Regression Verification for Multi-Threaded Programs

Arie Gurfinkel, Sagar Chaki — SEI/CMU

Ofer Strichman — Technion

Waterloo

Mentor Graphics

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UNIVERSITY OF WATERLOO


Going
Retro

Regression Verification

Formal equivalence checking of two similar programs

Three selling points:

- Specification:
  - not needed
- Complexity:
  - depends on the semantic difference between the programs, and not on their size
- Invariants:
  - Easy to derive automatically high-quality loop/recursion invariants

Applications of an “ideal” RV tool

Regression Verification

- Validate refactoring
- Understand how changes propagate through the API

Semantic Impact Analysis

Generic Translation Validation

Proving Determinism

- P is equivalent to itself IFF P is deterministic

And many more…

Definition: Partial Equivalence (Strichman et al.)

Program P_1 and P_2 are *partially equivalent (p.e.)* IFF

- Executions of P_1 and P_2 on equal inputs
  - …which terminate,
  - result in equal outputs.

Undecidable

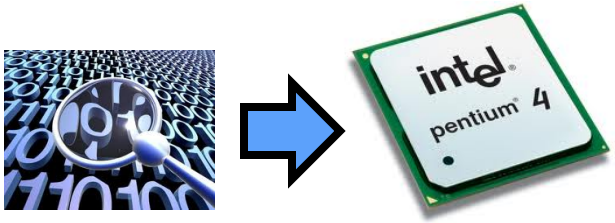
Supported by several tools

- RVT by Strichman et al.
- SymDiff by Lahiri et al.
- + LLRêve

Our Motivation

"Regression verification of Embedded Software"

- Explore use of regression verification to aid in migration of real-time software from single-core to multi-core platforms



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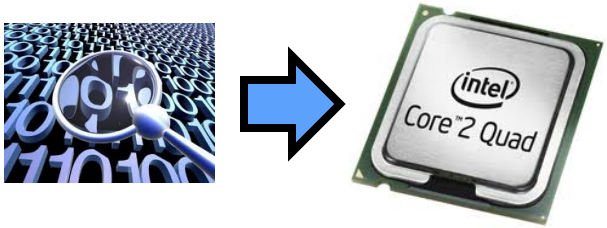
Need to extend regression verification to multi-threaded software first

- Real-time software is inherently multi-threaded
- Tasks run "in parallel", communicating via shared variables and locks
- Led to the research reported in this paper



Outline

What is a multi-threaded program?

$f_1 \parallel f_2$

Partial equivalence of multi-threaded programs

- Why the notion for sequential programs does not apply
- How to fix it

$f_1 \parallel f_2$

$=?$

$f'_1 \parallel f'_2?$

Sound proof rules for regression verification of multi-threaded programs

- What are the premises and the conclusion
- How to discharge the premises

$$\frac{\alpha, \beta, \gamma, \ldots}{f_1 \parallel f_2 = f'_1 \parallel f'_2}$$

