Verification of Parameterized Concurrent Programs By Modular Reasoning about Data and Control

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Parameterized concurrent programs

Goal

Compute numerical invariants (e.g. intervals, octagons, polyhedra) for parameterized concurrent programs.
Solution: annotation ι such that if some thread T's program counter is at v, then $\iota(v)$ holds over the globals & locals of T.

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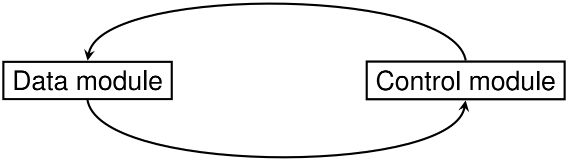
Natural model for device drivers, file systems, client/server-type programs, ...

Contributions

1. We develop an attack on the parameterized verification problem based on separating it into a **data** module and a **control** module
   - **Data module** computes numerical invariants
   - **Control module** computes a program model



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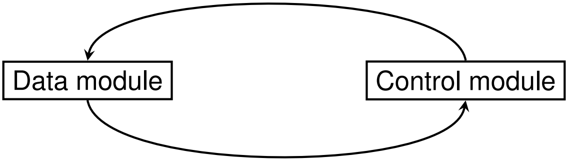

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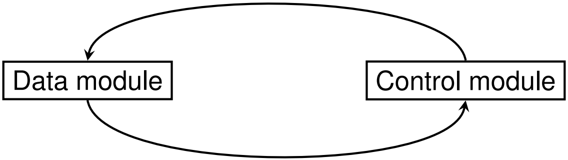

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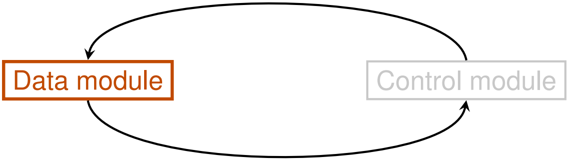

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Sequential program analysis

- Flow analysis: solve a system of equations valued over some abstract domain
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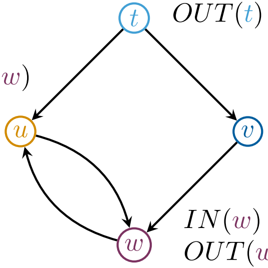

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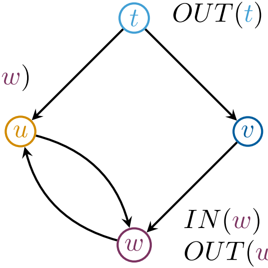

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- How about parameterized programs?

Data flow

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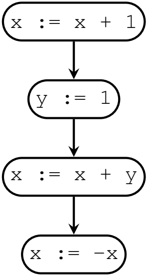

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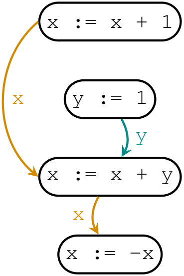

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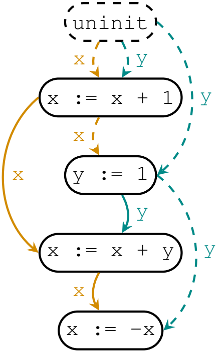
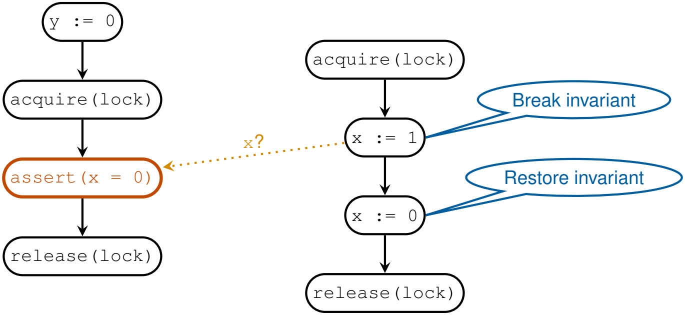


Why data flow?

