Centre Val de Loire
UNIVERSITÉ
Spirit of the Loire Valley

UNIVERSITE D'ORLEANS

VERIFICATION OF CONCURRENT PROGRAMS ASSISTED BY CODE AND SPECIFICATION TRANSFORMATION

PHD THESIS DEFENCE

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December 6th, 2016

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LABORATOIRE D'INFORMATIQUE FONDAMENTALE D'ORLEANS
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Table of Contents

Table of Contents

Programs

Complex software

- Software is composed of millions of lines of code
- More multi-core architectures
- More concurrent programs

Concurrent Programs

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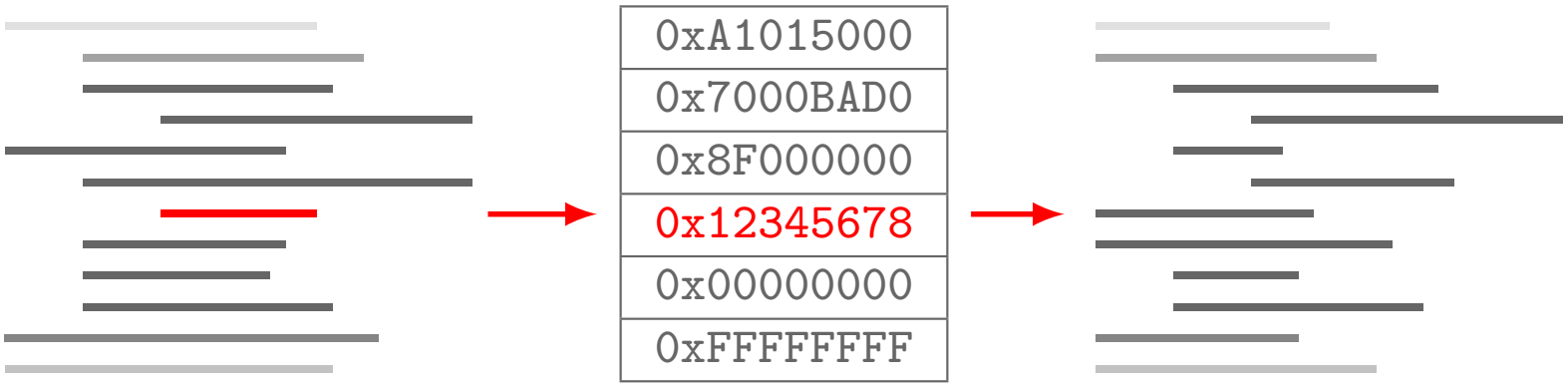

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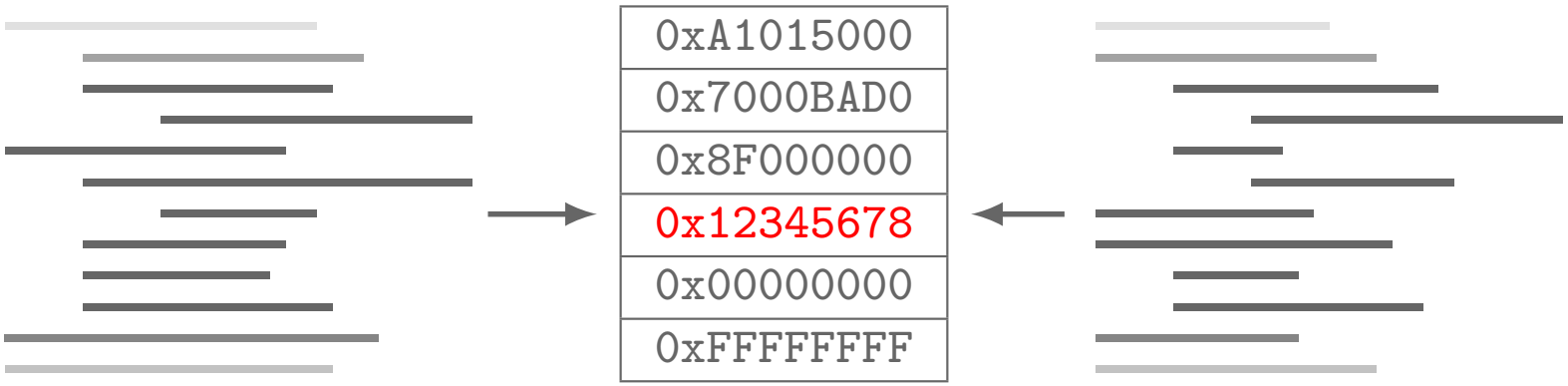

