Compiler Validation via Equivalence Modulo Inputs

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llvm bug 14972

```c
struct tiny { char c; char d; char e; };

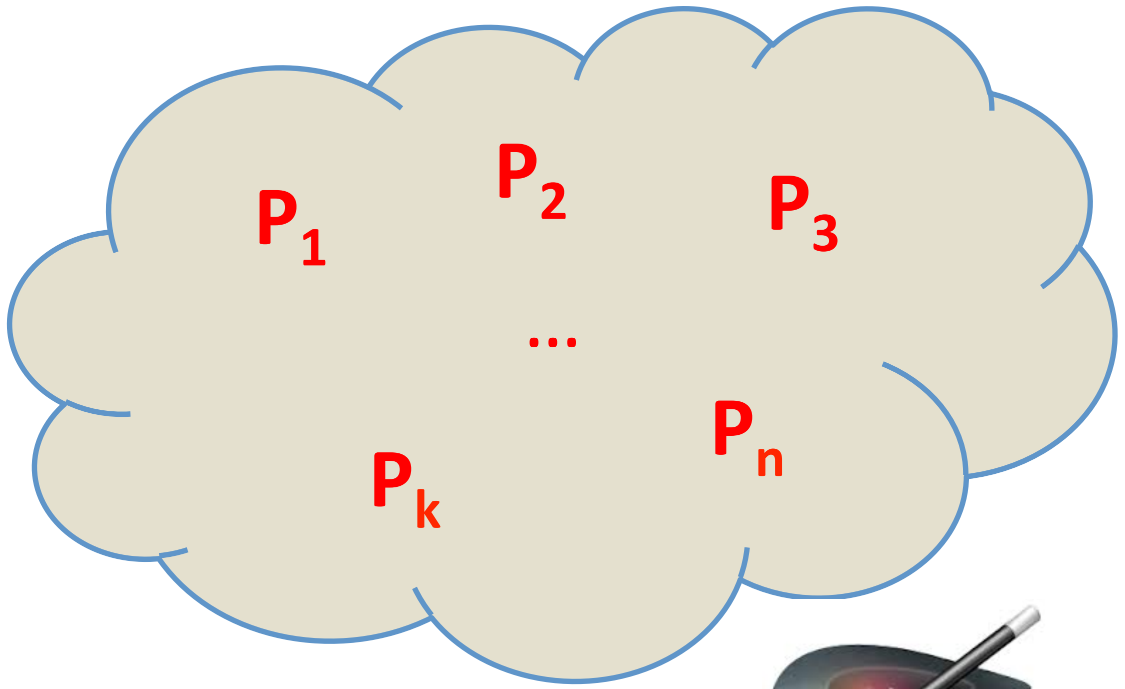
void foo(struct tiny x) {
    if (x.c != 1) abort();
    if (x.e != 1) abort();
}

int main() {
    struct tiny s;
    s.c = 1; s.d = 1; s.e = 1;
    foo(s);
    return 0;
}
```

```
$ clang -m32 -O0 test.c ; ./a.out
$ clang -m32 -O1 test.c ; ./a.out
Aborted (core dumped)
```

