendmail Code Revisited (Problems and Ideas)

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#define BUFFERSIZE 200
#define TRUE 1
#define FALSE 0
int copy_it (char *input, unsigned int length) {
    char c, localbuf[BUFFERSIZE];
    unsigned int upperlimit = BUFFERSIZE - 10; upperlimit ∈ [190, 190]
    unsigned int quotation = roundquote = FALSE;
    unsigned int inputIndex = outputIndex = 0;  inputIndex ∈ [0, 0], outputIndex ∈ [0, 0]
    while (inputIndex < length) { widening ∇: inputIndex ∈ [0, +∞], outputIndex ∈ [0, +∞]
        c = input[inputIndex++];   inputIndex ∈ [1, 1]
        if ((c == '<') && (!quotation)) {
            quotation = TRUE; upperlimit--;
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        }
        // If there is sufficient space in the buffer, write the character.
        if (outputIndex < upperlimit) { use threshold outputIndex < upperlimit for widening!
            localbuf[outputIndex] = c; prove that outputIndex < BUFFERSIZE holds
            outputIndex++;  outputIndex ∈ [1, 1]
        }   ⊔ : outputIndex ∈ [0, 1]
    }
    if (roundquote) { prove that invariant outputIndex < BUFFERSIZE holds
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            localbuf[outputIndex] = c;
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    unsigned int quotation = roundquote = FALSE;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) { widening ▽ removes bounds: upperlimit ∈ [−∞, +∞]
        c = input[inputIndex++];   use relation with flag variables quotation and roundquote
        if ((c == '<') && (!quotation)) { to keep upperlimit bounded!
            quotation = TRUE; upperlimit--;
        } ⊔ : upperlimit ∈ [189, 190]
        if ((c == '>') && (quotation)) {
            quotation = FALSE; upperlimit++;
        } ⊔ : upperlimit ∈ [189, 191]
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#define TRUE 1
#define FALSE 0
int copy_it (char *input, unsigned int length) {
    char c, localbuf[BUFFERSIZE];
    unsigned int upperlimit = BUFFERSIZE - 10;
    unsigned int quotation = roundquote = FALSE; quotation ∈ [0, 0], roundquote ∈ [0, 0]
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) {
        c = input[inputIndex++];
        if ((c == '<') && (!quotation)) {
            quotation = TRUE; upperlimit--;
        } ⊔ : quotation ∈ [0, 1]
        if ((c == '>') && (quotation)) {
            quotation = FALSE; upperlimit++;
        } ⊔ : quotation ∈ [0, 1]
        if ((c == '(') && (!quotation) && !roundquote) {
            roundquote = TRUE; upperlimit--; // decrementation was missing in bug
        } ⊔ : quotation ∈ [0, 1], roundquote ∈ [0, 1]
        if ((c == ')') && (!quotation) && roundquote) {
            roundquote = FALSE; upperlimit++;
        } ⊔ : quotation ∈ [0, 1], roundquote ∈ [0, 1]
        // If there is sufficient space in the buffer, write the character.
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (roundquote) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (quotation) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Sendmail Code Revisited (Problems and Ideas)

