Validating Optimizations of Concurrent C/C++ Programs

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Concurrent Programming

```
int X = 0;   int Y = 0;

Y = 4;  ‖  if (X)
X = 1;  ‖    r = Y;
```

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X = 1;  ‖     r = Y;
```

Race on `X` $\rightsquigarrow$ undefined semantics

$X == 1 \wedge r \neq 4$ is possible

(i.e., the program is wrong)

Concurrent Programming in C11

```
atomic_int X = 0;   int Y = 0;

Y = 4;                   ||  if (atomic_load(&X,
                         ||           mo_acquire))
atomic_store(&X, 1,      ||
     mo_release);        ||     r = Y;
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Concurrent Programming in C11

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```

Thread 1	Thread 2
`Y = 4;`	`if (atomic_load(&X, mo_acquire))`
`atomic_store(&X, 1, mo_release);`	`r = Y;`

Concurrent Programming in C11

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atomic_int X = 0;   int Y = 0;
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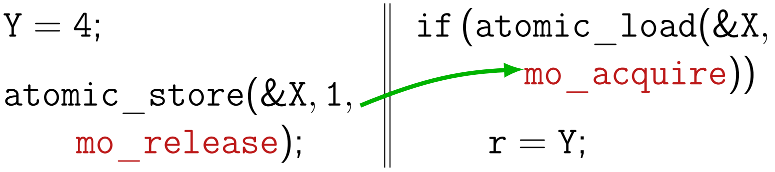

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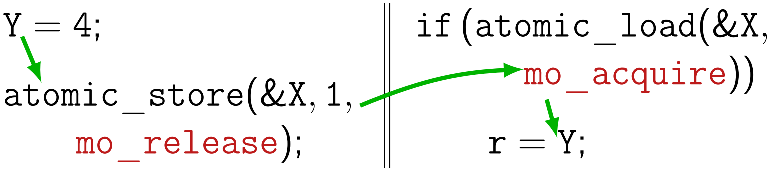

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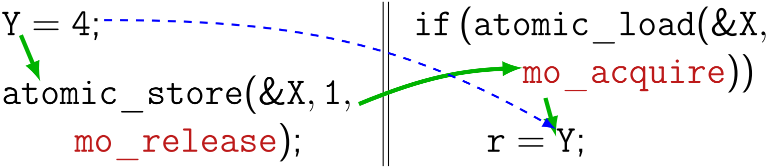

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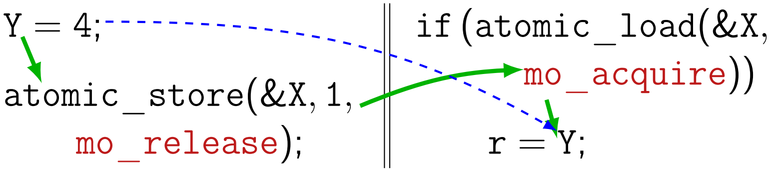

