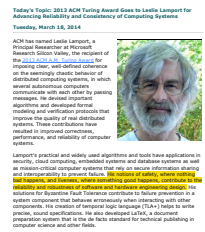
Graph Theory and Program Analysis

GRAPH-THEORETIC METHODS IN DATABASE THEORY

Mihalis Yannakakis

Secure programming via game-based synthesis

William Harris



Today's Topic: 2013 ACM Turing Award Goes to Leslie Lamport for Advancing Reliability and Consistency of Computing Systems

Tuesday, March 18, 2014

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Graph Theory

- Problems
  - transitive closure, shortest paths, bill of materials, critical paths, regular expressions
- Algorithms
  - Kleene's alg. for regular expressions
  - Floyd's alg. for shortest paths
  - Warshall's alg. for transitive closure

Matrix Multiply on Semiring

- A closed semiring
  - 0 and 1 exists
  - product x is associative, closed under finite products
  - sum + is associative/commutative, closed under finite sums
  - x distributes over +
- A graph
  - 0 is no path, 1 is null path
  - sum combines multiple paths
  - product extends a path

$$\textbf{for } k := 1 \textbf{ to } n \textbf{ do}$$
$$\quad \textbf{for all } i,\ j \textbf{ do}$$
$$\quad\quad A_{ij}^{k} := A_{ij}^{k-1} + A_{ik}^{k-1} \times (A_{kk}^{k-1})^{*} \times A_{kj}^{k-1}$$

Reachability

- Problem
  - Aij = 1 iff there is a path from i to j
- Solution
  - sum is ||, product is &&
  - initial Aij = 1 if ij connected; otherwise 0
- Explanation
  - connectivity including node k is the connectivity with node 1 to k-1, plus the connectivity from i to k, and plus the connectivity from k to j
- Transitive closure can then be computed easily

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Database Queries

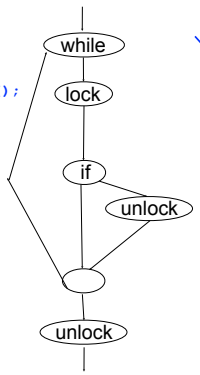
- Relational databases
  - "directed" hypergraphs, with labelled edges
  - a path "spells" a word
  - an L-path if the spelled word is in the language L
- Recursive queries
  - need to compute the transitive closure
  - not expressible in relational algebra/calculus
  - extensions in datalog and graph-oriented query languages
- Datalog language
  - example $p(X,Y) :- q_0(X,Z_1),\ q_1(Z_1,Z_2),\ldots,\ q_k(Z_k,Y),$
  - variables, predicates, recursion

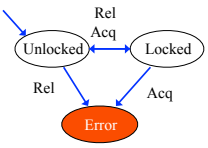
L-path

- A specification L
  - a regular expression
    - e.g. lock acquire/release/error DFA in SLAM
    - e.g. even-length paths
  - a context-free grammar
    - e.g. legal interprocedural paths in optimization
- A path satisfies L is an L-path
- SLAM
  - is there an L-path that reaches the error state anywhere in code?
    - is it an MOP problem?
- Interprocedural analysis
  - what is MOP invariance at every point?

Lock Safety

```
do {
   KeAcquireSpinLock();
   if(*){
        KeReleaseSpinLock();
   }
} while (*);
KeReleaseSpinLock();
```





RE specification?

Type State Analysis (one slide!)

languages. That is, we construct a graph H whose nodes are pairs (s,u) consisting of a state s of M and a node u of G, and which has an arc labelled a from a node (s,u) to another node (t,v) if M has a transition on letter a from state s to state t and G has an arc from u to v. (Actually, the labels in the product graph are not important.) Let s_0 be the initial state of M and F its set of accepting states. Then, the database graph G contains an L-path from a node x to a node y iff (s_0,x) can reach in the product graph a state (t,y) with $t \in F$.