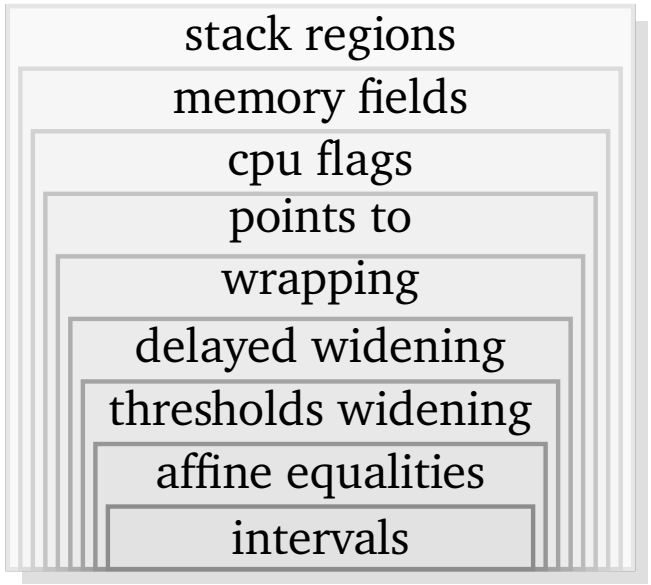
```
#define BUFFERSIZE 200
#define TRUE 1
#define FALSE 0
int copy_it (char *input, unsigned int length) {
    char c, localbuf[BUFFERSIZE];
    unsigned int upperlimit = BUFFERSIZE - 10;
    unsigned int quotation = roundquote = FALSE; quotation ∈ [0, 0], roundquote ∈ [0, 0]
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) { ▽ removes bounds: quotation ∈ [0, +∞], roundquote ∈ [0, +∞]
        c = input[inputIndex++];
        if ((c == '<') && (!quotation)) {
            quotation = TRUE; upperlimit--;
        } ⊔ : quotation ∈ [0, 1]
        if ((c == '>') && (quotation)) {
            quotation = FALSE; upperlimit++;
        } ⊔ : quotation ∈ [0, 1]
        if ((c == '(') && (!quotation) && !roundquote) {
            roundquote = TRUE; upperlimit--; // decrementation was missing in bug
        } ⊔ : quotation ∈ [0, 1], roundquote ∈ [0, 1]
        if ((c == ')') && (!quotation) && roundquote) {
            roundquote = FALSE; upperlimit++;
        } ⊔ : quotation ∈ [0, 1], roundquote ∈ [0, 1]
        // If there is sufficient space in the buffer, write the character.
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (roundquote) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (quotation) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Sendmail Code Revisited (Problems and Ideas)

```
#define BUFFERSIZE 200
#define TRUE 1
#define FALSE 0
int copy_it (char *input, unsigned int length) {
    char c, localbuf[BUFFERSIZE];
    unsigned int upperlimit = BUFFERSIZE - 10;
    unsigned int quotation = roundquote = FALSE; quotation ∈ [0, 0], roundquote ∈ [0, 0]
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) { ▽ removes bounds: quotation ∈ [0, +∞], roundquote ∈ [0, +∞]
        c = input[inputIndex++];   delay widening until flags and relations stable!
        if ((c == '<') && (!quotation)) {
            quotation = TRUE; upperlimit--;
        } ⊔ : quotation ∈ [0, 1]
        if ((c == '>') && (quotation)) {
            quotation = FALSE; upperlimit++;
        } ⊔ : quotation ∈ [0, 1]
        if ((c == '(') && (!quotation) && !roundquote) {
            roundquote = TRUE; upperlimit--; // decrementation was missing in bug
        } ⊔ : quotation ∈ [0, 1], roundquote ∈ [0, 1]
        if ((c == ')') && (!quotation) && roundquote) {
            roundquote = FALSE; upperlimit++;
        } ⊔ : quotation ∈ [0, 1], roundquote ∈ [0, 1]
        // If there is sufficient space in the buffer, write the character.
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (roundquote) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (quotation) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Stack of Required Domains

To verify the code (disassembled from the binary) we used these abstract domains:



Adding more domains (e.g. predicates, congruences, octagons, polyhedra, interval-sets) improves the precision of the inferred bounds after widening but is not necessary to verify the code.

Solving Sendmail with Abstract Interpretation

A Walkthrough the Sendmail Analysis using Bindead

Analysis Steps and inferred Values

Lets analyze the code!

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) {
        c = input[inputIndex++];
        if (... && (!q)) {
            q = 1; upperlimit--;
        }
        if (... && (q)) {
            q = 0; upperlimit++;
        }
        if (... && (!q) && !rq) {
            rq = TRUE; upperlimit--;
        }
        if (... && (!q) && rq) {
            rq = 0; upperlimit++;
        }
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

1st iteration: infers the affine equality between the variables: $upperlimit + q + rq = 190$

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) { inputIndex = 0, outputIndex = 0, length ∈ [−∞, +∞]
        c = input[inputIndex++];
        if (... && (!q)) { upperlimit = 190, q = 0, rq = 0
            q = 1; upperlimit--;
        }   ⊔ : upperlimit + q = 190, upperlimit ∈ [189, 190], q ∈ [0, 1]
        if (... && (q)) {
            q = 0; upperlimit++;
        }
        if (... && (!q) && !rq) {
            rq = TRUE; upperlimit--;
        }
        if (... && (!q) && rq) {
            rq = 0; upperlimit++;
        }
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

1st iteration: infers the affine equality between the variables: $upperlimit + q + rq = 190$