Summary and Future Thoughts

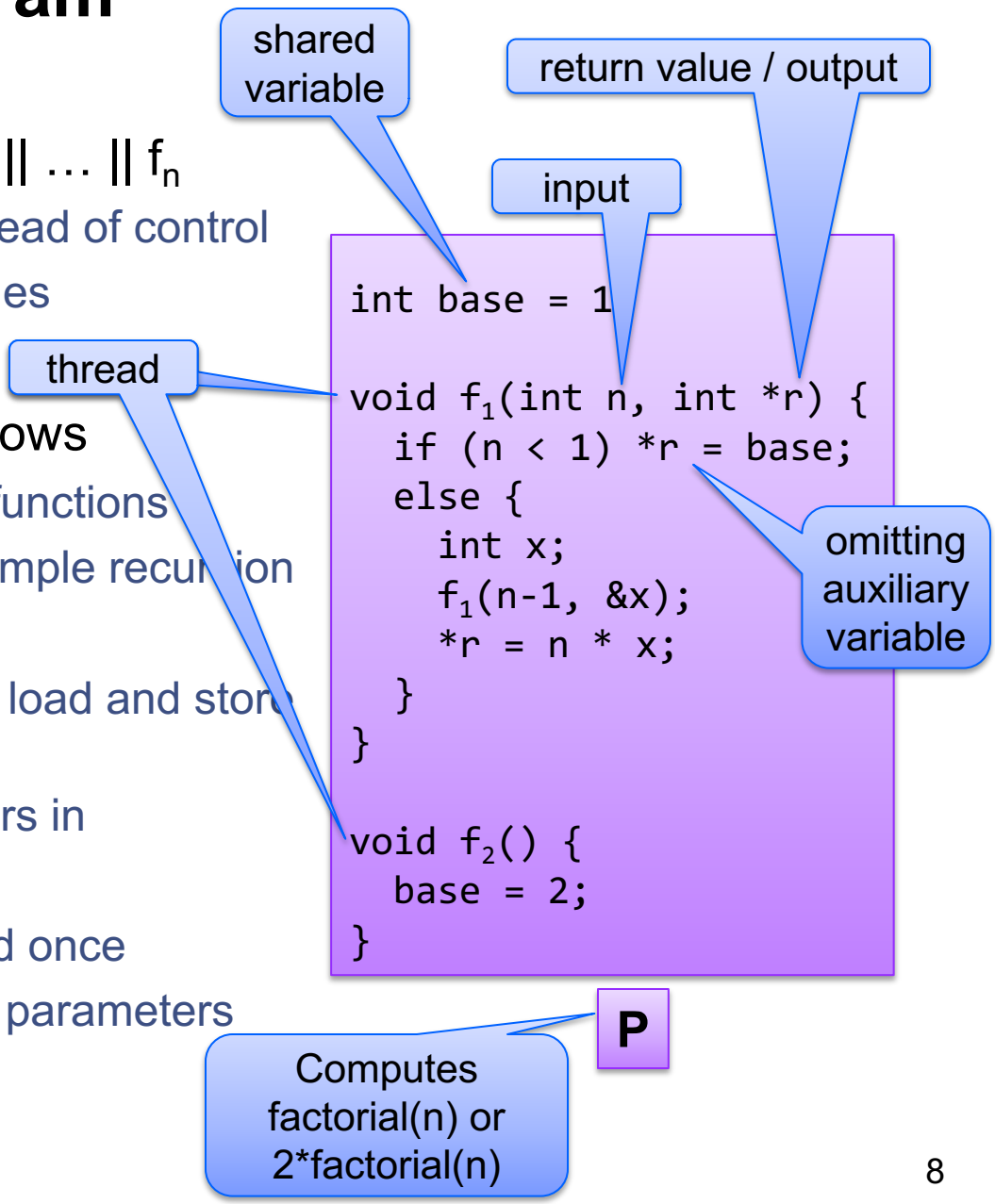
Multi-Threaded Program

Finite set of C functions : $P = f_1 \,||\, \ldots \,||\, f_n$

- Each executed in a separate thread of control
- Communicate via shared variables

Programs pre-processed as follows

- Loops are outlined to recursive functions
- Mutual recursion converted to simple recursion
- Non-recursive functions inlined
- Auxiliary variables introduced to load and store shared variables such that:
  - Shared variable x only appears in
    - t = x or x = exp
  - Each auxiliary variable is read once
- Functions return values through parameters passed by reference



Partial equivalence of multithreaded programs

Partial equivalence of sequential programs:

- P1 and P2 partially equivalent , all executions of P1 and P2 on equal inputs
  - …which terminate,
  - result in equal outputs

Consider multithreaded program P from previous slide

- Is P partially equivalent to itself?


```
int base = 1;

void f1(int n, int *r) {
  if (n < 1) *r = base;
  else {
    int x;
    f1(n-1, &x);
    *r = n * x;
  }
}

void f2() {
  base = 2;
}
```

Partial equivalence of multithreaded programs

P is a multi-threaded program (MTP)

Π(P): the set of terminating computations of P

R(P): relates inputs and outputs defined by Π(P):

- R(P) = { (*in*, *out*) | ∃π∈ Π(P). π begins in *in* and ends in *out* }

Definition: MTPs P_1, P_2 are *partially equivalent* if $R(P_1) = R(P_2)$

- denoted p.e. (P_1, P_2)