vision

$P \equiv$



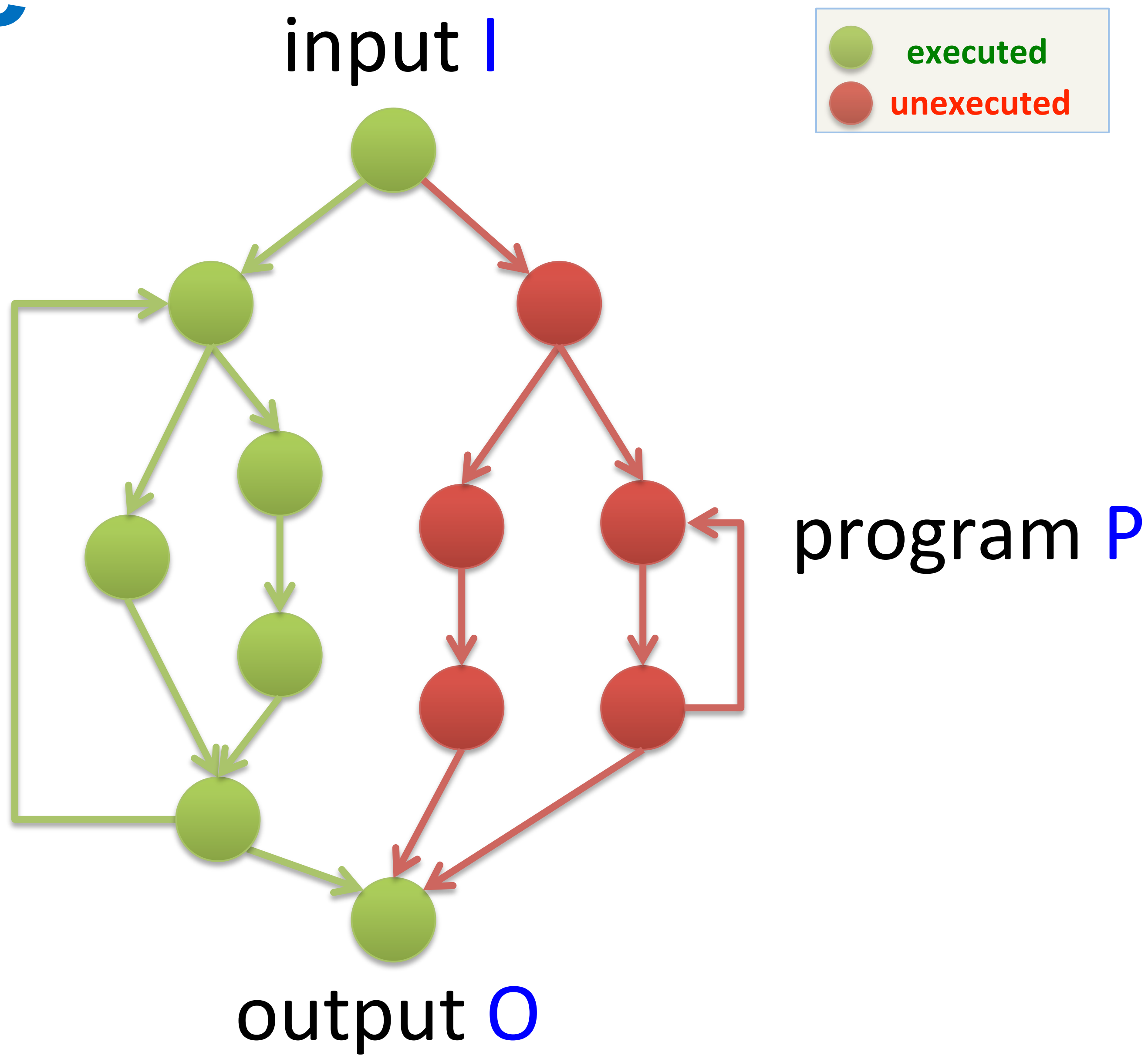
key challenges

- Generation
  - How to generate **different** but **equivalent** tests?
- Validation
  - How to check that tests are **indeed equivalent**?
- Both are long-standing hard issues