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     mo_release);        ||       r = Y;
```

⇓

$$X = Y = 0;$$

$$\begin{array}{l||l} Y = 4; & \text{if}(X_{\text{acq}}) \\ X_{\text{rel}} = 1; & \quad r = Y; \end{array}$$

An Unsafe Reordering

$$\begin{array}{c} X = Y = 0; \\ \updownarrow \left.\begin{array}{l} Y = 4; \\ X_{\mathrm{rel}} = 1; \end{array}\right\| \begin{array}{l} r = 4; \\ \mathrm{if}(X_{\mathrm{acq}}) \\ \qquad r = Y; \end{array} \end{array} \rightsquigarrow \begin{array}{c} X = Y = 0; \\ \left.\begin{array}{l} X_{\mathrm{rel}} = 1; \\ Y = 4; \end{array}\right\| \begin{array}{l} r = 4; \\ \mathrm{if}(X_{\mathrm{acq}}) \\ \qquad r = Y; \end{array} \end{array}$$

Always returns $r == 4$

May return $r == 0$

An Unsafe Reordering

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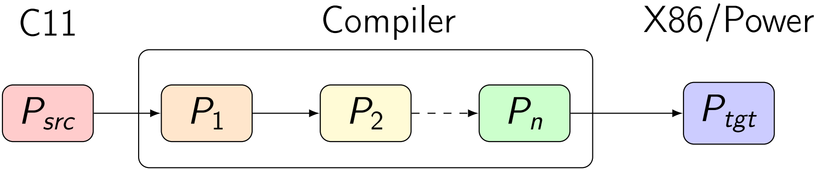
Always returns $r == 4$ May return $r == 0$

Optimizations for sequential programs are NOT always safe for concurrent programs.

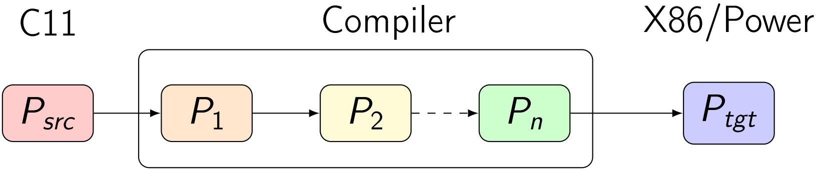
Questions



Q1: Which of the transformations are allowed?

Q2: Does a compiler perform only allowed transformations?

Questions



Q1: Which of the transformations are allowed?

C11 $\rightsquigarrow$ C11 [POPL'15]

- access(X); access(Y); $\rightsquigarrow$ access(Y); access(X);
- access(X); access(X); $\rightsquigarrow$ access(X);

Reordering Transformations

Reordering (a;b $\rightsquigarrow$ b;a)

$\downarrow$ a \ b $\rightarrow$	$\mathrm{R_{na}}$	$\mathrm{W_{na}}$	$\mathrm{R_{acq}}$	$\mathrm{W_{rel}}$	...
$\mathrm{R_{na}}$	✓	✓	✓	×	...
$\mathrm{W_{na}}$	✓	✓	✓	×	...
$\mathrm{R_{acq}}$	×	×	×	×	...
$\mathrm{W_{rel}}$	✓	✓	✓	×	...
...	...	...	...	...	...

$$t = X; s = Y_{\mathrm{acq}}; \rightsquigarrow s = Y_{\mathrm{acq}}; t = X; \quad \checkmark$$

$$s = Y_{\mathrm{acq}}; t = X; \rightsquigarrow t = X; s = Y_{\mathrm{acq}}; \quad \times$$