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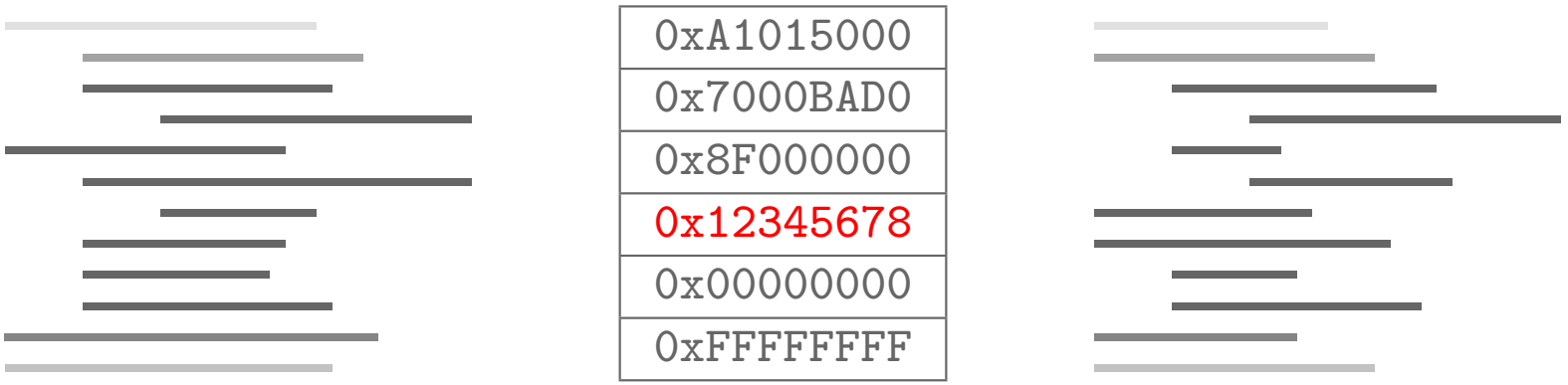


How can we ensure the validity of our software ?

Existing Methods

Most commonly used

- Program testing

Formal Methods

- Abstract interpretation
- Model-checking
- Theorem proving

Existing Methods

Most commonly used

- Program testing

Formal Methods

- Abstract interpretation
- Model-checking
- Theorem proving

Concurrent Programs Logics

Assuming sequentially consistent memory model

- HOARE 1975. Critical sections, abstract from time
- OWICKI-GRIES 1976. Resource invariant, ghost variables
- Rely-Guarantee, JONES 1983. Interferences
- Concurrent Separation Logic, O'HEARN et al 2007
- Combination of RG and CSL, VAFEIADIS et al 2007

Assuming weak memory models

- Relaxed separation logic, VAFEIADIS et al 2013
- Ghost, Procotols and Separation, VAFEIADIS et al 2014

Existing Verification Tools

Concurrent C code verification

- VCC (Owicki-Gries + $\sim$ Rely Guarantee + Ownership)
- Verifast (Separation logic)

FRAMA-C

- C code analysis
- Modular architecture based on plugins
- Most analyses do not handle concurrency

Contribution

Code and specification transformation

Transform a concurrent code into a (simulating) sequential one

- Experimented on a use case
- Automated in a FRAMA-C plugin
- Proved sound

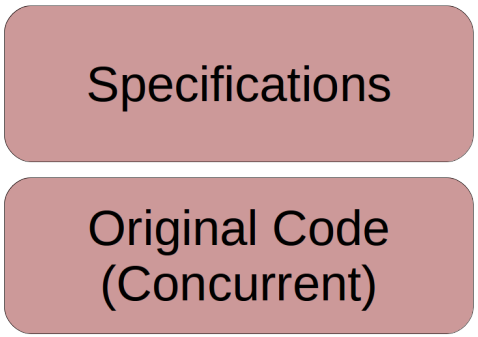
Weak memory models

A constraint based solver for weak memory behaviors

- Generate all candidate executions of a program
- Determine for each one if it is allowed by a given model

Table of Contents

Overview I



Requirements

- Equivalence of code must be proved
- Do not alter specification meaning
- Added specifications must always be automatically proved