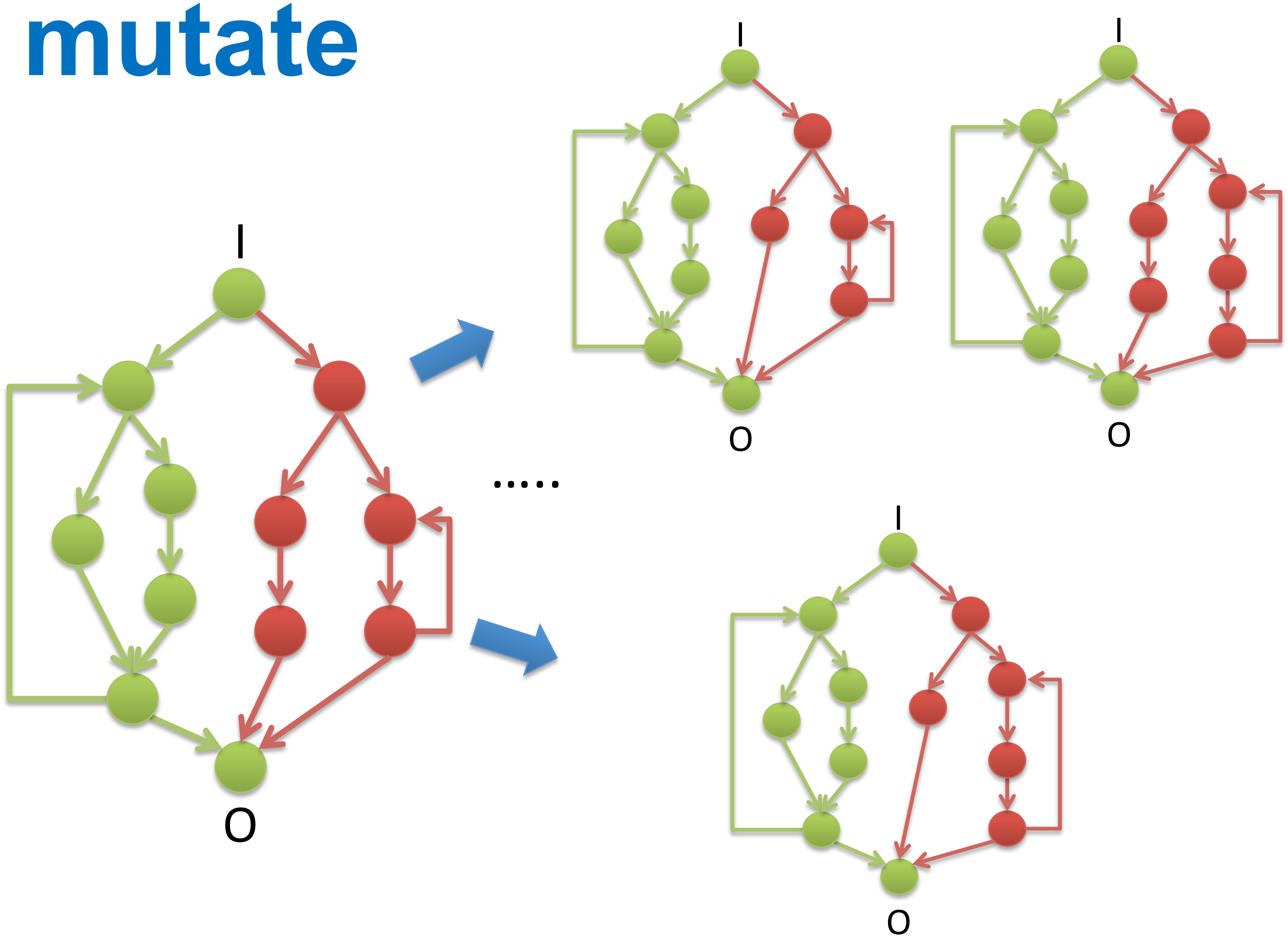
equiv. modulo inputs

- Relax equiv. wrt a **given input**
  - Variants must satisfy **$P(i) = P_k(i)$** on input **i**
  - But may differ on other input **j**: **$P(j) \neq P_k(j)$**
- Exploit close **interplay** between
  - **Dynamic** program execution on **some input**
  - **Static** compilation for **all input**

