Creation of a Static Analysis Algorithm Using Ad Hoc Programming Languages

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Outline

Example of C code

```c
#include <stdlib.h>
#include <string.h>

struct vec { size_t n; size_t el; void *els; };

void remove_eq(struct vec *v, const void *el) {
  for (size_t i = 0; i < v->n; ++i) {
    if (memcmp((const char *)v->els + v->el * i, el,
          v->el))
      continue;
    memmove((char *)v->els + v->el * i,
        (const char *)v->els + v->el * (i + 1),
        v->n-- - i - 1);
    --i;
  }
}
```

Decomposition of C code

Structs Just data with automatic accessors; can be repaced with bitwise operations on in-memory representations;

Flow control In case of `continue`, `break`, and `goto` which doesn't go backwards can be replaced with more verbose conditional statements;

Multiple types of numbers Specific cases of a more general notion of a number modulo some power of two;

Pointer arithmetics Many mechanisms applicable to the normal arithmetics can be used for pointers as well.

And so on. Evidently, one could write the same programs with a really small set of constructs.

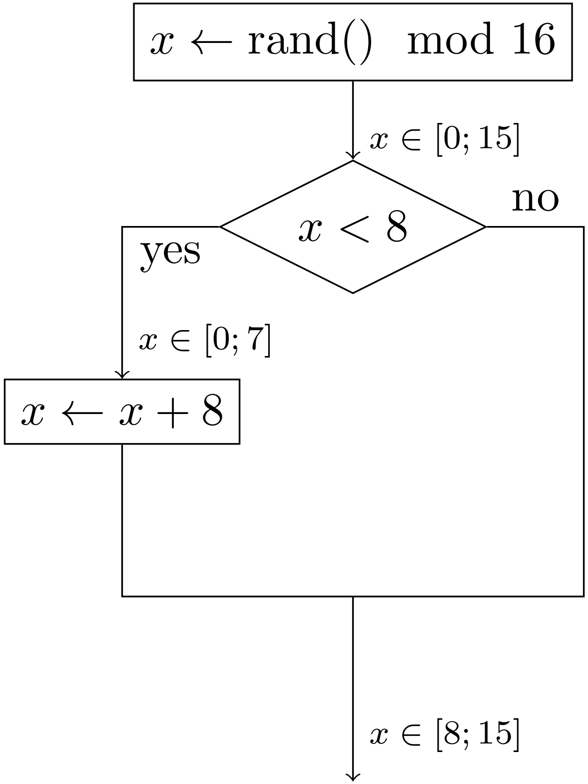
Example of Lisp code

```
(print
  ((lambda (n)
     (let ((cont #f))
       (let ((m (call/cc (lambda (k)
                           (set! cont k)
                           (cons 1 n)))))
         (if (> (cdr m) 0)
           (cont (cons (* (car m) (cdr m))
                       (- (cdr m) 1)))
           (car m)))))
   6))
```

Our method

1. Decide which class of data manipulation is of interest;
2. Create a type system which is capable solely of representing this precise data manipulation;
3. Determine the sufficient basis of operations which can be performed on the data and formalize the algorithm for them;
4. Extend the language with new constructs as needed, slightly adapting the algorithm.

Value range analysis



Type theory

Infinite numbers

- Have range $[0; +\infty)$;
- Support $[+], [-], [\times], [/], [<], [=]$;
- Type of integer is determined at time of analysis.

Modular numbers with parameter n

- Have range $[0; 2^n)$;
- Support $[+], [-], [\times], [/], [<], [=], [\wedge], [\vee], [\sim]$;
- At risk of overflow.

Exist conversions between the two kinds.

Arithmetics

- a `+` b, a `-` b, a `*` b, a `/` b, a `<` b, a `==` b — don't really need an introduction;
- a `&` b— bitwise AND;
- a `|` b— bitwise OR;
- `~`a— bitwise negation;
- `inf` a— conversion to a natural number;
- a `bits` N— a modulo 2^N.