In our example P, is partially equivalent to itself

- R(P) = {(n, n!), (n, 2 * n!) | n ∈ nat }

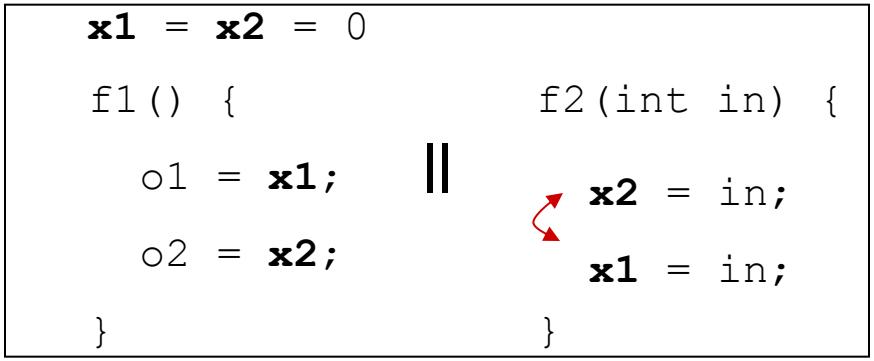
```
int base = 1;

void f1(int n, int *r) {
  if (n < 1) *r = base;
  else {
    int x;
    f1(n-1, &x);
    *r = n * x;
  }
}

void f2() {
  base = 2;
}
```

SOUND PROOF RULES FOR REGRESSION VERIFICATION OF MULTI-THREADED PROGRAMS

What affects partial equivalence of MTPs?



Swap write order

Before:

```
in = 1
o1 = 1, o2 = 0;
```

$(1, \langle 1, 0 \rangle) \in R(p)$

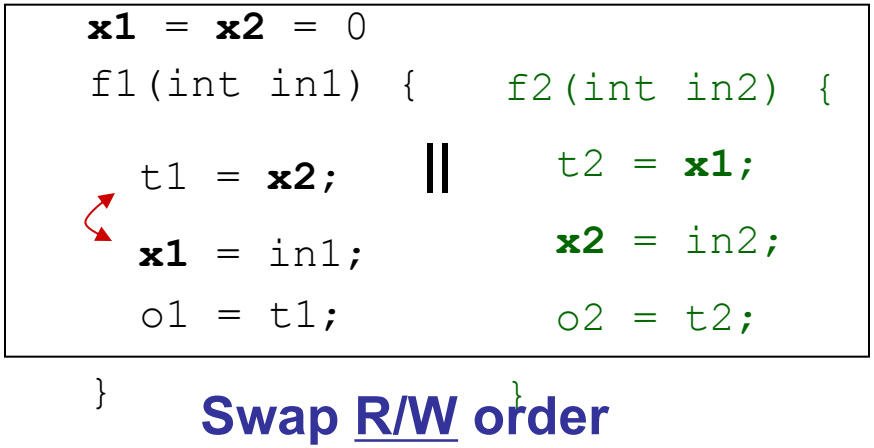
After:

```
in = 1
```

$o1 = 1 \Rightarrow o2 = 1$

$(1, \langle 1, 0 \rangle) \notin R(p)$

What affects partial equivalence of MTPs?



Before:

in1 = 1, in2 = 2

x1 = 1;

t2 = x1 = 1;

x2 = in2 = 2;

t1 = x2 = 2;

o1 = t1 = 2;

o2 = t2 = 1;

$(\langle 1,2\rangle, \langle 2,1\rangle) \in R(p)$

After:

in1 = 1, in2 = 2

o2 = 1 $\Rightarrow$

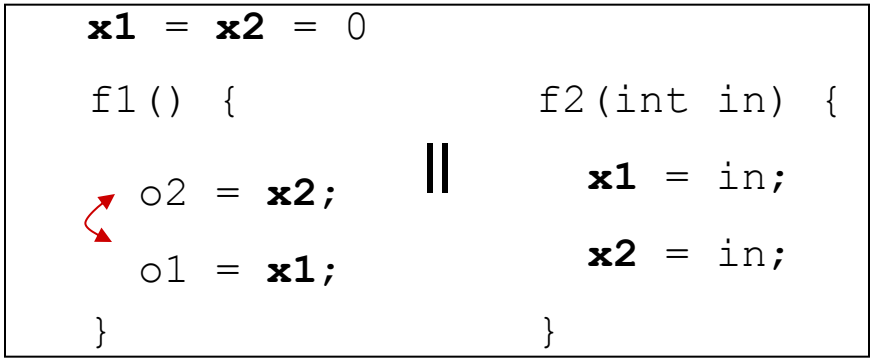
x1 = 1 < t2 = x1 $\Rightarrow$

t1 = 0 $\Rightarrow$

o1 = 0

$(\langle 1,2\rangle, \langle 2,1\rangle) \notin R(p)$

What affects partial equivalence of MTPs?