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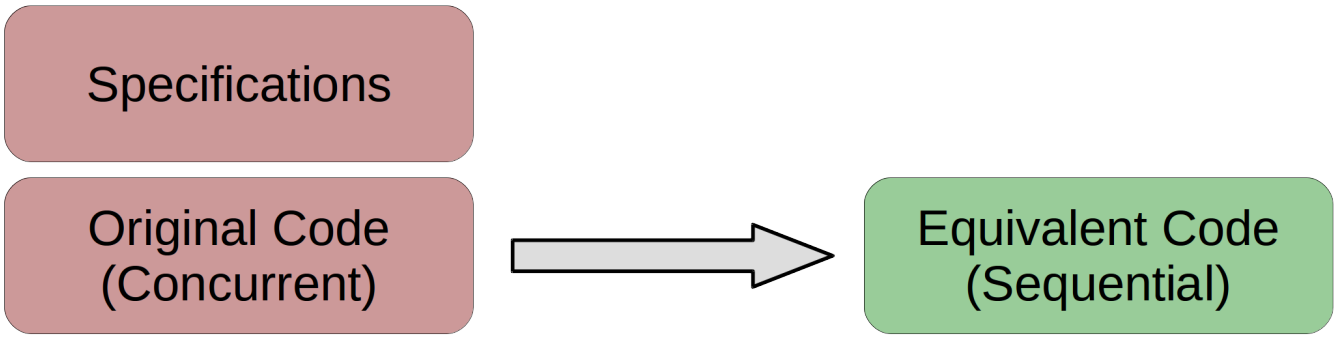

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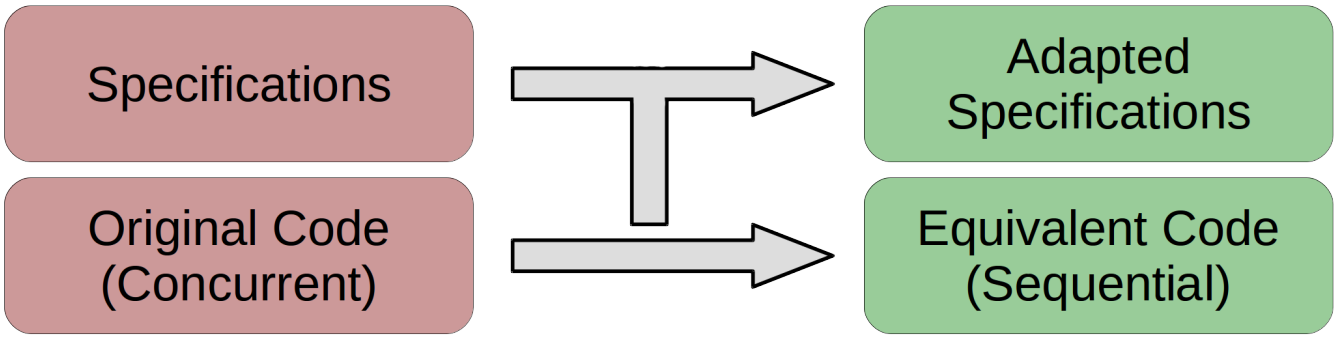

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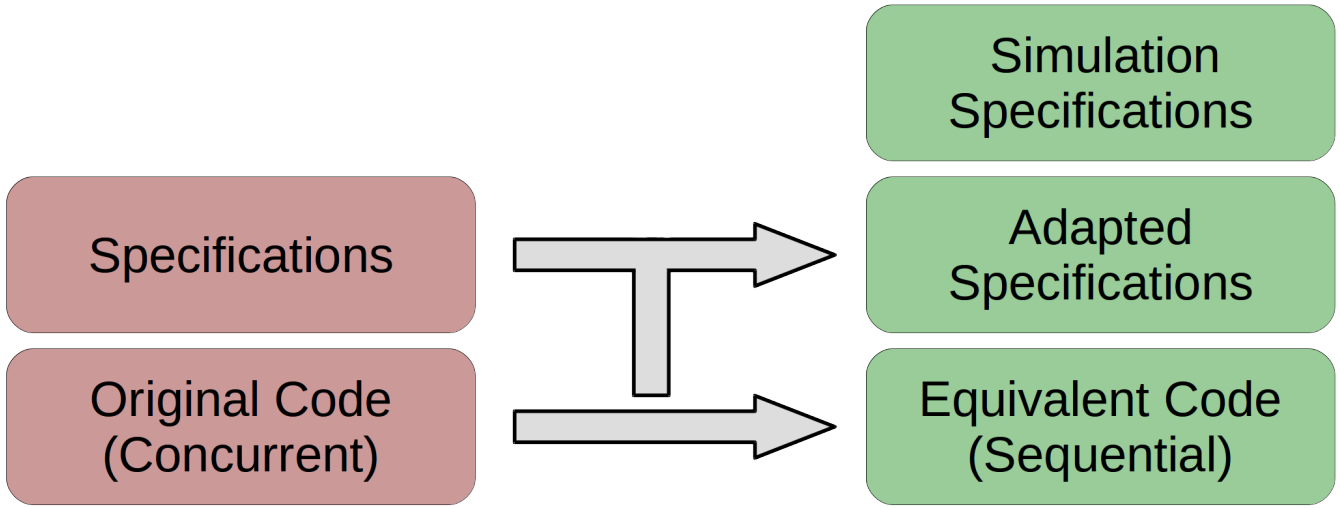