Invariant: $x = 0$



Data flow graphs

A DFG for a program P is a directed graph $P^\sharp = \langle Loc, \rightarrow \rangle$, where

- $\rightarrow \subseteq Loc \times Vars \times Loc$ is a set of directed edges labeled by program variables

- Loc contains a distinguished `uninit` vertex
- Note: # of vertices does not depend on # of threads

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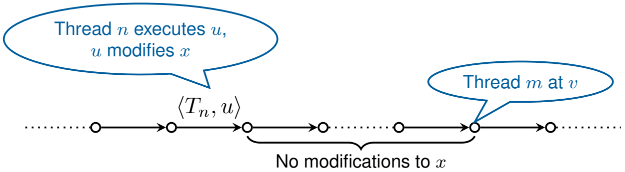

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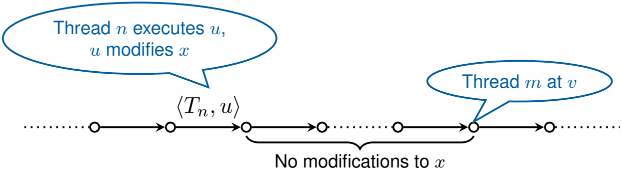

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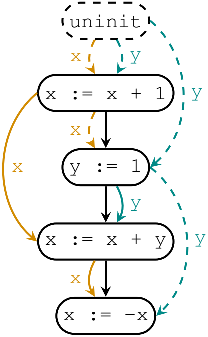

Computing invariants with DFGs

- DFGs induce a set of equations:

$$IN(v)_x = \bigvee_{u \to^x v} \exists (Vars \setminus \{x\}).OUT(u)$$
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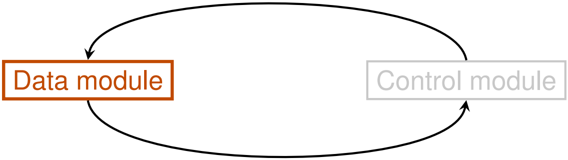
Theorem (DFG soundness)

If σ is a trace represented by a DFG $P^\sharp$, and ι is an inductive annotation for $P^\sharp$, then ι safely approximates the states reached by σ.

Overview



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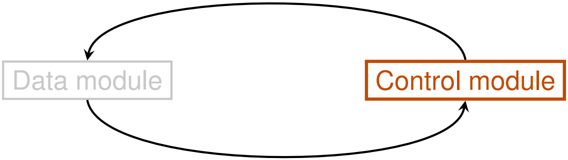

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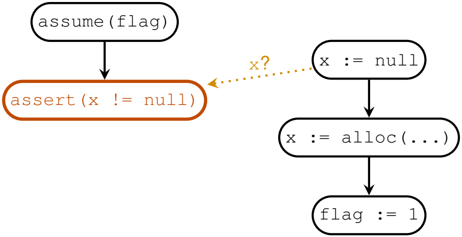
Precise DFG construction needs data

(`flag` is initially 0)



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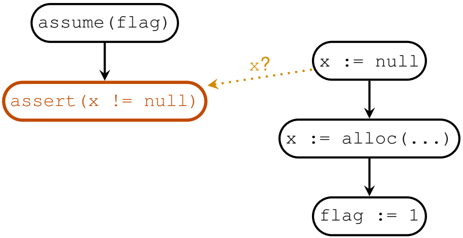

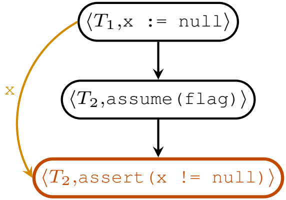

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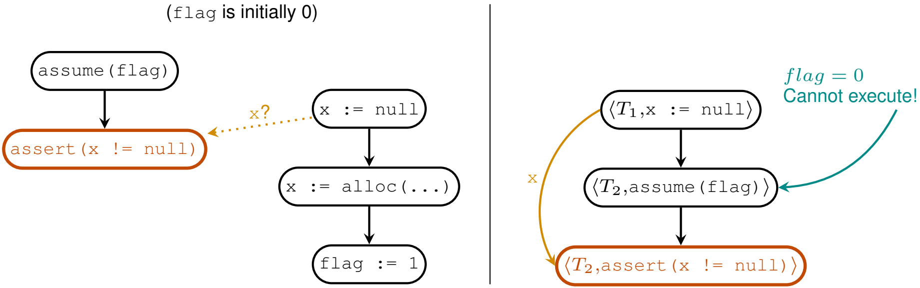