Swap read order

Before:

in = 1

o1 = 0, o2 = 1;

$(1, \langle 0, 1 \rangle) \in R(p)$

After:

in = 1

$o1 = 0 \Rightarrow o2 = 0$

$(1, \langle 0, 1 \rangle) \notin R(p)$

Mapping

Assume each function is used in a single thread.

- Otherwise, duplicate it

Find a mapping between the non-basic types

Find a bijective map between:

- threads
- shared variables
- functions (same prototype),
- in mapped functions: read globals, written-to globals

Without such a mapping: `goto end-of-talk`.

Function Semantics: Observable Stream

Consider a function *f* and input *in*

The observable stream of *f(in)*'s run is its sequence of

- function calls
- read/write of shared variables

Example: let *x* be a shared variable:

	The observable stream:
`x = in;`	
`t1 = t;`	
`t = x;`	
`g(t+1);`	

Observable Equivalence of Functions

Consider a function *f* and input *in*

The observable stream of *f(in)*'s run is its sequence of function calls and read/write of shared variables

- If the run is finite, we say it is a finite observable stream

f, f' are observably equivalent $\Leftrightarrow$
$\forall in.\ f(in)$, $f'(in)$ have equal sets of finite observable streams

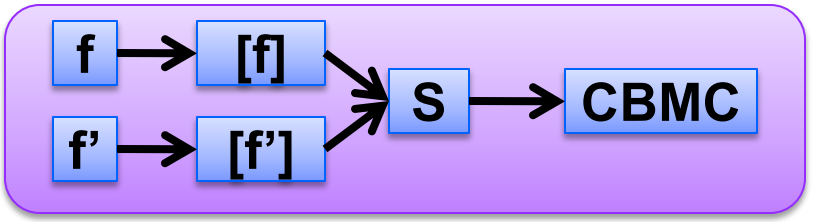
- Denoted by observe-equiv(f,f')

Assume: outputs are defined via shared variables (i.e., observable)
Then: observable equivalence $\Rightarrow$ partial equivalence

Checking Observable Equivalence of f and f'

Transform function f and f' to [f] and [f'] by:

- Reading shared variable x from an "input" stream UF_x
  - Maintain a location c in the stream
  - $t = x \leftarrow t = UF_x(c)$
- Recording outputs to the observable stream
  - shared variable accesses and function calls