Randomness

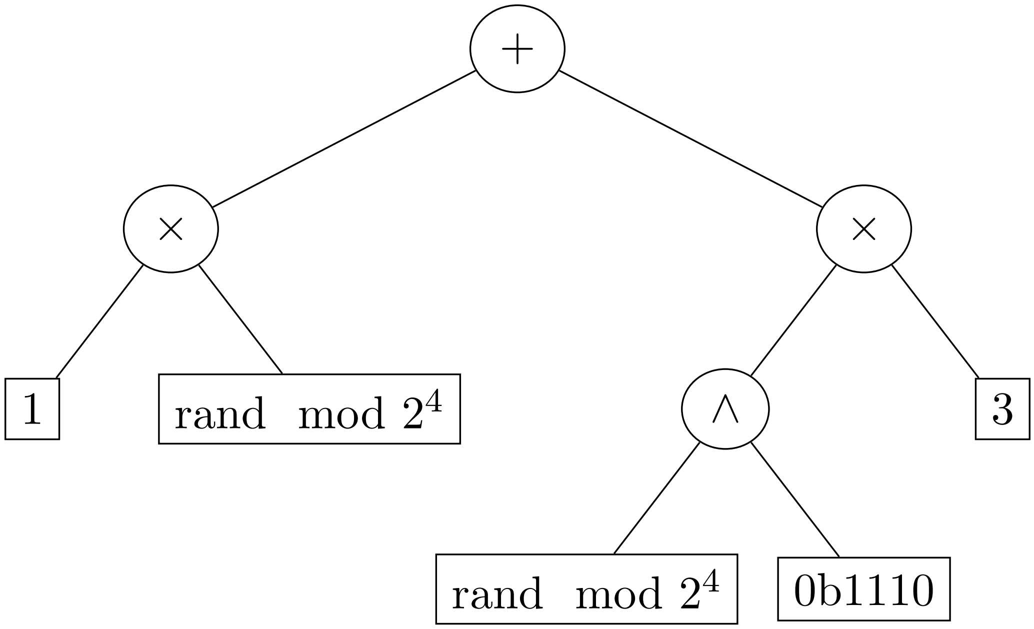
Rationale

Expressions like $(3 + (0\text{xF}8 \wedge 0\text{xA}) \times 4)$ are completely deterministic, don't allow us to simulate user input.

Format

`rand bits` N — an arbitrary value in $\left[0; 2^N\right)$.

Tree of arithmetic expressions



Chaining of assignments

Chaining

Chaining is ordered execution of statements, with statements commonly separated by semicolons:

$$s_1; s_2; \ldots; s_n$$

Assignment statement

Setting the value pointed to by the identifier v to the result of evaluation of expression e:

$$v \leftarrow e$$

Chaining of assignments: naive version

`@x = rand bits 4` $x \in [0; 15]$

;

`@y = @x + 2` $y \in [0 + 2; 15 + 2] = [2; 17]$

;

`@z = @x + 5` $z \in [0 + 5; 15 + 5] = [5; 20]$

;

`@m = @z - @y` $m \in [5 - 17; 20 - 2] = [-12; 18]$

Chaining of assignments: more robust version

`@x = rand bits 4` $x = \texttt{rand}_1\ \texttt{bits}\ 4$

;

`@y = @x + 2` $y = \texttt{rand}_1\ \texttt{bits}\ 4 + 2$

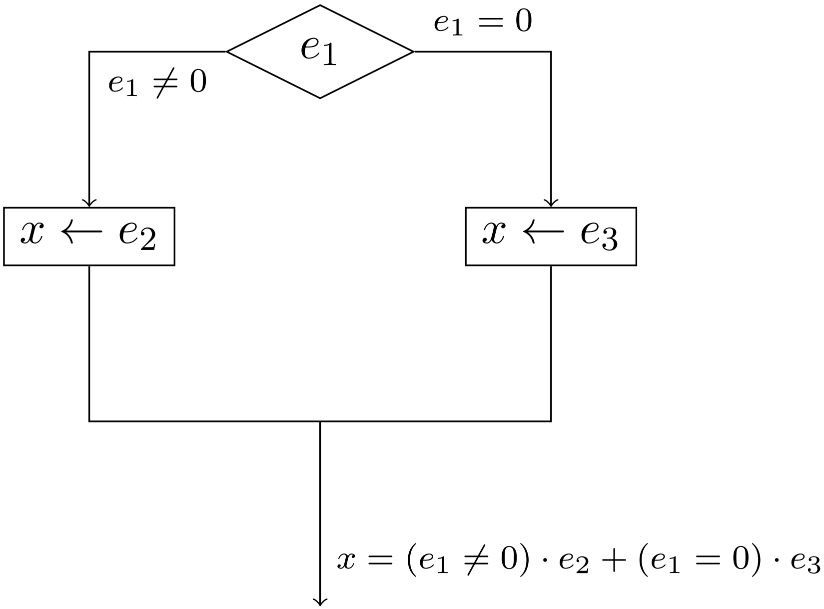
;

`@z = @x + 5` $z = \texttt{rand}_1\ \texttt{bits}\ 4 + 5$

;

`@m = @z - @y` $m = \texttt{rand}_1\ \texttt{bits}\ 4 + 5 - (\texttt{rand}_1\ \texttt{bits}\ 4 + 2) = 3$

Conditional expressions



Loops

$$\texttt{for } v \texttt{ to } e \texttt{ do } s \texttt{ done}, e \in [n; m]$$

$$\overbrace{s; s; s; \ldots; s}^{n};$$
$$\texttt{if } n < e \texttt{ then } s \texttt{ fi};$$
$$\texttt{if } n+1 < e \texttt{ then } s \texttt{ fi};$$
$$\vdots$$
$$\texttt{if } m-1 < e \texttt{ then } s \texttt{ fi};$$

Further extensions

- Pure functions: they are just operations on numbers, and their range analysis can be pre-compiled in a modular fashion;
- More types of numbers;
- Probabilistic model: determine not only the possibility of a certain execution path but its probability as well;
- Complex structures based on bitwise arithmetics;
- More complex loop handling with finding repeating states of interconnected variables in a loop.

Conclusion

- The algorithm we've developed can be easily checked due to modular approach taken during its development;
- The algorithm can easily be extended to account for more complex language features;
- Development has been a relatively simple task of creation, not implementation.