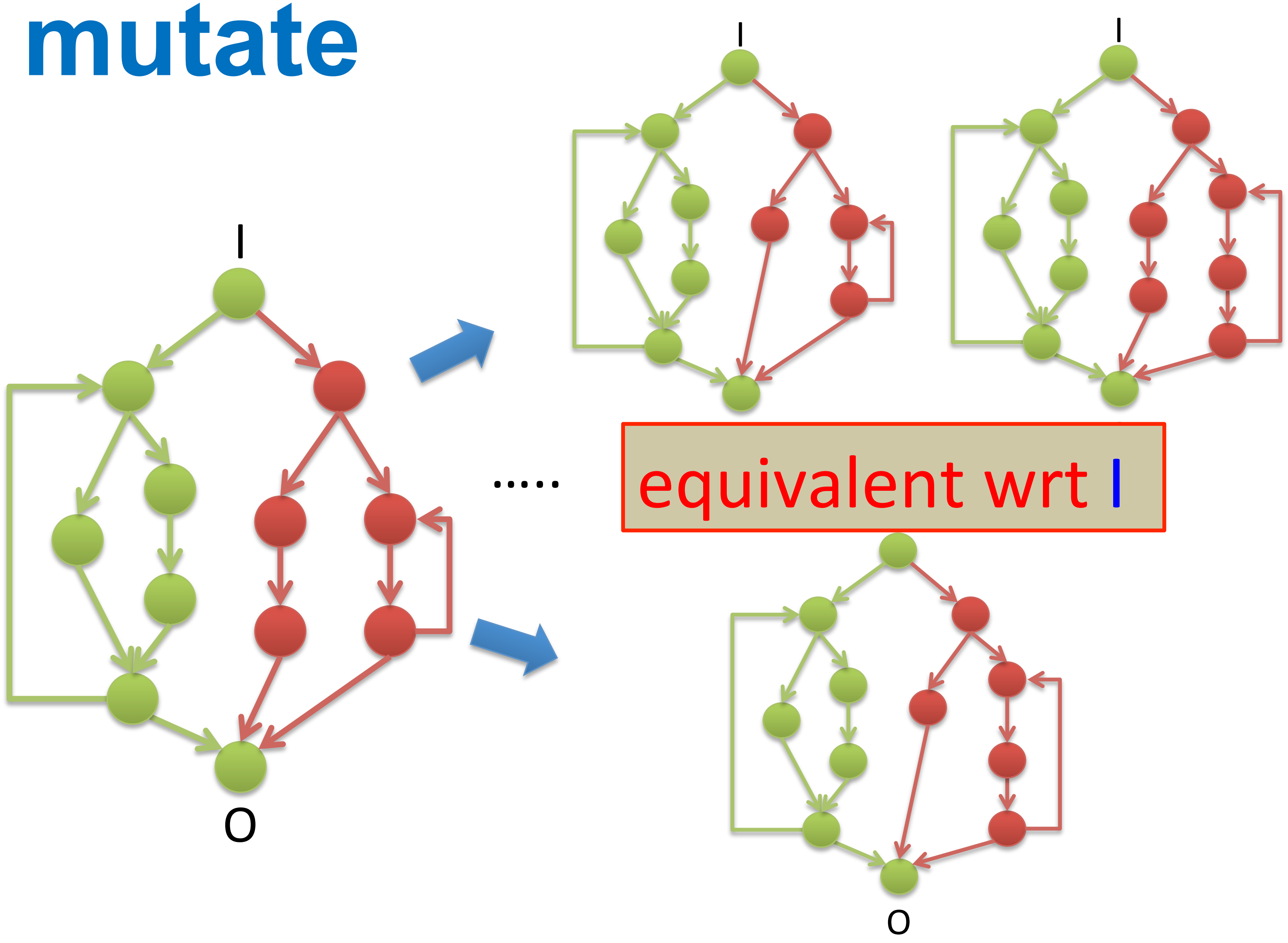
profile



mutate



mutate



equivalent wrt I

revisit challenges

- Generation (**easy**)
  - How to generate **different** but **equivalent** tests?
- Validation (**easy**)
  - How to check that tests are **indeed equivalent**?

- ~~Both are long-standing hard issues~~

llvm bug 14972

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    if (x.c != 1) abort();
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}

int main() {
    struct tiny s;
    s.c = 1; s.d = 1; s.e = 1;
    foo(s);
    return 0;
}
```

```
$ clang -m32 -O0 test.c ; ./a.out
$ clang -m32 -O1 test.c ; ./a.out
Aborted (core dumped)
```

seed file

```c
struct tiny { char c; char d; char e; };
f(int n, struct tiny x, struct tiny y,
  struct tiny z, long l) {
    if (x.c != 10) abort();
    if (x.d != 20) abort();
    if (x.e != 30) abort();
    if (y.c != 11) abort();
    if (y.d != 21) abort();
    if (y.e != 31) abort();
    if (z.c != 12) abort();
    if (z.d != 22) abort();
    if (z.e != 32) abort();
    if (l != 123) abort();
}
main() {
    struct tiny x[3];
    x[0].c = 10;
    x[1].c = 11;
    x[2].c = 12;
    x[0].d = 20;
    x[1].d = 21;
    x[2].d = 22;
    x[0].e = 30;
    x[1].e = 31;
    x[2].e = 32;
    f(3, x[0], x[1], x[2], (long)123);
    exit(0);
}
```

```
$ clang -m32 -O0 test.c ; ./a.out
$ clang -m32 -O1 test.c ; ./a.out
```

seed file

```
struct tiny { char c; char d; char e; };
f(int n, struct tiny x, struct tiny y,
  struct tiny z, long l) {
    if (x.c != 10) abort();
    if (x.d != 20) abort();
    if (x.e != 30) abort();
    if (y.c != 11) abort();
    if (y.d != 21) abort();
    if (y.e != 31) abort();
    if (z.c != 12) abort();
    if (z.d != 22) abort();
    if (z.e != 32) abort();
    if (l != 123) abort();
}
main() {
    struct tiny x[3];
    x[0].c = 10;
    x[1].c = 11;
    x[2].c = 12;
    x[0].d = 20;
    x[1].d = 21;
    x[2].d = 22;
    x[0].e = 30;
    x[1].e = 31;
    x[2].e = 32;
    f(3, x[0], x[1], x[2], (long)123);
    exit(0);
}
```

unexecuted

```
$ clang -m32 -O0 test.c ; ./a.out
$ clang -m32 -O1 test.c ; ./a.out
```

transformed file

```
struct tiny { char c; char d; char e; };
f(int n, struct tiny x, struct tiny y,
  struct tiny z, long l) {
    if (x.c != 10) /* deleted */;
    if (x.d != 20) abort();
    if (x.e != 30) /* deleted */;
    if (y.c != 11) abort();
    if (y.d != 21) abort();
    if (y.e != 31) /* deleted */;
    if (z.c != 12) abort();
    if (z.d != 22) /* deleted */;
    if (z.e != 32) abort();
    if (l != 123) /* deleted */;
}
main() {
    struct tiny x[3];
    x[0].c = 10;
    x[1].c = 11;
    x[2].c = 12;
    x[0].d = 20;
    x[1].d = 21;
    x[2].d = 22;
    x[0].e = 30;
    x[1].e = 31;
    x[2].e = 32;
    f(3, x[0], x[1], x[2], (long)123);
    exit(0);
}
```