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) {
        c = input[inputIndex++];
        if (... && (!q)) {
            q = 1; upperlimit--;
        }
        if (... && (q)) { upperlimit = 189, q = 1, rq = 0
            q = 0; upperlimit++;
        }   ⊔ : upperlimit + q = 190, upperlimit ∈ [189, 190], q ∈ [0, 1]
        if (... && (!q) && !rq) {
            rq = TRUE; upperlimit--;
        }
        if (... && (!q) && rq) {
            rq = 0; upperlimit++;
        }
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

1st iteration: infers the affine equality between the variables: $upperlimit + q + rq = 190$

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) {
        c = input[inputIndex++];
        if (... && (!q)) {
            q = 1; upperlimit--;
        }
        if (... && (q)) {
            q = 0; upperlimit++;
        }
        if (... && (!q) && !rq) { upperlimit = 190, q = 0, rq = 0
            rq = TRUE; upperlimit--;
        }   ⊔ : upperlimit + q + rq = 190, upperlimit ∈ [189, 190], q ∈ [0, 1], rq ∈ [0, 1]
        if (... && (!q) && rq) {
            rq = 0; upperlimit++;
        }
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

1st iteration: infers the affine equality between the variables: $upperlimit + q + rq = 190$

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) {
        c = input[inputIndex++];
        if (... && (!q)) {
            q = 1; upperlimit--;
        }
        if (... && (q)) {
            q = 0; upperlimit++;
        }
        if (... && (!q) && !rq) {
            rq = TRUE; upperlimit--;
        }
        if (... && (!q) && rq) {  upperlimit = 189, q = 0, rq = 1
            rq = 0; upperlimit++;
        }   ⊔ : upperlimit + q + rq = 190, upperlimit ∈ [189, 190], q ∈ [0, 1], rq ∈ [0, 1]
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

1st iteration: infers the affine equality between the variables: $upperlimit + q + rq = 190$

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) {
        c = input[inputIndex++];
        if (... && (!q)) {
            q = 1; upperlimit--;
        }
        if (... && (q)) {
            q = 0; upperlimit++;
        }
        if (... && (!q) && !rq) {
            rq = TRUE; upperlimit--;
        }
        if (... && (!q) && rq) {
            rq = 0; upperlimit++;
        }
        if (outputIndex < upperlimit) {  upperlimit ∈ [189, 190], outputIndex = 0
            localbuf[outputIndex] = c;
            outputIndex++;
        }    ⊔ : upperlimit ∈ [189, 190], outputIndex ∈ [0, 1]
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

2nd iteration: widening ∇ suppressed by the "delayed widening" domain because of the flag assignments. Join $\sqcup$ performed instead. We analyze the loop again with still valid equality: $upperlimit + q + rq = 190$

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) { ⊔ : inputIndex ∈ [0, 1], outputIndex ∈ [0, 1]
        c = input[inputIndex++];
        if (... && (!q)) { upperlimit + rq = 190, upperlimit ∈ [189, 190], q = 0, rq ∈ [0, 1]
            q = 1; upperlimit--;
        }   ⊔ : upperlimit + q + rq = 190, upperlimit ∈ [188, 190], q ∈ [0, 1], rq ∈ [0, 1]
        if (... && (q)) {
            q = 0; upperlimit++;
        }
        if (... && (!q) && !rq) {
            rq = TRUE; upperlimit--;
        }
        if (... && (!q) && rq) {
            rq = 0; upperlimit++;
        }
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

2nd iteration: widening ∇ suppressed by the "delayed widening" domain because of the flag assignments. Join $\sqcup$ performed instead. We analyze the loop again with still valid equality: $upperlimit + q + rq = 190$

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) {
        c = input[inputIndex++];
        if (... && (!q)) {
            q = 1; upperlimit--;
        }
        if (... && (q)) { upperlimit + rq = 189, upperlimit ∈ [188, 189], q = 1, rq ∈ [0, 1]
            q = 0; upperlimit++;
        }   ⊔ : upperlimit + q + rq = 190, upperlimit ∈ [188, 190], q ∈ [0, 1], rq ∈ [0, 1]
        if (... && (!q) && !rq) {
            rq = TRUE; upperlimit--;
        }
        if (... && (!q) && rq) {
            rq = 0; upperlimit++;
        }
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

2nd iteration: widening ∇ suppressed by the "delayed widening" domain because of the flag assignments. Join $\sqcup$ performed instead. We analyze the loop again with still valid equality: $upperlimit + q + rq = 190$