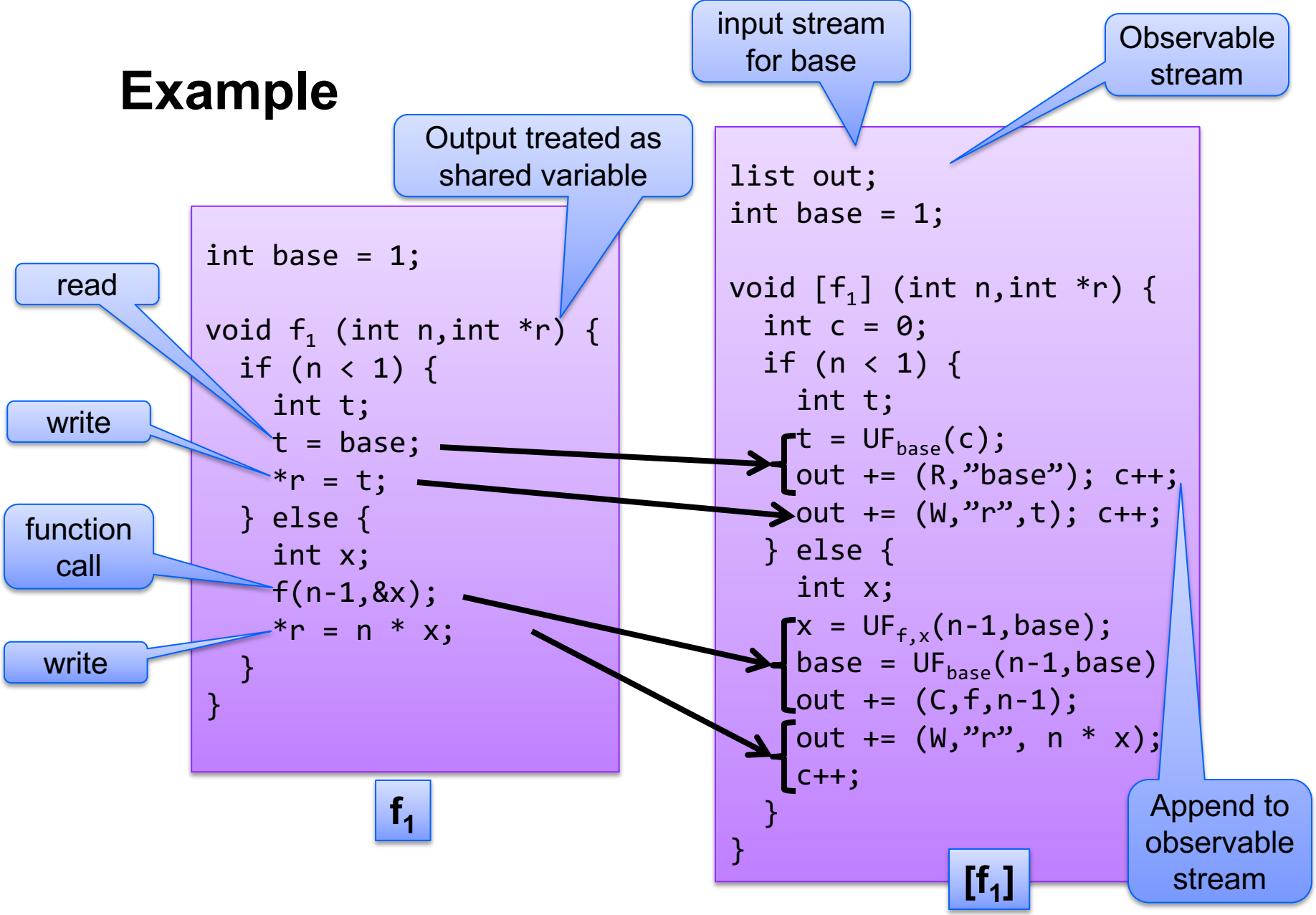


Generate sequential program S that calls [f];[f'] but also

- Ensures that inputs to f and f' are non-deterministic but equal
  - assume equal arguments and $UF_x = UF_{x'}$
- Asserts at the end that the observable streams of f and f' are equal
- S is linear in size of f and f'

Check validity (i.e., no assertion failure) of S (e.g., with CBMC)

Example


input stream for base
Observable stream
Output treated as shared variable
read
write
function call
write
int base = 1;
void f1 (int n,int *r) {
if (n < 1) {
int t;
t = base;
*r = t;
} else {
int x;
f(n-1,&x);
*r = n * x;
}
}
f1
list out;
int base = 1;
void [f1] (int n,int *r) {
int c = 0;
if (n < 1) {
int t;
t = UFbase(c);
out += (R,"base"); c++;
out += (W,"r",t); c++;
} else {
int x;
x = UFf,x(n-1,base);
base = UFbase(n-1,base)
out += (C,f,n-1);
out += (W,"r", n * x);
c++;
}
}
[f1]
Append to observable stream

```
void f1(int td, int *o) {
  int t1, t2, t3;
  if (td <= 0) t2 = x;
  else {
    t1 = x;
    t3 = t1 % td;
    x  = td;
    f1(t3, &t2);
  }
  *o = t2;
}

void f2() {
  int t;
  x = t;
}
```

```
void f1'(int td, int *o') {
  int t1, t2;
  t2 = x';
  if (td > 0) {
    t1 = x';
    x' = td;
    f1'(t1 % td, &t2);
  }

  *o' = t2;
}

f2'() {
  int t;
  x' = t;
}
```