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Overview II

Code transformation

- Each local variable becomes a simulating array
- Each instruction becomes a function
- All functions are interleaved to simulate concurrency

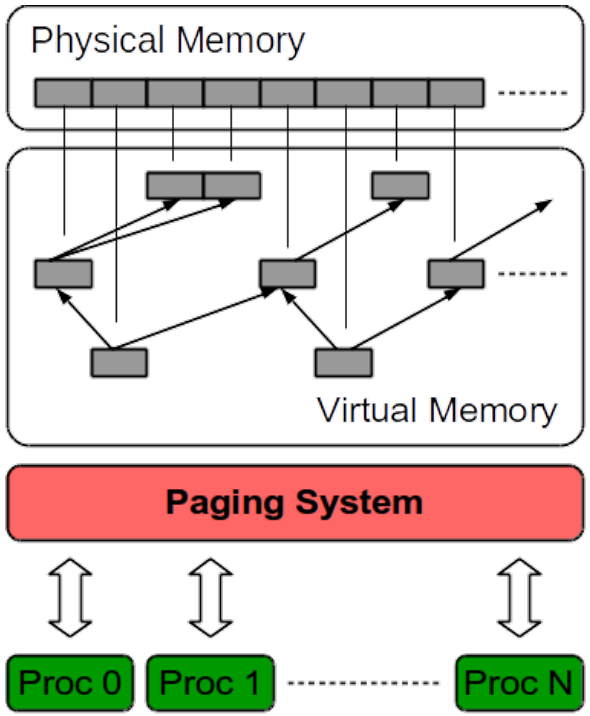
We suppose an interleaving semantics $\Rightarrow$ SC memory model

Specifications transformation

- Invariants are simulating functions pre/post conditions
- Each variable is replaced by its simulation counterpart

Case study – Micro-kernel code

- Anaxagoros Microkernel Virtual Memory Subsystem
  - Manages memory pages
  - Organized as hierarchy
  - **Counts mappings to pages**
- We want to verify the function used to update page tables
  - For any page, the indicated number of mappings must be greater or equal to the reality



Case study – Verification results

For atomic low-level functions

- ACSL specifications
- Proof with FRAMA-C and WP

For the page update function (concurrent)

- Specification and proof for sequential version
- Simulation of concurrent executions
- Weakening of the specification and proof:
  - Mostly automatic with FRAMA-C and WP
  - Auxiliary lemmas proved with COQ

Case study – Simulation

Original Code

```
#define NOF 2048
#define MAX  256

uint mappings[NOF];

int set_entry(uint fn, uint idx, uint new){
  uint c_n = mappings[new];
  if(c_n >= MAX) return 1;
  if(!CAS(&mappings[new], c_n, c_n+1))
    return 1;

  page_t p = get_frame(fn);
  uint old = atomic_exchange(&p[idx], new);

  if(!old) return 0;

  fetch_and_sub(&mappings[old], 1);
  return 0;
}
```

Simulating Code

```
#define THD 16

uint pct[THD];

uint fn [THD];
uint idx[THD];
uint new[THD];
uint c_n[THD];
uint old[THD];

//@ghost uint ref[THD]

...
```

Case study – Simulation

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#define NOF 2048
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  fetch_and_sub(&mappings[old], 1);
  return 0;
}
```

Simulating Code

```
...

void gen_args(uint th){
  fn[th]  = random_page();
  idx[th] = random_idx();
  new[th] = random_page();
  pct[th] = 1;
}

...
```

Case study – Simulation

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#define NOF 2048
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  uint old = atomic_exchange(&p[idx], new);

  if(!old) return 0;

  fetch_and_sub(&mappings[old], 1);
  return 0;
}
```

Simulating Code

```
...

void read_map_new(uint th){
  c_n[th] = mappings[new[th]];
  pct[th] = 2;
}

...
```

Case study – Simulation

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```
#define NOF 2048
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uint mappings[NOF];

int set_entry(uint fn, uint idx, uint new){
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  if(!CAS(&mappings[new], c_n, c_n+1))
    return 1;

  page_t p = get_frame(fn);
  uint old = atomic_exchange(&p[idx], new);

  if(!old) return 0;

  fetch_and_sub(&mappings[old], 1);
  return 0;
}
```

Simulating Code

```
...