```
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reduced file

```c
struct tiny { char c; char d; char e; };

void foo(struct tiny x) {
    if (x.c != 1) abort();
    if (x.e != 1) abort();
}

int main() {
    struct tiny s;
    s.c = 1; s.d = 1; s.e = 1;
    foo(s);
    return 0;
}
```

```
$ clang -m32 -O0 test.c ; ./a.out
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```

llvm bug autopsy

```c
struct tiny { char c; char d; char e; };

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     if (x.c != 1) abort();
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}

int main() {
     struct tiny s;
     s.c = 1; s.d = 1; s.e = 1;
     foo(s);
     return 0;
}
```

GVN: load struct using 32-bit load

```
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llvm bug autopsy

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    s.c = 1; s.d = 1; s.e = 1;
    foo(s);
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}
```

GVN: load struct using 32-bit load

SRoA: read past the struct's end ➔ undefined behavior

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llvm bug autopsy

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    foo(s);
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```

GVN: load struct using 32-bit load

SRoA: read past the struct's end ➔ undefined behavior

remove

```
$ clang -m32 -O0 test.c ; ./a.out
$ clang -m32 -O1 test.c ; ./a.out
Aborted (core dumped)
```

developers

"… very, very concerning when I got to the root cause, and very annoying to fix …"

http://llvm.org/bugs/show_bug.cgi?id=14972

gcc bug 58731

```c
int a, b, c, d, e;
int main() {
    for (b = 4; b > -30; b--)
        for (; c;)
            for (;;) {
                e = a > 2147483647 - b;
                if (d) break;
            }
    return 0;
}
```

```
$ gcc -O0 test.c ; ./a.out
$ gcc -O3 test.c ; ./a.out
^C
```

gcc bug autopsy

```
int a, b, c, d, e;
int main() {
    for (b = 4; b > -30; b--)
        for (; c;)
            for (;;) {
                e = a > 2147483647 - b;
                if (d) break;
            }
    return 0;
}
```

PRE: loop invariant

```
$ gcc -O0 test.c ; ./a.out
$ gcc -O3 test.c ; ./a.out
^C
```

gcc bug autopsy

```c
int a, b, c, d, e;
int main() {
    for (b = 4; b > -30; b--)
        int f = 2147483647 - b;
        for (; c;)
            for (;;) {
                e = a > f;
                if (d) break;
            }
    return 0;
}
```

LIM

```
$ gcc -O0 test.c ; ./a.out
$ gcc -O3 test.c ; ./a.out
^C
```

gcc bug autopsy

```c
int a, b, c, d, e;
int main() {
    for (b = 4; b > -30; b--)
        int f = 2147483647 - b;
        for (; c;)
            for (;;) {
                e = a > f;
                if (d) break;
            }
    return 0;
}
```

integer overflow

```
$ gcc -O0 test.c ; ./a.out
$ gcc -O3 test.c ; ./a.out
^C
```

seed program

```
int a, b, c, d, e;
int main() {
    for (b = 4; b > -30; b--)
        for (; c;)
            for (;;) {
                b++;
                e = a > 2147483647 - b;
                if (d) break;
            }
    return 0;
}
```

no longer a loop invariant