ι-feasible traces

Use an annotation ι to rule out infeasible traces: a trace σ is ι-*in*feasible if there is some subtrace $\sigma'\langle T_n, v\rangle$, some thread m, and some location u such that

- Thread m is at location u after executing σ'
- Thread n may not execute v in any state satisfying $\iota(u)$.

ι-feasible traces: example

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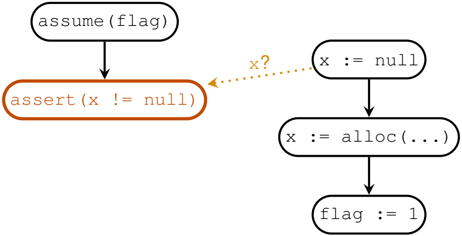

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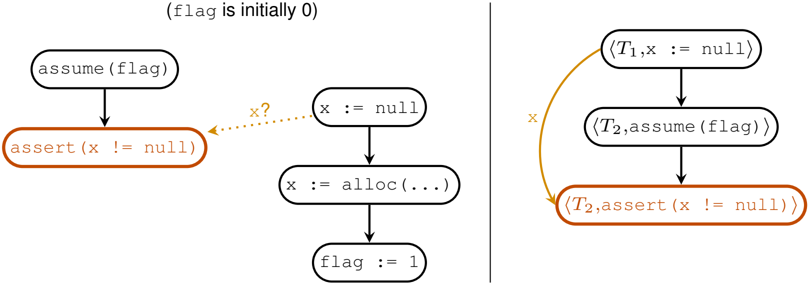

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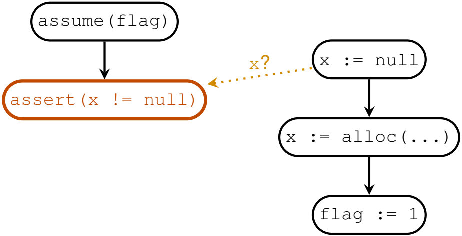

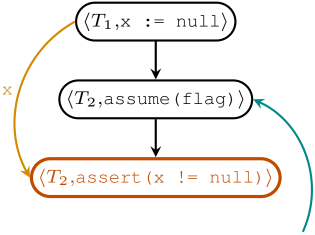

guard: $flag \neq 0$
T_1 at `x := alloc(...)`
T_2 at `assume(flag)`
is $\iota($`x := alloc(...)`$) \wedge flag \neq 0$
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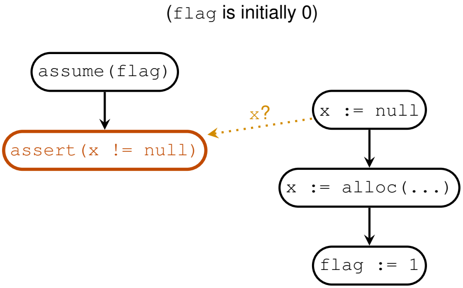

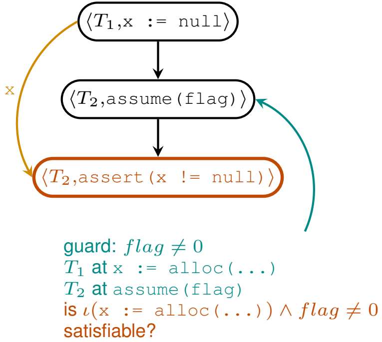

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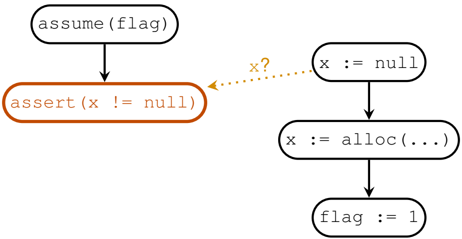