void interleaving(){
  while(true){
    uint th = choose_a_thread();

    switch(pct[th]){
    case 0 : gen_args(th);      break;
    case 1 : read_map_new(th); break;
    case 2 : test_map_new(th); break;
    case 3 : cas_map_new(th);  break;
    case 4 : exch_entry(th);   break;
    case 5 : test_old(th);      break;
    case 6 : fas_map_old(th);  break;
    }
  }
}
```

Case study – Benefits and Limitations

Verification results

- Using FRAMA-C with WP
- Mostly automatic thanks to SMT solvers (CVC4, Z3)
- Completed by interactive proof using COQ

Limitations

- Most of the work could have been done automatically
- Known fixed-size arrays : fixed number of threads
- Limited scaling expected

CONC2SEQ – Features

CONC2SEQ role

- Perform code transformation
- Adapt specifications

Supported

- Most C instructions
- Thread local variables
- Atomic operations (`stdatomic.h`)
- Atomic blocks of code
- Global invariants

CONC2SEQ – Code transformation: variables

Original Code

```
int global;
int th_v thread_local;

void foo(){
  int v;
}
```

Generated Code

```
int* pct;
int  global;
int* tl_th_v;
int* foo_v;

/*@ axiomatic Validity_of_sim_vars {
predicate simulation{L} reads <sim ptrs>;

axiom all_simulations_separated{L}:
simulation ==>
\separated( <memory blocks/globals> );

axiom pct_is_valid{L}:
simulation ==>
( \forall integer j; valid_th(j) ==>
    \valid(\at(pct,L)+j));
//...
} */
```

simulating variables separation

simulating variables validity

CONC2SEQ – Code transformation: atomic instructions

Original Code

```
void foo(){
  int v;
  th_v = atomic_load(&global);



  /*@ atomic \true; */{
    v = 42;
    global += v;
  }
}
```

Generated Code

```
void foo_Call_1(uint th){
  tl_th_v[th] = atomic_load(&global);
  pct[th] = 2;
}

void foo_Atomic_2(uint th){
  foo_v[th] = 42;
  global += foo_v[th];
  pct[th] = 3;
}
```

Conc2Seq – ACSL fold

New ACSL built-in to talk about threads

A logic fold operation on the value of a variable for all threads

- Generate an axiomatic definition for each usage ...
- ... according to provided types and logic function.

Idea