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) {
        c = input[inputIndex++];
        if (... && (!q)) {
            q = 1; upperlimit--;
        }
        if (... && (q)) {
            q = 0; upperlimit++;
        }
        if (... && (!q) && !rq) { upperlimit = 190, q = 0, rq = 0
            rq = TRUE; upperlimit--;
        }   ⊔ : upperlimit + q + rq = 190, upperlimit ∈ [188, 190], q ∈ [0, 1], rq ∈ [0, 1]
        if (... && (!q) && rq) {
            rq = 0; upperlimit++;
        }
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

2nd iteration: widening ∇ suppressed by the "delayed widening" domain because of the flag assignments. Join $\sqcup$ performed instead. We analyze the loop again with still valid equality: $upperlimit + q + rq = 190$

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) {
        c = input[inputIndex++];
        if (... && (!q)) {
            q = 1; upperlimit--;
        }
        if (... && (q)) {
            q = 0; upperlimit++;
        }
        if (... && (!q) && !rq) {
            rq = TRUE; upperlimit--;
        }
        if (... && (!q) && rq) {  upperlimit = 189, q = 0, rq = 1
            rq = 0; upperlimit++;
        }   ⊔ : upperlimit + q + rq = 190, upperlimit ∈ [188, 190], q ∈ [0, 1], rq ∈ [0, 1]
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

2nd iteration: widening ∇ suppressed by the "delayed widening" domain because of the flag assignments. Join $\sqcup$ performed instead. We analyze the loop again with still valid equality: $upperlimit + q + rq = 190$

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) {
        c = input[inputIndex++];
        if (... && (!q)) {
            q = 1; upperlimit--;
        }
        if (... && (q)) {
            q = 0; upperlimit++;
        }
        if (... && (!q) && !rq) {
            rq = TRUE; upperlimit--;
        }
        if (... && (!q) && rq) {
            rq = 0; upperlimit++;
        }
        if (outputIndex < upperlimit) {  upperlimit ∈ [188, 190], outputIndex ∈ [0, 1]
            localbuf[outputIndex] = c;
            outputIndex++;
        }    ⊔ : upperlimit ∈ [188, 190], outputIndex ∈ [0, 2]
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

3rd iteration: now widening ∇ is applied using the widening threshold: $outputIndex - 1 < upperlimit$.
Widening changes the lower bound of *upperlimit* but reduction with the equality $upperlimit + q + rq = 190$ restores it

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) { ∇ : inputIndex ∈ [0, +∞],outputIndex ∈ [0, 190],upperlimit ∈ [0, 190]
        c = input[inputIndex++];
        if (... && (!q)) { upperlimit + rq = 190, upperlimit ∈ [189, 190], q = 0, rq ∈ [0, 1]
            q = 1; upperlimit--;
        }   ⊔ : upperlimit + q + rq = 190, upperlimit ∈ [188, 190], q ∈ [0, 1], rq ∈ [0, 1]
        if (... && (q)) {
            q = 0; upperlimit++;
        }
        if (... && (!q) && !rq) {
            rq = TRUE; upperlimit--;
        }
        if (... && (!q) && rq) {
            rq = 0; upperlimit++;
        }
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

3rd iteration: now widening ∇ is applied using the widening threshold: $outputIndex - 1 < upperlimit$.
Widening changes the lower bound of *upperlimit* but reduction with the equality $upperlimit + q + rq = 190$ restores it

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) {
        c = input[inputIndex++];
        if (... && (!q)) {
            q = 1; upperlimit--;
        }
        if (... && (q)) {  upperlimit + rq = 189, upperlimit ∈ [188, 189], q = 1, rq ∈ [0, 1]
            q = 0; upperlimit++;
        }   ⊔ : upperlimit + q + rq = 190, upperlimit ∈ [188, 190], q ∈ [0, 1], rq ∈ [0, 1]
        if (... && (!q) && !rq) {
            rq = TRUE; upperlimit--;
        }
        if (... && (!q) && rq) {
            rq = 0; upperlimit++;
        }
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

3rd iteration: now widening ∇ is applied using the widening threshold: $\mathit{outputIndex} - 1 < \mathit{upperlimit}$.
Widening changes the lower bound of *upperlimit* but reduction with the equality $\mathit{upperlimit} + q + rq = 190$ restores it