```
$ gcc -O0 test.c ; ./a.out
$ gcc -O3 test.c ; ./a.out
```

why effective?

- Compilers produce correct code for **all input**

why effective?

- Compilers produce correct code for all input
- Variants have different data & control flow
  - Exercise **various** optimization strategies
  - Demand exact **same output** on the given input

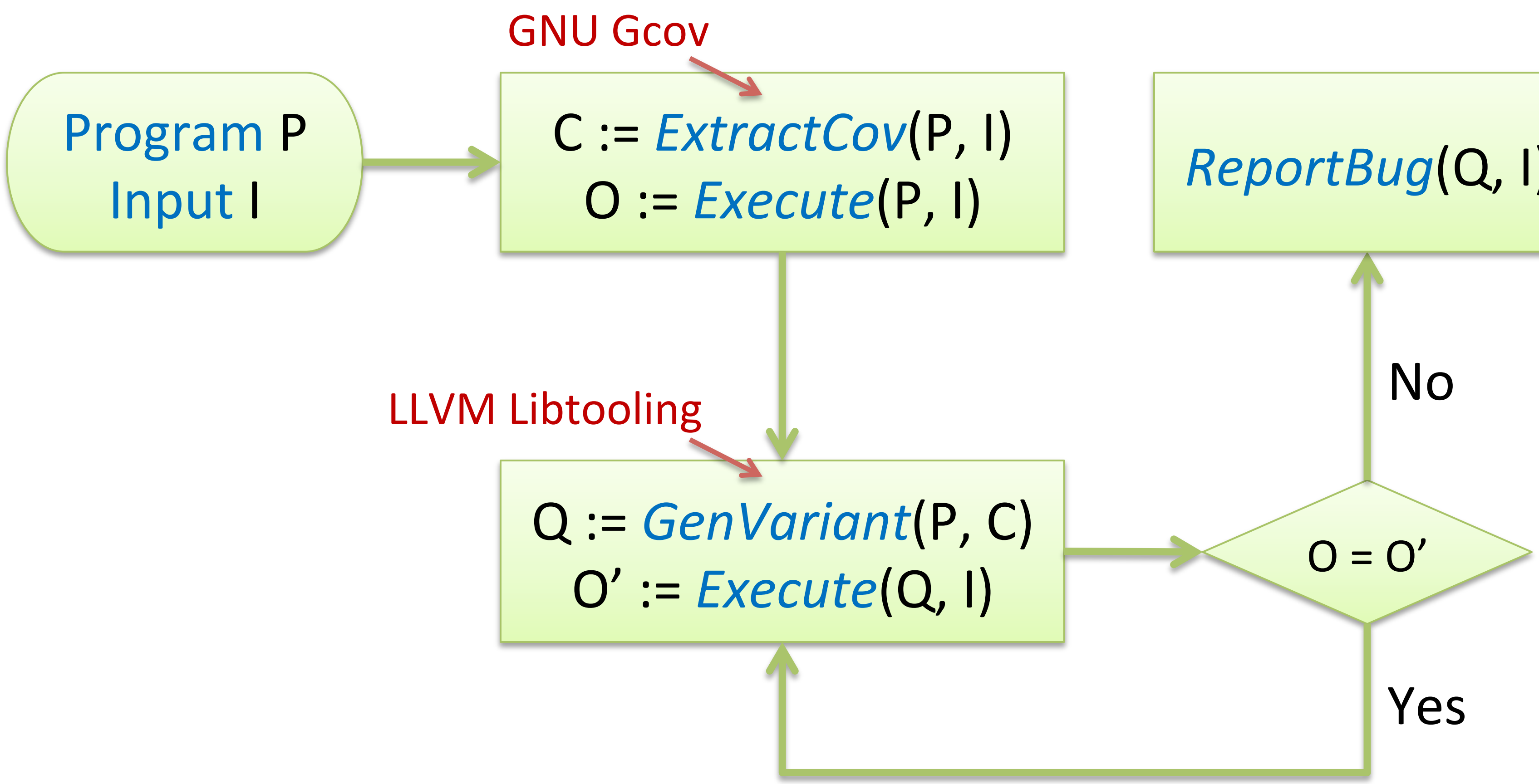
orion

- A practical realization of EMI

orion

- A practical realization of EMI
- Targeting C compilers
  - Randomly **prune** unexecuted code
  - Extremely **effective**

orion


GNU Gcov
Program P
Input I
C := *ExtractCov*(P, I)
O := *Execute*(P, I)
ReportBug(Q, I)
No
LLVM Libtooling
Q := *GenVariant*(P, C)
O' := *Execute*(Q, I)
O = O'
Yes

evaluation

- Two multi-core Ubuntu machines
- April 2013 – March 2014
- Seed programs
  - Compiler regression test suites