```
thread_reduction(func, v, init)
⇔
func(sim_v[0], func(..., func(sim_v[NTH], init)))
```

Soundness proof – Simplified language

mth	::=	$m(\mathit{list}\ x)\mathit{block}$	$m \in \mathit{Names}$
main	::=	$m(\mathit{list}\ e)$	
c	::=	$x := e$	local assignment
	|	$x[y] := e$	memory store
	|	$x := y[e]$	memory load
	|	**while** e **do** *block*	
	|	**if** e **then** *block* **else** *block*	
	|	$m(\mathit{list}\ e)$	call
	|	**atomic** *block*	
v	::=	$n \mid l \mid b$	$n \in \mathbb{Z}, l \in \mathbb{L}, b \in \mathbb{B},$
e	::=	$v \mid x \mid op(\bar{e})$	$x \in \mathcal{X}$

Soundness proof – Definitions: States and Traces

States

local environments	$P = \{\rho : \mathcal{X} \rightharpoonup \mathcal{V}\}$
heaps	$\Sigma = \{\sigma : \mathbb{L} \rightharpoonup \mathbb{N} \rightharpoonup \mathcal{V}\}$
global state (seq)	$\gamma_{seq} : \Sigma \times \overline{Names \times P \times \mathcal{C}}$
global state ($\|\|$)	$\gamma_{\|\|} : \Sigma \times (\mathbb{T} \to \overline{Names \times P \times \mathcal{C}})$

Traces

Actions:

- $a ::= \tau \mid \texttt{call}\ m \mid \texttt{return}\ m \mid \texttt{read}\ l\ n\ v \mid \texttt{write}\ l\ n\ v$
- $\texttt{atomic}\ a*$

Soundness proof – Hypotheses

Memory

- Statically allocated
- Does not initially contain addresses

Forbidden actions

- Nested atomic blocks
- Thread spawning
- Recursive functions

Soundness proof – Function call/return

New simulating memory blocks

- For each function we add an address *from* in the heap
- It indicates the next instruction to perform in the caller

Call/Return simulation

- Call simulation updates *from* for the executed thread
- Return simulation puts the program counter to this value

Soundness proof – Equivalences

State equivalence

- $\sigma_{sim} = \sigma_{||} \sqcup \sigma_{sim,\mathcal{X}}$
- $\sigma_{sim,\mathcal{X}}$ correctly represents every local environment
- $\sigma_{sim,\mathcal{X}}$ correctly models every stacks

Trace equivalence

- Forall action (t, a), we have a list of actions $(\texttt{write}\ \ ptid\ 0\ t) :: l$, where:
  - $l = []$ if a is τ
  - $l = [a]$ if a is a memory access
  - $l = [\texttt{call}\ \ m]$ if a is a call/return and m is its simulation
  - l is the list of actions of a, if a is an atomic block action.

Soundness proof – Main result

Theorem

Forall (safe) $p_{||}$, p_s its simulation, from states $\gamma_{||,init}$ and $\gamma_{s,init}$

- by simulation initialization, we reach $\gamma_{s,0}$ equivalent to $\gamma_{||,init}$
- forall γ_s reachable from $\gamma_{s,0}$ with a trace t_s, there exists $\gamma_{||}$ reachable from $\gamma_{||,init}$ with a trace $t_{||}$ equivalent to t_s.
- forall $\gamma_{||}$ reachable from $\gamma_{||,init}$ with a trace $t_{||}$, there exists γ_s reachable from $\gamma_{s,0}$ with a trace t_s equivalent to $t_{||}$.

Proof ideas

- Sequential actions are deterministic, their translation too
- Thread selection: just choose the same thread