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) {
        c = input[inputIndex++];
        if (... && (!q)) {
            q = 1; upperlimit--;
        }
        if (... && (q)) {
            q = 0; upperlimit++;
        }
        if (... && (!q) && !rq) {  upperlimit = 190, q = 0, rq = 0
            rq = TRUE; upperlimit--;
        }    ⊔ : upperlimit + q + rq = 190, upperlimit ∈ [188, 190], q ∈ [0, 1], rq ∈ [0, 1]
        if (... && (!q) && rq) {
            rq = 0; upperlimit++;
        }
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

3rd iteration: now widening ∇ is applied using the widening threshold: $\mathit{outputIndex} - 1 < \mathit{upperlimit}$.
Widening changes the lower bound of *upperlimit* but reduction with the equality $\mathit{upperlimit} + q + rq = 190$ restores it

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) {
        c = input[inputIndex++];
        if (... && (!q)) {
            q = 1; upperlimit--;
        }
        if (... && (q)) {
            q = 0; upperlimit++;
        }
        if (... && (!q) && !rq) {
            rq = TRUE; upperlimit--;
        }
        if (... && (!q) && rq) {  upperlimit = 189, q = 0, rq = 1
            rq = 0; upperlimit++;
        }   ⊔ : upperlimit + q + rq = 190, upperlimit ∈ [188, 190], q ∈ [0, 1], rq ∈ [0, 1]
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

3rd iteration: now widening ∇ is applied using the widening threshold: $outputIndex - 1 < upperlimit$.
Widening changes the lower bound of *upperlimit* but reduction with the equality $upperlimit + q + rq = 190$ restores it

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) {
        c = input[inputIndex++];
        if (... && (!q)) {
            q = 1; upperlimit--;
        }
        if (... && (q)) {
            q = 0; upperlimit++;
        }
        if (... && (!q) && !rq) {
            rq = TRUE; upperlimit--;
        }
        if (... && (!q) && rq) {
            rq = 0; upperlimit++;
        }
        if (outputIndex < upperlimit) {  upperlimit ∈ [188, 190], outputIndex ∈ [0, 189]
            localbuf[outputIndex] = c;
            outputIndex++;
        }    ⊔ : upperlimit ∈ [188, 190], outputIndex ∈ [0, 190]
    }
    if (rq) {
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Analysis Steps and inferred Values

4th iteration: loop is stable; outside of the loop body the value of *outputIndex* is still bounded!

```
int copy_it (char *input, unsigned int length) {
    char c, localbuf[200];
    unsigned int upperlimit = 190;
    unsigned int q = rq = 0;
    unsigned int inputIndex = outputIndex = 0;
    while (inputIndex < length) { ⊑: inputIndex ∈ [0, +∞], outputIndex ∈ [0, 190]
        c = input[inputIndex++];
        if (... && (!q)) {
            q = 1; upperlimit--;
        }
        if (... && (q)) {
            q = 0; upperlimit++;
        }
        if (... && (!q) && !rq) {
            rq = TRUE; upperlimit--;
        }
        if (... && (!q) && rq) {
            rq = 0; upperlimit++;
        }
        if (outputIndex < upperlimit) {
            localbuf[outputIndex] = c;
            outputIndex++;
        }
    }
    if (rq) { outputIndex ∈ [0, 190]
        localbuf[outputIndex] = ')'; outputIndex++; }
    if (q) {  outputIndex ∈ [1, 191]
        localbuf[outputIndex] = '>'; outputIndex++; }
}
```

Key Points

- widening needs to be suppressed until the flag variables are stable to infer the equality relation with *upperlimit*
- the inferred equality $\mathit{upperlimit} + q + \mathit{rq} = 190$ and reduction between domains results in more precise values for *upperlimit*; it recovers the precision loss of widening

Key Points (continued)

- narrowing does not help here; instead the threshold $\mathit{outputIndex} < \mathit{upperlimit}$ must be used for widening
  $\leadsto$ *outputIndex* is also restricted outside of the loop for the following two writes to the buffer

- in the vulnerable version because of the missing decrementation the equality relation does not hold
  $\leadsto$ *upperlimit* is unbounded after widening

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$\rightsquigarrow$ we cannot yet automatically prove the invariant on that code; the non-vulnerable version is flagged as vulnerable, too

Analysis Results of various Tools

Now lets look how other tools fare on the simplified example ...