Elimination Transformations

Read-after-Read(RAR)

$t = X; t' = X; \rightsquigarrow t = X; t' = t;$ ✓

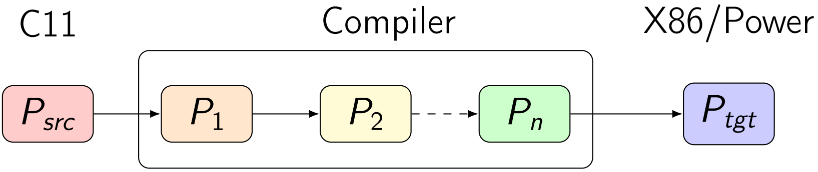
Read-after-Read(RAW)

$X = 1; t = X; \rightsquigarrow X = 1; t = 1;$ ✓

Over-written Writes(OW)

$X = 1; X = 2; \rightsquigarrow X = 2;$ ✓

Questions



Q1: Which of the transformations are allowed?

- C11 $\rightsquigarrow$ C11 [POPL'15]

Q2: Does a compiler perform only allowed transformations?

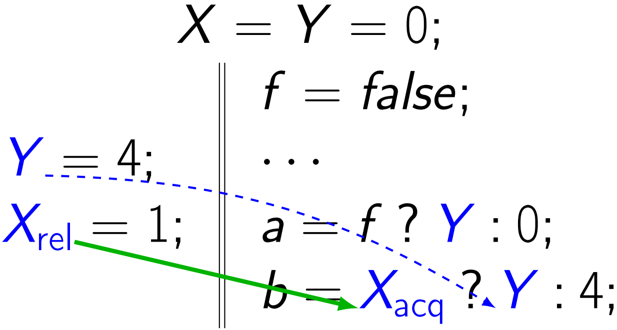
- C11 compilation by LLVM [CGO'16]

Another Example

$$X = Y = 0;$$

$$\begin{array}{r||l} & f = \mathit{false}; \\ Y = 4; & \dots \\ X_{\mathrm{rel}} = 1; & a = f \;?\; Y : 0; \\ & b = X_{\mathrm{acq}} \;?\; Y : 4; \end{array}$$

Another Example



$$X = Y = 0;$$

$$\begin{array}{l||l} & f = \mathit{false}; \\ Y = 4; & \ldots \\ X_{\text{rel}} = 1; & a = f \; ? \; Y : 0; \\ & b = X_{\text{acq}} \; ? \; Y : 4; \end{array}$$

Output: $b == 4$ always

LLVM Compilation Bug #22514

$$\begin{array}{l} X = Y = 0; \\ f = \mathit{false}; \\ \ldots \\ a = f \mathrel{?} Y : 0; \\ b = X_{\mathrm{acq}} \mathrel{?} Y : 4; \end{array} \overset{-O3}{\rightsquigarrow} \begin{array}{l} X = Y = 0; \\ f = \mathit{false}; \\ \ldots \\ s = Y; \\ a = f \mathrel{?} s : 0; \\ t = X_{\mathrm{acq}}; \\ b = t \mathrel{?} s : 4; \end{array}$$

Context:

$$\left[\; \parallel \; \begin{array}{l} Y = 4; \\ X_{\mathrm{rel}} = 1; \end{array} \right]$$

Output $b == 0$ possible in target.

LLVM Compilation Bug in More Detail

$$\begin{array}{l} X = Y = 0; \\ f = \mathit{false}; \\ \ldots \\ a = f \; ? \; Y : 0; \\ b = X_{\mathrm{acq}} \; ? \; Y : 4; \end{array}$$

$$\overset{(1)}{\leadsto}$$

$$\begin{array}{l} X = Y = 0; \\ f = \mathit{false}; \\ \ldots \\ s = Y; \\ a = f \; ? \; s : 0; \\ t = X_{\mathrm{acq}}; \\ r = Y; \\ b = t \; ? \; r : 4; \end{array}$$