Formalization – Toward a Coq proof

Implemented up to known

- Language and semantics
- Transformation function

Next steps

- Write equivalence in Coq
- Perform the Coq proof

Table of Contents

Sequential Consistency (Lamport 1979)

A simple program

$$\mathtt{x} := 0;\ \mathtt{y} := 0$$

Thread 0	Thread 1
$\mathtt{x} := 1;$	$\mathtt{y} := 1;$
$\mathtt{r}_0 := \mathtt{y};$	$\mathtt{r}_1 := \mathtt{x};$

Possible results :

- $\mathtt{r}_0 = 1 \wedge \mathtt{r}_1 = 1$
- $\mathtt{r}_0 = 0 \wedge \mathtt{r}_1 = 1$
- $\mathtt{r}_0 = 1 \wedge \mathtt{r}_1 = 0$

Impossible result :

- $\mathtt{r}_0 = 0 \wedge \mathtt{r}_1 = 0$

Existing dedicated tools

Herding cats (Alglave et al. 2014)

Generic framework for weak behaviors

- Written in OCaml
- Provides a language to specify memory models

JMMSolve (Schrijvers 2004) based on CCMM (Saraswat 2004)

Program executions under Java Memory Model

- Based on Concurrent Constraint-based Memory Machines
- Written using Constraint Handling Rules (CHR)

Prolog and CHR

Prolog

Declarative language for logic programming

Constraint Handling Rules

Declarative language for constraint programming

- Maintains a store of constraints ($\sim$ terms)
- Handled by rules that will add or remove constraints

Goals of our solver

To identify allowed executions

- For a given parallel program
- According to a given memory model

Additional goals

- Possibility to add new memory models
- Support of specific instructions

Chosen approach

Generate all candidate executions

An execution is represented by ordering relations :

- For each location *l*, a total ordering of every store to *l* (CO)
- For each load, a store having written the read value (RF)
- We combine all permutations of CO/RF using backtracking

Filter out forbidden executions

- Apply model rules to deduce more ordering relations
- Incoherent execution: an action must happen before itself (which means that some relations exhibit a cycle)

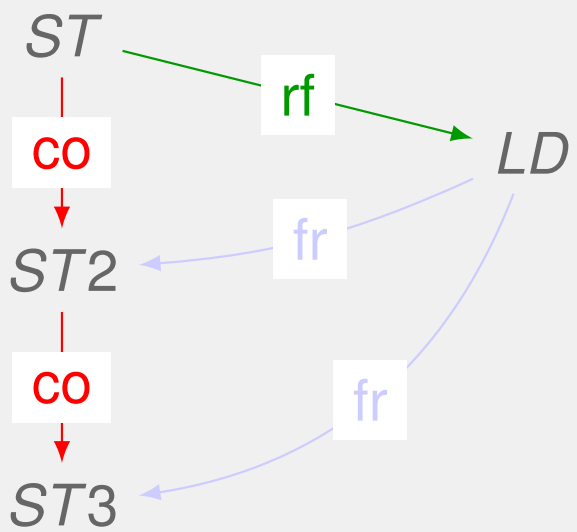
Express and derive relations with CHR

Ordering relations vs. CHR constraints

Relation	CHR constraint
$x := 0 \xrightarrow{CO} x := 1$	$\texttt{co}(\texttt{x} := 0, \texttt{x} := 1)$
$x := 2 \xrightarrow{RF} r := x$	$\texttt{rf}(\texttt{x} := 2, \texttt{r} := \texttt{x}(2))$

CHR rules to derive new relations :

- $\texttt{rf}(\texttt{ST}, \texttt{LD}), \texttt{co}(\texttt{ST}, \texttt{ST2}) \Rightarrow \texttt{fr}(\texttt{LD}, \texttt{ST2})$.
- $\texttt{fr}(\texttt{LD}, \texttt{ST2}), \texttt{co}(\texttt{ST2}, \texttt{ST3}) \Rightarrow \texttt{fr}(\texttt{LD}, \texttt{ST3})$.



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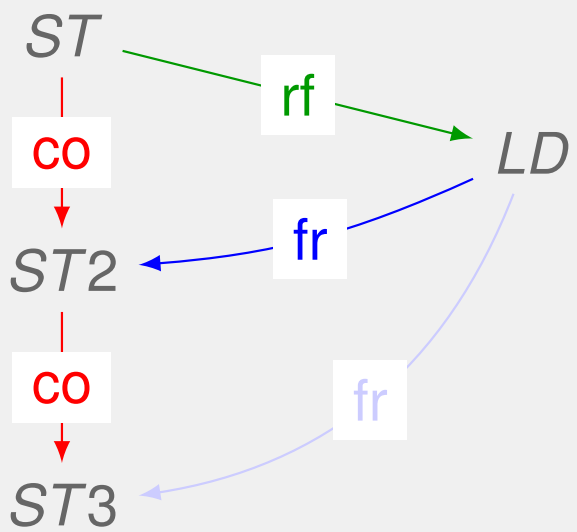

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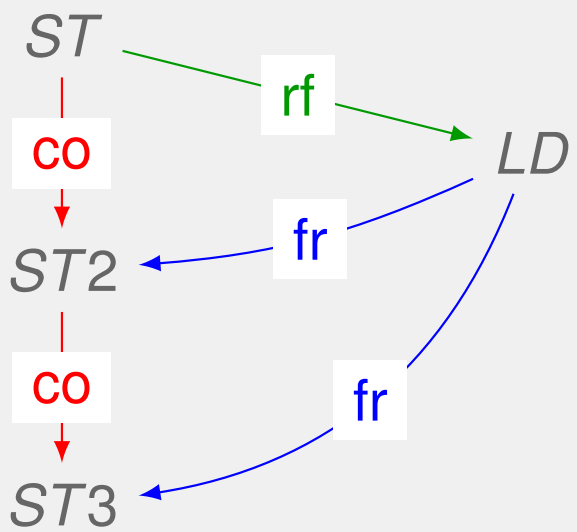
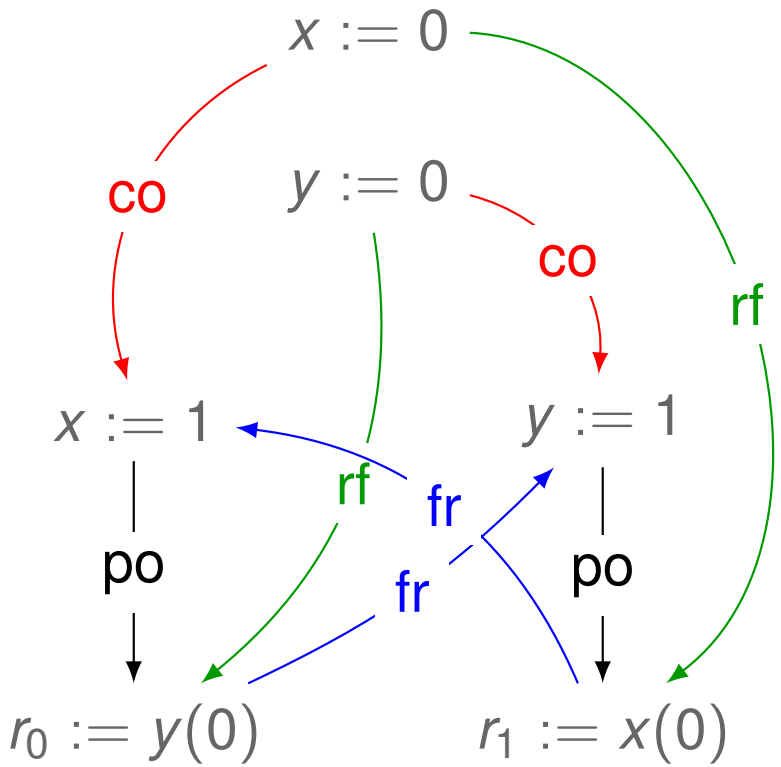


Definition of a model : SC

Definition of a model

- Define a new relation as the union of maintained relations

