Liveness-Driven Random Program Generation

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Motivation

Context: automatic tool for finding *missed optimizations*

Generated source code:

```
int f(int p, int q) {
  return q + (p % 6) / 9;
}
```

($p \% 6 \in [-5, 5]$,
division truncates to 0)
recently fixed

Clang:

```
movw r2, #43691
movt r2, #10922
smmul r2, r0, r2
add r2, r2, r2, lsr #31
add r2, r2, r2, lsl #1
sub r0, r0, r2, lsl #1
movw r2, #36409
movt r2, #14563
smmul r0, r0, r2
asr r2, r0, #1
add r0, r2, r0, lsr #31
add r0, r0, r1
bx lr
```

GCC:

```
mov r0, r1
bx lr
```

Randomized differential testing

popularized by Yang et al., “Finding and understanding bugs in C compilers”, PLDI ’11

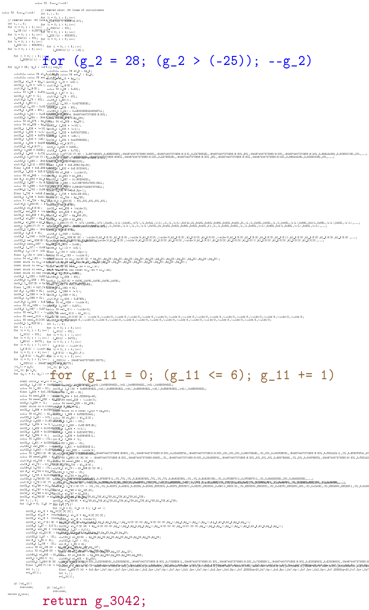
How to find compiler bugs:

- generate random source code
- compile with different compilers
- compare binaries (code or behavior)

Csmith: standard C program generator, has found hundreds of bugs

this work: ldrgen, new random C code generator

A problem with Csmith



162 LOC (without 100 lines of inits) compiles to 8 instructions:

```
func_1:
    movl $27, %eax
.L2:
    movl %eax, g_2(%rip)
    subl $1, %eax
    movl $7, g_11(%rip)
    cmpl $-26, %eax
    jne .L2
    movl g_3042(%rip), %eax
    ret
```

vast majority of code is dead code

Liveness and dead code

live variable: variable that may be used in the future
dead variable: variable that is definitely not used in the future

```
x = y + z;
return x;
```

x live after assignment

```
x = y + z;
return y;
```

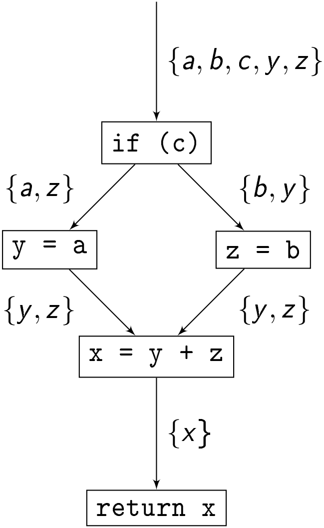
x dead after assignment

by extension: live code computes value maybe used in future
dead code elimination: standard compiler pass, removes dead code

Dead $\neq$ unreachable: dead code more than `if (false) ...`

Live variable analysis

backwards data flow analysis



live-in set $S^\bullet$: live before S
live-out set S°: live after S

transfer function for $\mathtt{v} = \mathtt{e}$:

$$S^\bullet = (S^\circ \setminus \{v\}) \cup FV(e)$$

control flow split:

$$S^\circ = \bigcup_{S_i \in succ(S)} S_i^\bullet$$

compute least fixed point

Generation of fully live programs

want to generate fully live programs: all statements are live

idea: perform liveness analysis during (backwards!) generation

but I am lazy:

- do not want to generate a control flow graph
- do not want to backtrack/iterate to fixed point

long-forgotten idea:

structural data-flow analysis

Structural (full) liveness analysis

liveness triple: $\langle S^\bullet \rangle \;\; S \;\; \langle S^\circ \rangle$

$$\text{Assign}\;\frac{v \in S^\circ \qquad S^\bullet = (S^\circ \setminus \{v\}) \cup FV(e)}{\langle S^\bullet \rangle \;\; v = e \;\; \langle S^\circ \rangle}$$

$$\text{Sequence}\;\frac{\langle S_1^\bullet \rangle \;\; S_1 \;\; \langle S_2^\bullet \rangle \qquad \langle S_2^\bullet \rangle \;\; S_2 \;\; \langle S_2^\circ \rangle \qquad S_2^\bullet \neq \emptyset}{\langle S_1^\bullet \rangle \;\; S_1 \; ; \; S_2 \;\; \langle S_2^\circ \rangle}$$

$$\text{If}\;\frac{\langle S_1^\bullet \rangle \;\; S_1 \;\; \langle S^\circ \rangle \qquad \langle S_2^\bullet \rangle \;\; S_2 \;\; \langle S^\circ \rangle \qquad S^\bullet = S_1^\bullet \cup S_2^\bullet \cup FV(c)}{\langle S^\bullet \rangle \;\; \texttt{if}\ (c)\ S_1\ \texttt{else}\ S_2 \;\; \langle S^\circ \rangle}$$

side conditions to ensure full liveness
program S fully live iff $\langle S^\bullet \rangle \;\; S \;\; \langle \emptyset \rangle$ derivable

Example: Failed derivation

Programs with dead code cannot be proved fully live:

$$\text{Sequence}\ \dfrac{\text{Assign}\ \dfrac{\color{red}{\texttt{x} \notin \{\texttt{y}\}\ \lightning}}{\langle S^{\bullet}\rangle\ \texttt{x = y + z}\ \langle\{\texttt{y}\}\rangle} \qquad \langle\{\texttt{y}\}\rangle\ \texttt{return y}\ \langle\emptyset\rangle}{\langle S^{\bullet}\rangle\ \texttt{x = y + z; return y}\ \langle\emptyset\rangle}$$

Analyzing loops

While

$$\frac{\langle B^\bullet \rangle \;\; B \;\; \langle B^\circ \rangle \qquad \begin{array}{c} L^\bullet = B^\bullet \cup L^\circ \qquad L^\circ \neq \emptyset \\ B^\circ = L^\circ \cup B^\bullet \cup FV(c) \text{ (minimal)} \end{array}}{\langle L^\bullet \rangle \;\; \texttt{while}\ (c)\ B \;\; \langle L^\circ \rangle}$$

Not constructive: How to compute the fixed point?