Compute `gcd(td,x)`, where x is a shared variable set in another thread

```
void f1 (int td, int *o) {
  int t1, t2, t3, c = 0;
  if (td <= 0) {
    //2 ▷ t2 = x;
    t2 = UF_x(c);
    out1 += (R, "x"); c++;
  } else {
    //2 ▷ t1 = x;
    t1 = UF_x(c);
    out1 += (R, "x"); c++;
    //3 ▷ x  = td;
    t3 = t1 % td;
    x  = td;
    out1 += (W, "x", td); c++;
    //3 ▷ t2 = f1(t3, &t2);
    t2 = UF_f1_o(t3, x);
    x  = UF_f1_x(t3, x);
    out1 += (C, f1, t3, x);
  }
  //1 ▷ *o = t2;
  out1 += (W, "*o", t2); c++;
}
```

```
void f1'(int td, int *o') {
  int t1, t2, c = 0;
  //2 ▷ t2 = x';
  t2 = UF_x(c);
  out2 += (R, "x'"); c++;
  if (td > 0) {
    //2 ▷ t1 = x';
    t1 = UF_x(c);
    out2 += (R, "x'"); c++;
    //2 ▷ x' = td;
    x' = td;
    out2 += (W, "x'", td); c++;
    //3 ▷ f1'(t1 % td, &t2);
    t2 = UF_f1_o(t1 % td, x');
    x'  = UF_f1_x(t1 % td, x');
    out2 += (C, f1, t1 % td, x');
  }
  //1 ▷ *o' = t2;
  out2 += (W, "*o'", t2); c++;
}

main() {
  int in;
  f1(in);  f1'(in);
  rename(out2);
  assert(out1 == out2);
}
```

Proof Rule 1

Compositional:

- check one function pair at a time (supports recursion)
- requires verification of sequential program only (no thread composition)
- even when there are more than two threads
- shows that regression verification is “easier” than verification even for MTPs

ween the functions of P_1 and P_2

Sound (proof in the paper)

$$\frac{\forall\ f,f' \in \textit{map}.\ \textbf{observe-equiv}(f,f')}{\textbf{p.e.}\ (P_1, P_2)}$$

However:

- Premises are very strong
- f must be equivalent to f’ under all environments

Proof Rule 2

Premises are weaker than Rule 1 but harder to discharge

- More “complete” than Rule 1
- Details in the paper

Observable equivalence of f and f’ under environments compatible with the other threads in the program

Key insights:

since there are no loops, each function f reads shared variables atmost K times (K depends on f)

the environment of f compatible with another thread f_q is abstracted by a K-recursion-bounded abstraction of f_q

intuitively, the abstraction allows all behaviors with at most K recursive calls of f_q

$$\frac{\forall\ f,f' \in \mathit{map}.\ \Delta\ (f,f')}{\text{p.e. } (P_1, P_2)}$$

Compositional (like Proof Rule 1)

check one function pair at a time (supports recursion)

requires verification of sequential program only (no thread composition)

even when there are more than two threads

Other extensions

Support arbitrary many threads with dynamic thread creation

- Track thread creation in the output stream
- As long as same threads are crated, p.e. holds

Support atomic sections

- Necessary for modeling synchronization primitives such as locks
- Use local read/write (i.e., no UF) for shared variables written under atomic section

Sagar Chaki, Arie Gurfinkel, Ofer Strichman: Regression verification for multi-threaded programs (with extensions to locks and dynamic thread creation). Formal Methods in System Design 47(3): 287-301 (2015)

Summary and Future Thoughts

Foundations of regression verification for multi-threaded programs

- Notion of partial equivalence of multi-threaded programs
- Two (sound) proof rules

Implementation and experimental validation

Synchronization primitives

- Locks, semaphores, atomic blocks

Real-time software

- Different execution (e.g., reactive) and scheduler model (e.g., priority-based)
- Different synchronization primitives (e.g., priority-ceiling, priority-inheritance)

THANK YOU!

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Contact Information

Arie Gurfinkel
Senior Member of Technical Staff
RTSS Program
Telephone: +1 412-268-7788
Email: arie@cmu.edu

U.S. Mail
Software Engineering Institute
Customer Relations
4500 Fifth Avenue
Pittsburgh, PA 15213-2612
USA

Web
www.sei.cmu.edu/staff/arie

Customer Relations
Email: info@sei.cmu.edu
Telephone: +1 412-268-5800
SEI Phone: +1 412-268-5800
SEI Fax: +1 412-268-6257

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