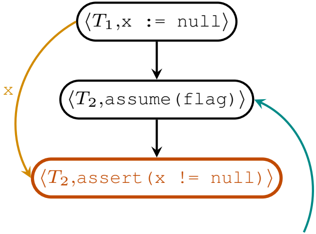

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- ι(`x := alloc(...)`) : $flag = 0 \Rightarrow$ infeasible
- ι(`x := alloc(...)`) : $true \Rightarrow$ feasible

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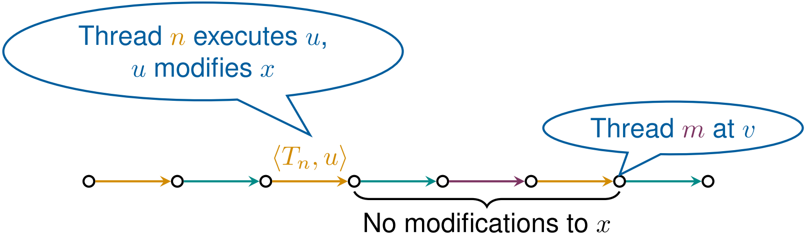
    - Data flow edges for 2-thread ι-feasible witnesses can be computed efficiently

Projection

Lemma (projection)

Let ι be an annotation, let σ be an ι-feasible trace, and let N be a set of threads. Then $\sigma|_N$, the projection of σ onto N, is also ι-feasible.



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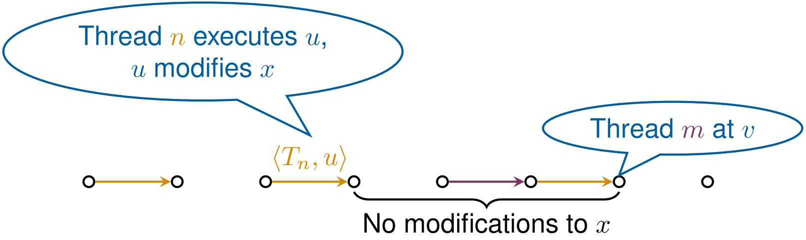

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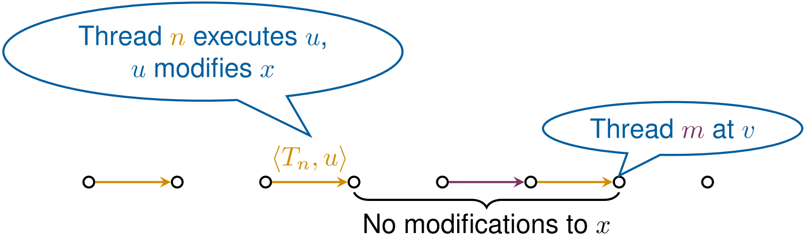

- A data flow edge $u \rightarrow^x v$ has an ι-feasible witness iff it has a 2-thread ι-feasible witness

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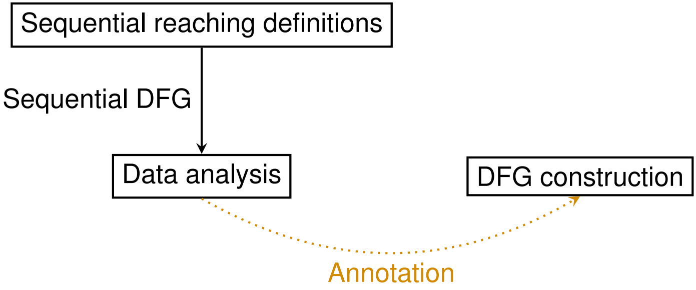