- A state space H for lock-safety analysis
  - (prog point, lock status)
  - (s,u) -> (t,v) if s->t and u->v
  - problem: if (start, unlocked) can reach any (s, error) in H
  - single-source transitive closure

Program Analysis as Queries

- Queries
  - proposition logic
    - SQL
  - recursive
    - regular
      - e.g. lock safety spec
    - context-free
      - e.g. datalog
- Type of queries
  - existential: does something exist?
  - universal: does the property always hold?

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Type interpretation

Definition (Type interpretation)

The *type interpretation* $\mathcal{T}[\![.]\!]$ compositionally maps a regular expression E to the corresponding simple type:

$\mathcal{T}[\![0]\!]$	$=$	$\emptyset$	empty type
$\mathcal{T}[\![1]\!]$	$=$	$\{()\}$	unit type
$\mathcal{T}[\![a]\!]$	$=$	$\{a\}$	singleton type
$\mathcal{T}[\![E+F]\!]$	$=$	$\mathcal{T}[\![E]\!]+\mathcal{T}[\![F]\!]$	sum type
$\mathcal{L}[\![E\times F]\!]$	$=$	$\mathcal{T}[\![E]\!]\times\mathcal{T}[\![F]\!]$	product type
$\mathcal{T}[\![E^*]\!]$	$=$	$\{[v_1,\ldots,v_n] \mid v_i \in \mathcal{T}[\![E]\!]\}$	list type

http://www.cs.ox.ac.uk/ralf.hinze/WG2.8/27/slides/fritz.pdf

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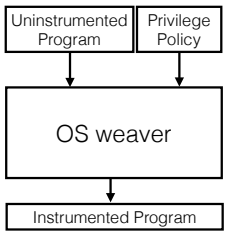


URCS Department Seminar, March 2014

Weaver **PL** results

- Automatically reproduced manually-written programs and automatically wrote new ones from **small, declarative policies that forbid known vulnerabilities**
- Reduced weaving to game-based synthesis, and proposed and evaluated **a novel symbolic game-solving algorithm [CAV '12]**

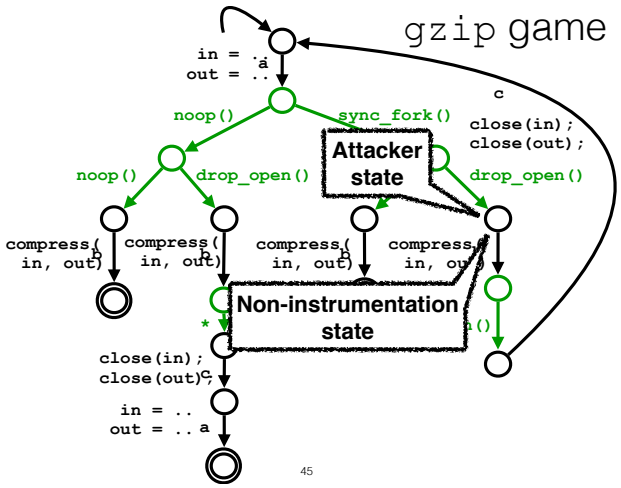
gzip on Capsicum

Server

```
gzip(argv):
   foreach (nm in argv):
IN:  in = open(nm);
OUT: out = open(nm + ".gz");
     sync_fork();
     drop_open();
     compress(in, out);
     sync_join();
     close(in);
     close(out);
```

At `compress`, `gzip` should have exactly the the last descriptors allocated at `IN` and `OUT`

gzip game



Weaver **systems** results

- Internal adoption: have engaged **both Capsicum and HiStar developers**
- External adoption: used by **DARPA** evaluation team to rewrite secure **PHP** interpreter as layer of prototype secure software stack
- Future goal: release Capsicum weaver to **`capsicum-dev`**

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Program Security

- Security = Safety + Liveness
- OS weaver
  - safety
    - i.e. 'compress' cannot have certain privileges
  - liveness
    - i.e. 'compress' can still be used correctly
    - Xiaochen's question at the talk
- Reachability analysis
  - can check for safety
  - can it insert code as OS Weaver can?
  - what about liveness?