  - Open-source projects
  - Csmith-generated programs

bug counts

	GCC	LLVM	TOTAL
Reported	111	84	**195**
Marked Duplicate	28	7	**35**
Confirmed	79	68	**147**
Fixed	56	54	**110**

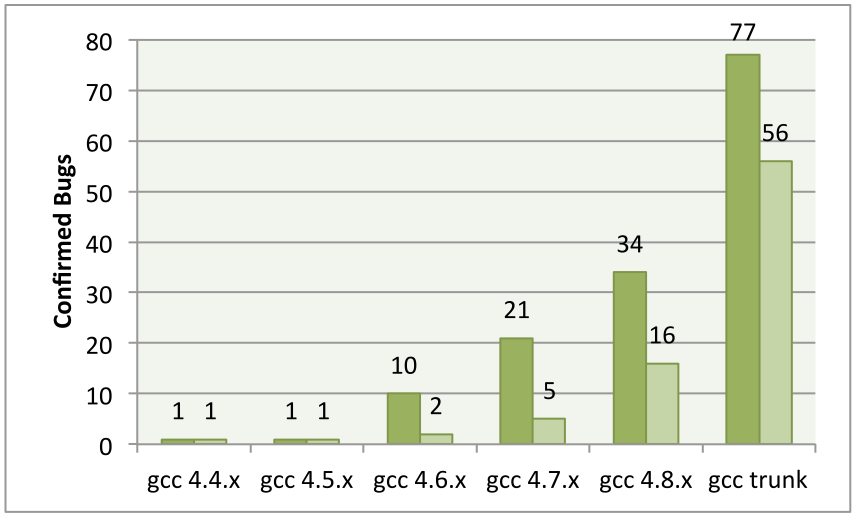
bug types

	GCC	LLVM	TOTAL
Wrong code	46	49	**95**
Crash	23	10	**33**
Performance	10	9	**19**

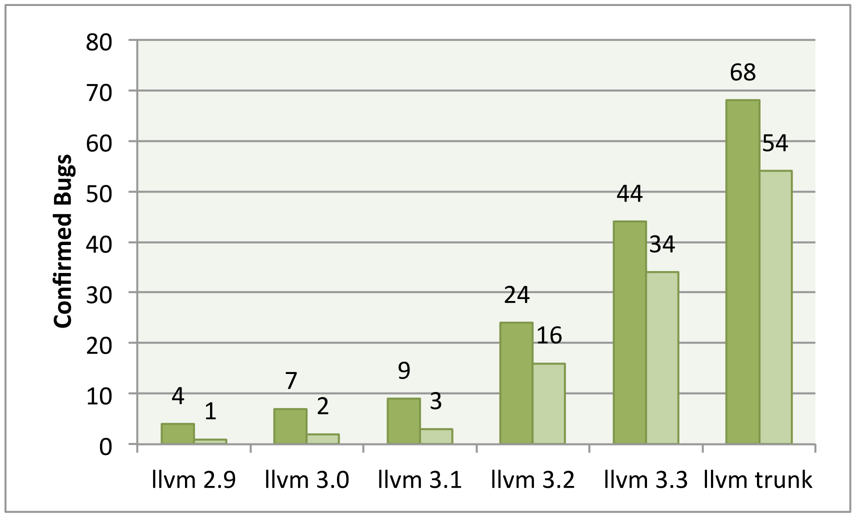
bug importance

- Most bugs have already been **fixed**
- Many were **critical**, **release-blocking**
- Some affected **real-world** projects

affected versions

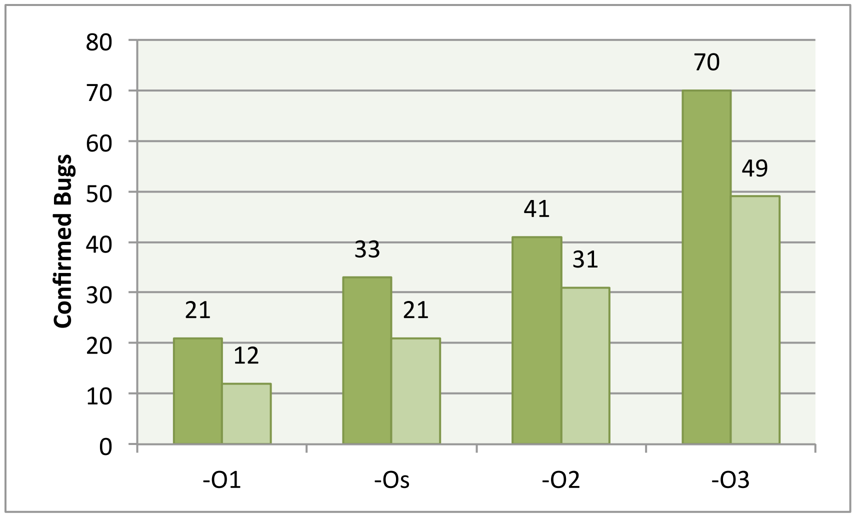


GCC

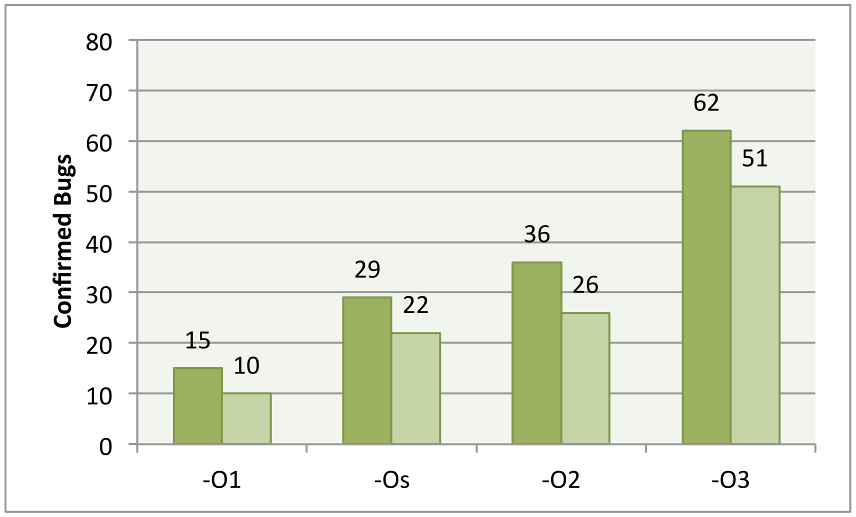


LLVM

affected opt. levels

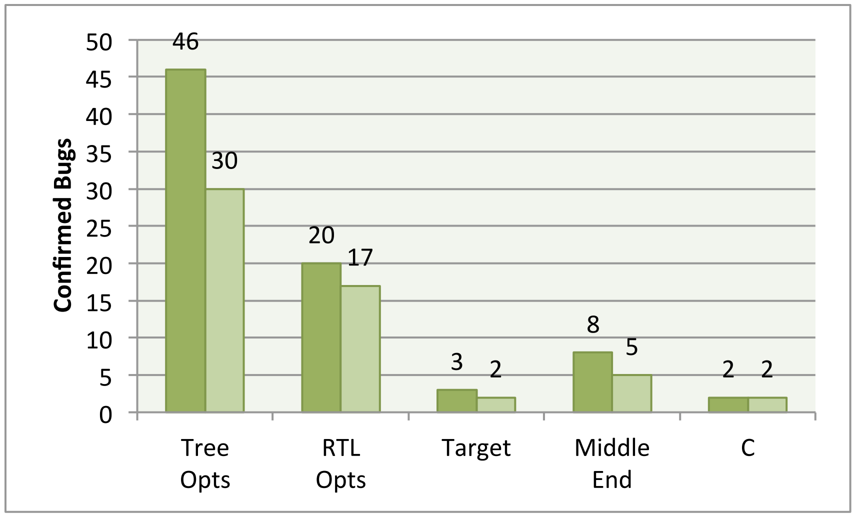


GCC

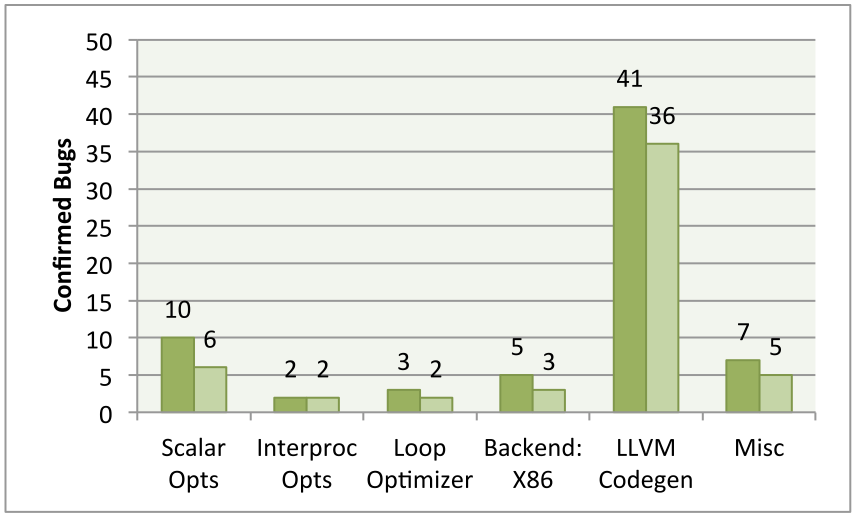


LLVM

affected components



GCC



LLVM

related work

- Verified compiler
- Translation validation
- Random program generation

future work

- Investigate other **mutation strategies**
- Extend EMI to handle **floating-point** code
- Adapt EMI to other **languages** & **settings**

conclusion

- EMI is **general** and **widely applicable**
  - Can test compilers, analysis and transformation tools
  - Generates real-world tests
  - Requires no reference compilers
- Orion is very **effective**
  - Has uncovered **200+ bugs** in GCC and LLVM
  - Majority of the bugs were **miscompilations**

conclusion

- EMI is **general** and **widely applicable**
  - Can test compilers, analysis and transformation tools
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- Orion is very **effective**
  - Has uncovered **200+ bugs** in GCC and LLVM
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Exciting new direction with **many applications**