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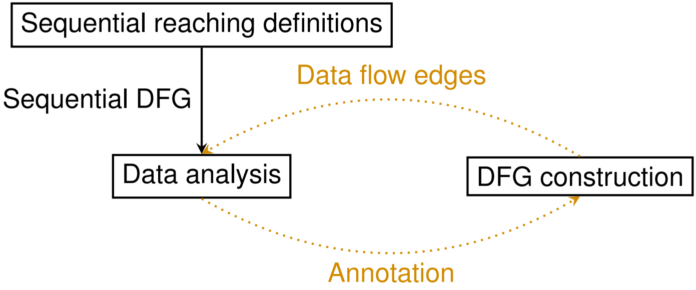

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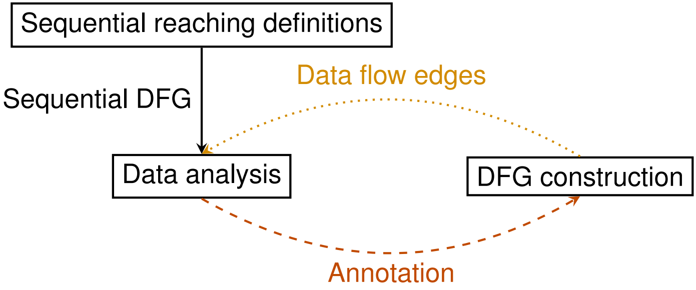

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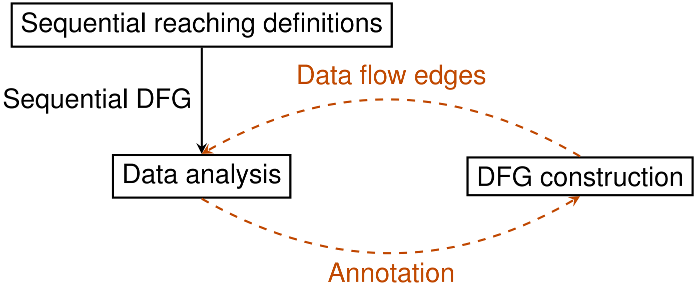

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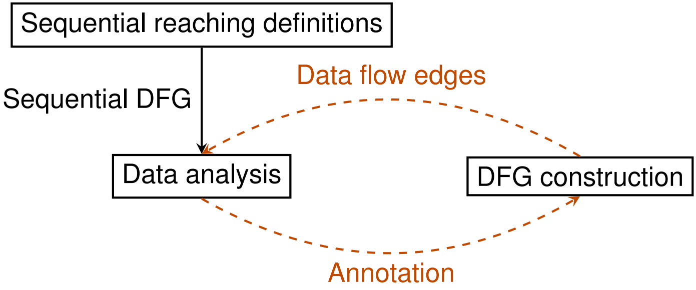

Experimental results

- We implemented our algorithm in a tool, DUET
- Integer overflow & array bounds checks for 15 Linux device drivers
    - DUET proves 1312/1597 (82%) assertions correct in 13m9s

Experimental results: Boolean programs

Boolean abstractions of Linux device drivers:

Suite 1	DUET	Linear interfaces[1]	Improvement
Assertions proved	2503	1382	81% increase
Average time	3.4s	16.9s	5x speedup

Suite 2	DUET	Dynamic cutoff detection[2]	Improvement
Assertions proved	55	19	189% increase
Average time	8.2s	24.9s	3x speedup

[1] S. La Torre, P. Madhusudan, and G. Parlato. Model-checking parameterized concurrent programs using linear interfaces. In CAV, pages 629–644. 2010.

[2] A. Kaiser, D. Kroening, and T. Wahl. Dynamic cutoff detection in parameterized concurrent programs. In CAV, pages 645–659. 2010.

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- Semi-compositional DFG construction algorithm

Questions?

Thank you for your attention.

Bonus slide: future work

- Improved algorithms for inferring groups of related variables to improve DFGs analyses over relational domains (e.g., octagons, polyhedra)
- Extension to handle aliasing