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LLVM Compilation Bug in More Detail

$X = Y = 0;$
$f = \mathit{false};$
$\ldots$
$a = f\ ?\ Y : 0;$
$b = X_{\mathrm{acq}}\ ?\ Y : 4;$

$\overset{(1)}{\rightsquigarrow}$

$X = Y = 0;$
$f = \mathit{false};$
$\ldots$
$s = Y;$
$a = f\ ?\ s : 0;$
$t = X_{\mathrm{acq}};$
$r = Y;$
$b = t\ ?\ r : 4;$

$\overset{(2)}{\rightsquigarrow}$

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C11: (1) **Error**

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C11: (1) **Error** (2) **Correct**

LLVM Compilation Bug in More Detail

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C11: (1) **Error** (2) **Correct**

LLVM: (1) **Correct**

LLVM Compilation Bug in More Detail

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C11: (1) **Error** (2) **Correct**

LLVM: (1) **Correct** (2) **Error**

Our Approach: LLVM Validation

$$P_{src} \xRightarrow{\text{LLVM}} P_{tgt} \; ? \; \textbf{Correct} : \textbf{Potential Error}$$

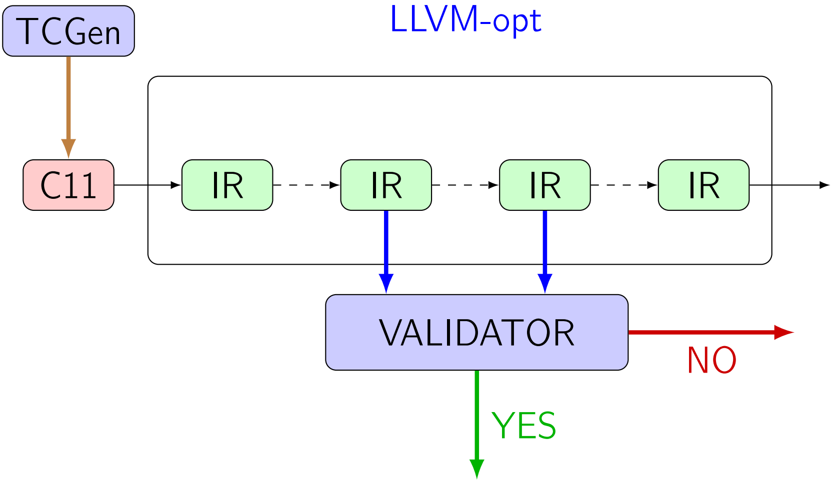
$$\Downarrow$$

$$P_{src} \xRightarrow{(R \cup E)^*} P_{tgt} \; ? \; \textbf{Correct} : \textbf{Potential Error}$$

w.r.t. safe reorderings (R) & eliminations (E):

- For the LLVM model
- For the C11 model

Tool Flow



Exposed concurrency compilation bugs in LLVM 3.6

- Reported and fixed in LLVM 3.7

Validation Schemes

Compiler Independent Matching (CIM)

- Can be used in validating other compilers.

Metadata Based Matching (MD)

- LLVM specific, uses metadata in LLVM.

Compiler Independent Matching Steps

Compiler Independent Matching (CIM)

- Can be used in validating other compilers.

Steps:

- Identify corresponding program paths
- Compute deletability of accesses
- Match access sequences and analyze

Example: Compiler Independent Matching

$$s_1 = X$$