Analysis Results of various Tools

Evaluated on the simplified Sendmail Crackaddr Example

Tool	non-vuln.	vuln.	Techniques used	Input
Bindead	✓	✓	AI	binary
Jakstab		✓	AI	binary
Astrée		✓	AI	C
Goblint		✓	AI	C
TIS-Analyzer/Frama-C	✓(m)	✓	AI + MC	C
PAGAI	✓	✓	AI + MC	LLVM
SeaHorn	✓	✓	AI + MC	LLVM
HAVOC	✓(m)	✓	MC	C
CProver	✓(m)	✓	MC	C
AFL		✓	Fuzz	C
Radamsa		✓	Fuzz	binary

m: manual hints from user required

AI: Abstract Interpretation MC: Model Checking Fuzz: fuzz fuzz fuzz

Still to test: KLEE, S2E, BAP, Java Path Finder, Triton, PySymEmu, Moflow, Angr, McSema, OpenREIL, Bincoa, CodeSonar, Polyspace, Goanna, Clousot . . .

Conclusion

Program analysis tools can infer surprisingly nice results.
$\rightsquigarrow$ here an invariant that shows the programmer's intention

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- but the tools are quite complex
  $\rightsquigarrow$ hard to understand and to reason about the results
- if an expected invariant cannot be proved it is difficult to find out why and fix it
- however, being able to understand, use and debug an analyzer is key to building useful analyses!
  $\rightsquigarrow$ general adoption of static analyzers is an uphill battle :(

Demo!

Initializing ... demo

Project page: https://bitbucket.org/mihaila/bindead

Demo!

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... ... 25%

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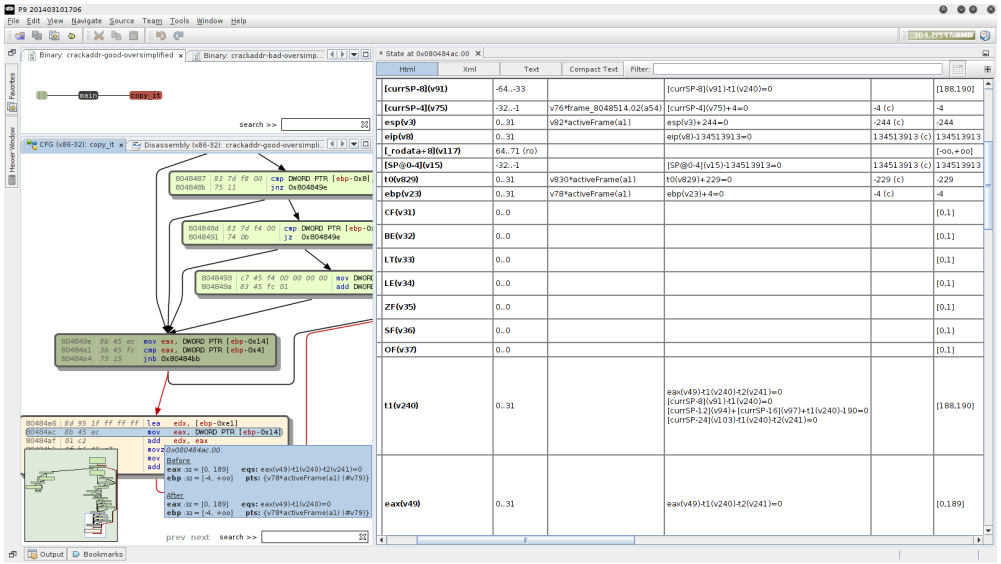

Project page: https://bitbucket.org/mihaila/bindead

A Merci Beaucoup goes to ...

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Hackito Ergo Sum

2015

Some previous material on Sendmail Crackaddr

Presentations

- Checking the Boundaries of Static Analysis - Halvar Flake 2013
- Exploitation and State Machines - Halvar Flake 2012
- Exploit-Generation with Acceleration - Daniel Kröning et al. 2013
- Modern Static Security Checking of C/C++ Code - Julien Vanegue 2012
- Practical AI Applications to Information Security - Fyodor Yarochkin 2003

Papers and Web Resources

- TIS Analyzer Sendmail Crackaddr Analysis Report - Pascal Cuoq 2014
- SMT Solvers for Software Security - Julien Vanegue et al. 2012
- Technical Analysis and Exploitation of Sendmail Bug - LSD 2003
- Sendmail Crackaddr CVE-2002-1337 - MITRE Co. 2003
- Remote Sendmail Header Processing Vulnerability - IBM ISS 2003