```
co(I,J) ==> sc(I,J).
rf(I,J) ==> sc(I,J).
fr(I,J) ==> sc(I,J).
po(I,J) ==> sc(I,J).
```



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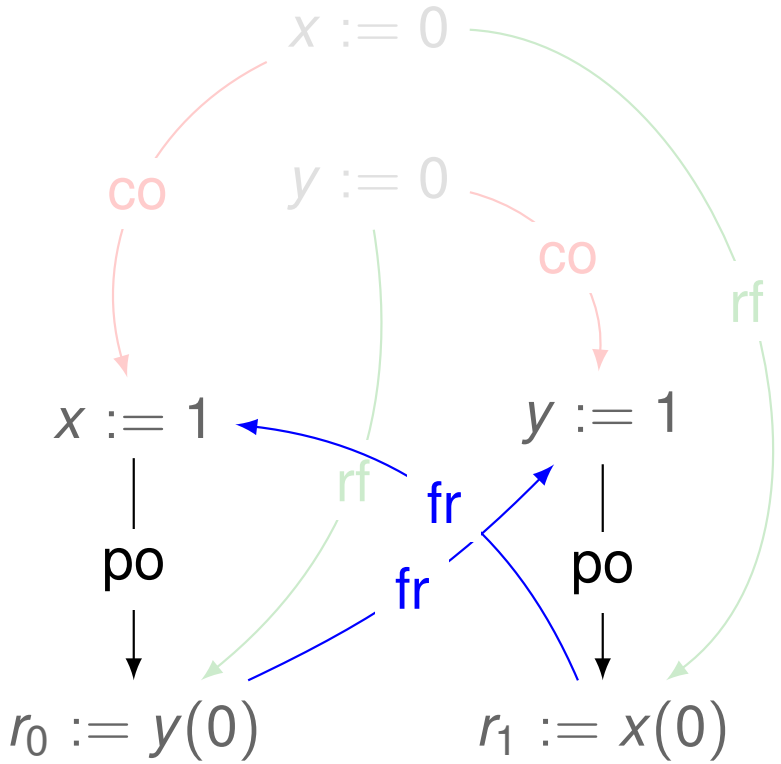

Validation

Available Models

- SC, TSO, PSO and ARM (Almost finished)
- Easy to extend new memory models

Program samples from Herd

Our solver has been tested on 18 examples of litmus programs

- Message passing,
- Basic uniproc relations,
- ...

We observe the same results found by Herd.

Performance tests

Multiple message passing

Example	Model	#exec	Herd	CHR Solver
MP3	Generic	147 436	**1.2s**	3.3s
	PSO	2 258	**3.8s**	6.4s
	TSO	800	4.1s	**3.2s**
	SC	678	5.5s	**3.3s**
MP4	Generic	255 000 000	**1405s**	$>$ 1h
	PSO	516 030	$>$ 1h	**2796s**
	TSO	96 498	$>$ 1h	**752s**
	SC	81 882	$>$ 1h	**747s**

Early pruning makes the solver efficient for “long” programs.
Our solver was not so hard to implement.

Table of Contents

Contribution

A method for the verification of concurrent code

- Under sequentially consistent memory model
- Based on code and specification transformation

Our method is

- Successfully applied on a part of a microkernel [FMICS 2015]
- Now automated in a Frama-C plugin [SCAM 2016]
- Proved sound on paper, to be proved using Coq.

A CHR based solver for weak memory behaviors [CSTVA 2016]

- It can identify executions allowed by a memory model
- It has interesting performances on “big” programs

Future Work

Make the plugin compatible with other plugins

- Currently only WP is supported
- Determine critical features

Make further experiments

- Integrate function call in CONC2SEQ
- Analyze more case studies

Add new features to our CHR solver

- Complete ARM
- Arithmetic and branching instructions

Combine CONC2SEQ and our CHR solver

- Validate sequentialy consistent behavior using the solver

Publications

Allan Blanchard, Nikolai Kosmatov, Matthieu Lemerre, and Frédéric Loulergue
A case study on formal verification of the Anaxagoros hypervisor paging system with Frama-C
In *International Workshop on Formal Methods for Industrial Critical Systems* (FMICS 2015), LNCS, pages 15–30, Oslo, Norway, June 2015. Springer

Allan Blanchard, Nikolai Kosmatov, and Frédéric Loulergue
A CHR-Based Solver for Weak Memory Behaviors
In *Proceedings of the 7th Workshop on Constraint Solvers in Testing, Verification (CSTVA 2016), and Analysis co-located with The International Symposium on Software Testing and Analysis (ISSTA 2016), Saarbrücken, Germany, July 17th, 2016.*, pages 15–22, 2016

Allan Blanchard, Nikolai Kosmatov, Matthieu Lemerre, and Frédéric Loulergue
Conc2Seq: A Frama-C Plugin for Verification of Parallel Compositions of C Programs
In *16th IEEE International Working Conference on Source Code Analysis and Manipulation* (SCAM 2016), 2-3 October 2016, Raleigh, NC USA, 2016

Publications

Thank you for your attention !

Allan Blanchard, Nikolai Kosmatov, Matthieu Lemerre, and Frédéric Loulergue
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Thank you for your attention

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