$$s_2 = X$$

$$V = 1$$

$$s_4 = Z_{\text{acq}}$$

$$Y = 1$$

$$Y = 2$$

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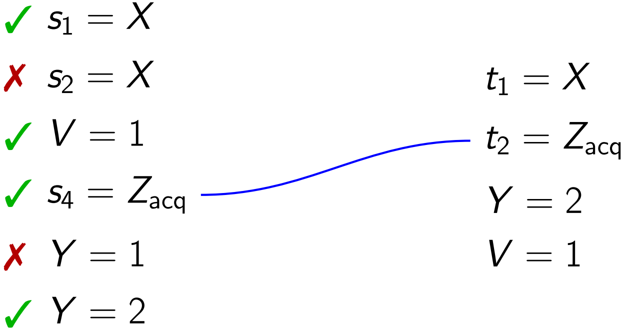

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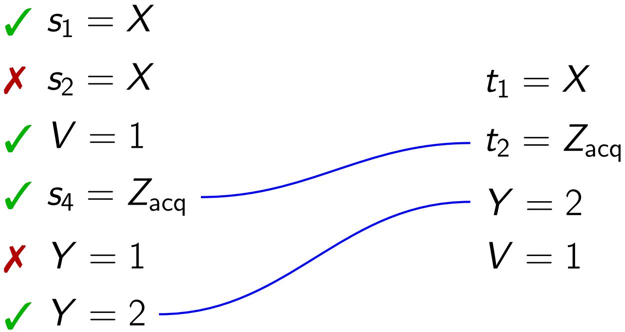

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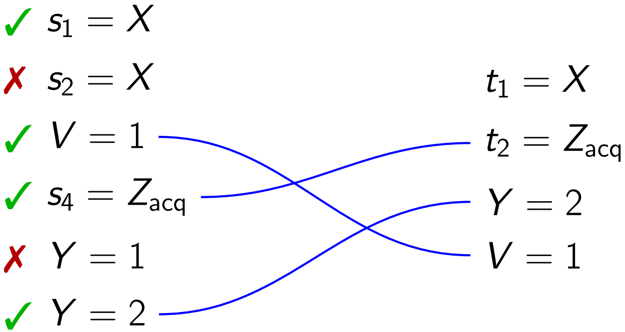

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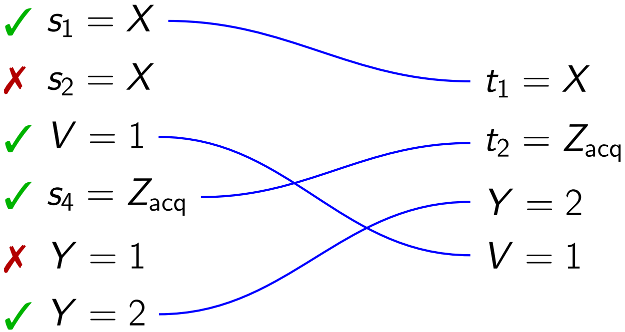

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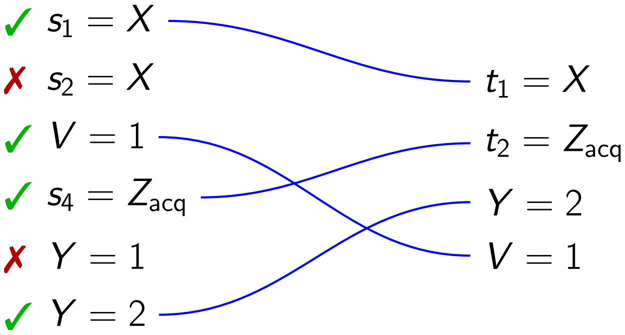

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- Check that unmatched accesses are deletable
- Check that reorderings are allowed

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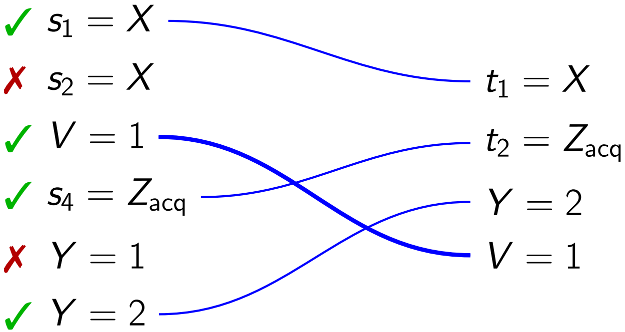

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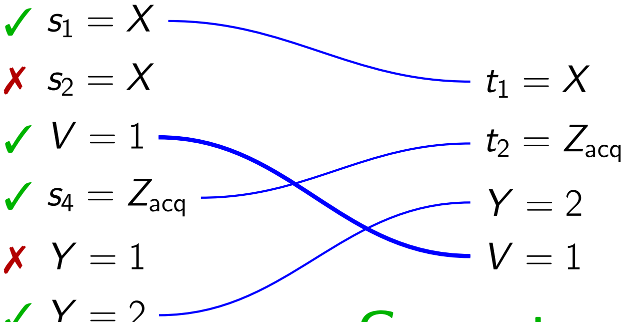

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Correct

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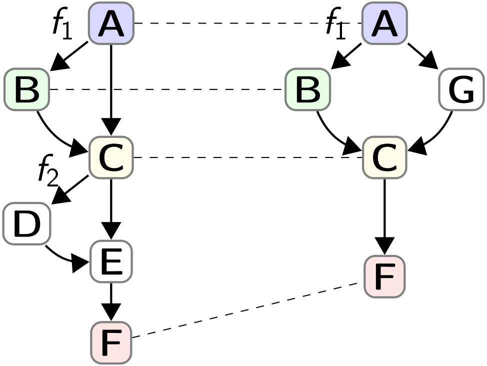
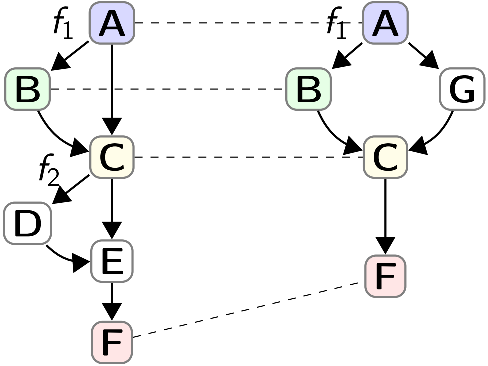
Program with Control Flow



$\{ABCDEF, ABCEF\} \Longrightarrow ABCF, \ \{ACDEF, ACEF\} \Longrightarrow AGCF$

- Use branching conditions to match the paths
  - using Z3 SMT solver
- Match access sequences for each path pair

Program with Loops



- Unroll loops a fixed number of times
- Use branching conditions to match the paths
  - using Z3 SMT solver
- Match access sequences for each path pair

Summary

Compiler optimizations require careful analysis

Reported LLVM concurrency compilation bugs; all were fixed.

Validator: `http://plv.mpi-sws.org/validc/`

Future Work

Integrate with validator for sequential programs.

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Handle loops effectively.

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Thank you !