Not a problem for random generation: chooose least fixed point.

Example derivation

$$\dfrac{\dfrac{\dfrac{\dfrac{\langle\{a,b,n\}\rangle\ \texttt{t = a + b}\ \langle\{b,n,t\}\rangle \quad \dfrac{\langle\{b,n,t\}\rangle\ \texttt{a = b}\ \langle\{a,n,t\}\rangle \quad \dfrac{\langle\{a,n,t\}\rangle\ \texttt{b = t}\ \langle\{a,b,n\}\rangle \quad \dfrac{\langle\{a,b,n\}\rangle\ \texttt{n = n - 1}\ \langle\{a,b,n\}\rangle}{\vdots}}{\vdots}}{\vdots}}{\langle\{a,b,n\}\rangle\ \texttt{t = a + b; a = b; b = t; n = n - 1}\ \langle\{a,b,n\}\rangle}}{\langle\{a,b,n\}\rangle\ \texttt{while (n > 0) \{ t = a + b; a = b; b = t; n = n - 1 \}}\ \langle\{a\}\rangle}}{\vdots}}{\langle\{n\}\rangle\ \texttt{a = 0; b = 1; while (n > 0) \{ t = a + b; a = b; b = t; n = n - 1 \}; return a}\ \langle\emptyset\rangle}$$

From structural analysis to code generation (1/2)

$$\text{Assign}\ \frac{v \in S^\circ \qquad S^\bullet = (S^\circ \setminus \{v\}) \cup FV(e)}{\langle S^\bullet \rangle\ \ v = e\ \ \langle S^\circ \rangle}$$

let assignment S° =
  let v = random_select S° **in**
  let e = random_expression () **in**
  ("v = e", $(S^\circ \setminus \{v\}) \cup FV(e)$)

From structural analysis to code generation (2/2)

$$\text{If}\ \frac{\langle S_1^\bullet\rangle\ \ S_1\ \ \langle S^\circ\rangle \qquad \langle S_2^\bullet\rangle\ \ S_2\ \ \langle S^\circ\rangle \qquad S^\bullet = S_1^\bullet \cup S_2^\bullet \cup FV(c)}{\langle S^\bullet\rangle\ \ \texttt{if}\ (c)\ S_1\ \texttt{else}\ S_2\ \ \langle S^\circ\rangle}$$

let branch S° =
  let (t, $S_1^\bullet$) = random_statements S° **in**
  let (f, $S_2^\bullet$) = random_statements S° **in**
  let c = random_expression () **in**
  ("if (c) t else f", $S_1^\bullet \cup S_2^\bullet \cup FV(c)$)

Generation of loops

While

$$\frac{\langle B^\bullet \rangle \;\; B \;\; \langle B^\circ \rangle \qquad \begin{array}{c} L^\bullet = B^\bullet \cup L^\circ \qquad L^\circ \neq \emptyset \\ B^\circ = L^\circ \cup B^\bullet \cup FV(c) \text{ (minimal)} \end{array}}{\langle L^\bullet \rangle \;\; \texttt{while}\ (c)\ B \;\; \langle L^\circ \rangle}$$

Idea:

- generate random variable set B', condition c
- assume least fixed point $B^\circ = L^\circ \cup B' \cup FV(c)$
- generate body given B°
- add statements to ensure all $v \in B'$ used in body and live-in

Implementation (1/2)

Plugin for Frama-C analysis platform
Generator: about 600 lines of OCaml
Features:

- arithmetic, simple arrays and pointers
- `if`, `while`
- `for` loops implementing map-reduce on arrays:

  ```
  v = ...;
  for (unsigned int i = 0; i < N; i++) {
      v = v ∘ f(arr[i]);
  }
  ```

- many flags for customization:

  ```
  -fp -fp-only -int-only -bitwise -div-mod
  -expr-depth -stmt-depth -block-length -loops
  -max-args -max-live
  ```

Implementation (2/2)

Limitations:

- no `struct` (coming at some point)
- very limited use of pointers, no pointer arithmetic
- strictly structured code only (no `break`, `continue`, `goto`)
- a single function, no `main` function

Csmith is much, much more general.

Evaluation

1000 programs generated each

	generator	min	median	max	total
lines of code	Csmith	25	368.5	2953	459021
	`ldrgen`	12	411.5	1003	389939
instructions	Csmith	1	15.0	1006	45606
	`ldrgen`	1	952.5	4420	1063503
unique opcodes	Csmith	1	8	74	146
	`ldrgen`	1	95	124	204

generator	time (sec)	lines/sec	instrs/sec
Csmith	871	527	52.4
`ldrgen`	124	3140	8562.8

Summary

- random program generation for testing compiler optimizations
- fully live programs by structural analysis during generation
- much more effective than Csmith for this use case

https://github.com/gergo-/ldrgen

Thank you for your attention

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